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CONSTRUCTION OF AN INFORMATION MODEL OF THE DIGITAL TWIN OF THE TECHNOLOGICAL PROCESS IN A POWER UNIT AT A NUCLEAR POWER PLANT

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This study's object is the technological process that occurs at the power unit of a nuclear power plant, which is considered as a complex technical system with a multi-level hierarchical structure of functional subsystems. This paper addresses the task to improve the efficiency of modeling, monitoring, and controlling the technological process at a nuclear power plant as a complex technical system with a multi-level hierarchical structure.

A new approach to modeling the modes of a nuclear power plant based on system-cluster theory has been proposed. A cluster structure with key subclusters has been built: power control, protection, heat carrier adjustment, and emergency shutdown. Mathematical models have been constructed that take into account physical processes and logical-dynamic behavior of the monitoring and control system.

A feature of the devised approach is the use of the value of fractal dimensionality as a quantitative indicator of the self-similar scaled structure of functional subclusters. An algorithm for calculating fractal dimensionality has been proposed, which allows for real-time analysis of dynamic changes in the external and internal structure of the power unit process control.

Threshold values of the fractal dimensionality of subclusters have been determined for comparison with current parameters under normal and emergency modes.

It was established that the loss of one control level in a subcluster leads to a decrease in fractal dimensionality from 1.83 to 1.60, signaling a possible degradation of the SCADA level.

A model of a digital twin of the power unit process has been built based on a system-cluster approach, which allows for the implementation of visualization, simulation, monitoring, and diagnostics functions

Keywords: power plant, fractal dimensionality, cluster modeling, digital twin, technological parameters, emergency

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1. Introduction

At present, nuclear power is one of the most important sectors of critical infrastructure, ensuring the strategic energy security of the state. In the context of global challenges related to providing stable energy supply, environmental safety, efficient use of resources, and growing requirements for reliability, research aimed at increasing the technological level of management at nuclear power facilities is gaining particular relevance. In particular, the attention of scientists and engineers is increasingly attracted by the issue of constructing high-precision digital models of technological processes of power units at nuclear power plants (NPPs), which make it possible to significantly improve the quality of monitoring, diagnostics, and forecasting the state of systems.

The relevance of this topic is due to a number of factors. First, the technological processes in NPP power units are characterized by an extremely high level of complexity, a multi-level structure, and require constant monitoring of a large number of parameters. Second, enhanced requirements for the safety and reliability of the operation of such facilities require the introduction of intelligent analysis and management tools capable of detecting emergencies at an early stage. Thirdly, the rapid development of information technologies creates prerequisites for the widespread application of the concept of a digital twin – a virtual analog of a physical object that continuously reflects its real state.

The introduction of digital twins in nuclear power opens up new prospects: ensuring predictive maintenance, increasing the efficiency of personnel training, optimizing operation processes, and quickly responding to changing external conditions. However, the construction of such models requires not only a modern technical base but also a thorough scientific approach to formalizing complex relationships within the power unit. In this regard, there is a need to conduct fundamental research aimed at devising innovative modeling methods that could provide accurate and scalable description of technological processes, taking into account their structural and functional complexity.

Thus, research on information modeling of technological processes in NPP power units is extremely relevant. It has both important theoretical significance for the development of a systematic approach to the analysis of complex technical objects, and practical value for improving the level of automation, adaptability, and safety of nuclear power in general. The results to be obtained within the framework of such studies could become the basis for implementing new generations of information and control systems for software-technical complexes (STC) within technological process automated control systems (TP ACS), which meet modern requirements.

2. Literature review and problem statement

In [1], the implementation of multi-zone models for power dynamics control over VVER-1000 reactors is considered. The authors formalized the axial offset as an indicator of stability but did not apply clustering of control subsystems and fractal characteristics to assess structural complexity.

In [2], a model for analyzing the thermal hydraulics of the nuclear reactor core in transient regimes is described. Although the work has high engineering accuracy, it does not take into account the fractal hierarchy of regulators and actuators, which is essential in the context of building a digital twin. In [3], an approach to visualizing thermal processes in the reactor vessel is reported. The authors focus on hydrodynamic phenomena but do not include modeling of neutron kinetics and do not analyze the cluster structure of control elements.

In [4], the mechanics of the operation of control elements are modeled based on a multi-body approach. This allows the authors to take into account the dynamics of rod ejection but does not take into account the hierarchical structuring of control signals or the influence of fractal complexity on the system performance. In paper [5], mathematical modeling of the nuclear fuel cycle was carried out, including critical coefficients and energy balance. However, the structuring of the reactor in the form of a cluster model was not implemented, which limits its application in accident prediction problems. In [6], an attempt is made to combine fractal approaches with analysis of the percolation properties of the neutron field. The work has theoretical novelty but does not contain adaptation to the specific structure of the reactor of a nuclear power plant reactor.

Study [7] focuses on the conceptual construction of hierarchical cluster systems in complex technical objects. The authors proposed a fractal-cluster decomposition for reliability analysis but did not apply it to a specific nuclear installation.

In [8], general approaches to building digital twins for nuclear power units are given. Although the study covers the interaction between subsystems of TP ACS, the fractal-cluster structure is not used as a formalized mathematical basis.

In [9], the structural complexity of NPP control systems is analyzed from the point of view of multilevel automation. Despite the relevance of the topic, the authors do not use fractal methods for assessing or verifying the structure.

In [10], the possibility of applying system analysis to VVER-type reactors is considered, in particular, by clustering control functions. However, fractal dimensionality is not used as a quantitative indicator of complexity.

In [11], a fractal-cluster method is proposed for assessing the state of tightness of VVER-1000 fuel element claddings, which is based on monitoring the fractal dimensionality of the cladding surface and defect parameters. This approach demonstrates the potential of using fractal metrics in technical monitoring but does not structure the mathematical model of the reactor plant into clusters.

In paper [12], the authors use percolation and fractal geometry to describe the neutron chain reaction and diffusion processes with fractal characteristics. However, the proposed theoretical scheme is not adapted to a specific type of NPP reactor.

In study [13], compartmental and fractional-differentiated neutron kinetics are considered, which allows for an improved description of the dynamics of weakly transient processes in reactors, but without a hierarchical clustered approach.

In work [14], fractal derivatives are presented in the modeling of neutron diffusion, including the influence of fractal dimensionality on the intensity of processes in the core. However, a formalized cluster hierarchy is absent.

Study [15] considered the impact of changes in thermal-neutron parameters during the operation of control and protection systems in VVER-1000, which makes it possible to model the consequences of emergencies. However, the hierarchical clustering of subsystems is not taken into account.

Our review of the literature [1–15] illustrates a significant variety of approaches to modeling physical processes occurring at NPP power units. Despite the depth of individual technical solutions, such as the method of numerical analysis and visualization of flows, multi-body methods, digital twins, or fractal geometry, none of the studies implements a comprehensive integration of the system-cluster structure. This also applies to models of control over the technological process in a NPP power unit. Existing approaches, as a rule, are either limited to individual aspects (thermal hydraulics, neutron kinetics, mechanics of regulators), or ignore the structural complexity of the system as a holistic object with a multi-level hierarchy of control elements.

Thus, a common unresolved problem is the lack of a formalized model of NPP power unit control based on a system-cluster approach, which would integrate neutron kinetics, thermal hydraulics, and dynamics of control systems into a single digital platform. The would-be model of a digital twin of the technological process in ACS power unit could provide the ability to assess structural complexity, reliability, and predict emergency modes based on the clustering of actuators and the use of fractal metrics.

3. The aim and objectives of the study

The aim of our study is to build a simulation model of a digital twin of the technological process at a nuclear power plant based on a system-cluster approach, which could make it possible to assess the hierarchical self-similar scaled structure of subsystems, using the quantitative value of fractal dimensionality. This would make it possible, through continuous monitoring, to detect deviations in technological parameters from the norm at the pre-accident stage and to ensure adaptive response to non-standard emergencies in real time.

To achieve the goal, the following tasks were set:

– to model the technological process of a nuclear power plant's power unit based on a system-cluster approach;

– to consider the hierarchical structure of an information-control system at the power unit to implement an algorithm of the digital twin model;

– to implement in practice the system-cluster model using a digital twin of the power unit of the technological process at a nuclear power plant.

4. The study materials and methods

The object of our study is the technological process of an NPP power unit under normal, pre-accident, and emergency operating modes, considered as a complex technical system with a hierarchical cluster structure of automated control subsystems.

The principal hypothesis of the study assumes that the use of a digital twin simulation model, built on the basis of a system-cluster approach, makes it possible to continuously monitor and control changes in the dynamics of technological parameters of the NPP power unit.

The study was conducted using the digital twin method, which enabled simulation of the power unit operating modes based on archival data and generation of model scenarios. For this purpose, a software environment based on the HTML5 language was implemented, which included libraries for working with graph structures, numerical data processing, and visualization. Data on the technological parameters of NPP were fed to the input of the digital model, which included four main subclusters according to the key subsystems of the power unit: power control, protection, heat carrier adjustment, emergency shutdown.

At each time step of the simulation, the fractal dimensionality of the cluster structure of the system was estimated. For this purpose, a covering method was used, according to which the structure was covered with cells of a fixed size, and the number of such cells required to reproduce the geometry of the relationships was calculated. The resulting values of fractal dimensionality allowed us to track changes in the complexity and density of interactions between subsystems. The algorithm itself was implemented as a separate software module, which automatically received structural data from the digital twin model and displayed a plot of dimensionality changes over time.

All calculations were performed under conditions as close to real ones as possible – to this end, a simulation environment was used that reproduced the behavior of the reactor plant based on archived parameter profiles. Thus, the formed system allowed us to design a functional platform for virtual stability testing, to detect deviations in the control structure and assess potential risk points. The constructed data flow diagram reflects the logic of interaction between the control subsystems of the power unit, the digital twin model, analysis, and visualization units, as well as SCADA sources that provide the primary input of technological parameters in real time. Owing to this approach, it became possible not only to simulate the behavior of the technological process of the power unit in various scenarios but also formalize the process of detecting a decrease in the stability of the system by changing the fractal structure of its internal organization.

5. Results of research on the construction of a system-cluster dynamic model of a digital twin of a nuclear power plant's power unit

5. 1. Modeling the technological process of a nuclear power plant's power unit based on a system-cluster approach

Within the framework of the system-cluster approach to modeling complex technical systems, the technological process of a nuclear power plant's power unit is considered as a hierarchical structure with a cluster organization, which makes it possible to formally describe the relationships between its functional components. The cluster structure provides analytical divisibility and the possibility of integrating subsystems into a single mathematical model.

In the proposed model, the main cluster (cluster 1) is responsible for the functioning of the NPP's power unit. It is proposed to structurally divide this cluster into four functional subclusters that cover key aspects of dynamic control and reactor plant safety:

– $C_{1,1}$ – power control subcluster;

– $C_{1,2}$ – reactor protection subcluster;

– $C_{1,3}$ – heat carrier parameter control subcluster;

– $C_{1,4}$– reactor emergency shutdown subcluster.

Each of the specified subclusters describes a separate dynamic subsystem, which implements critically important functions to enable reliable operation of the nuclear reactor in an NPP's power unit under both standard and emergency conditions. Let us consider their mathematical models in more detail.

The power control subcluster $C_{1,1}$ enables regulation of the neutron flux and thermal power of an NPP's reactor core. Its model is based on point neutron equations, modified taking into account feedbacks on the fuel and heat carrier temperatures, as shown by the reactor power change equation (1) and the delayed neutron equation (2):

$$\frac{dP(t)}{dt}=\frac{\rho(t)-\beta}{\Lambda}P(t)+\sum_{i=1}^{n}\lambda_i C_i(t), \tag{1}$$

$$\frac{dC_i(t)}{dt}=\frac{\beta_i}{\Lambda}P(t)-\lambda_i C_i(t), \tag{2}$$

where dP is the reactor power at time t, MW;

$\rho(t)$ is the instantaneous reactivity, a dimensionless quantity that determines the deviation from the critical state;

β is the total fraction of delayed neutrons;

Λ is the neutron generation period, s ($\Lambda \approx 10^{-3}$ s);

λ_i is the decay constant (damping) of the i-th group of delayed neutrons;

$C_i(t)$ is the concentration of delayed neutrons of the i-th group at time t;

β_i is the fraction of delayed neutrons belonging to the i-th group.

The reactor protection subcluster $C_{1,2}$ forms a system of automatic response to critical deviations of technological parameters. Protection is implemented by analyzing threshold values of temperature, pressure, power, neutron flux. The basis of the model is discrete-continuous logical-dynamic algorithms (3)

$$Z_k(t) = \begin{cases} 1, & \text{if } x_k(t) > x_{thres}, \\ 0, & \text{otherwise,} \end{cases} \tag{3}$$

where $Z_k(t)$ – protection tripping state for the kth parameter; $x_k(t)$ – current value of the technological parameter; x_{thres} – threshold value of the technological parameter.

The heat carrier parameter control subcluster $C_{1,3}$ is responsible for ensuring effective heat removal from the core of the nuclear reactor of the NPP power unit by regulating the heat carrier parameters (pressure, temperature, flow rate). The dynamics are described by the thermal hydraulics equation (4)

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho h v) = Q - \nabla \cdot q, \tag{4}$$

where ρ is density; h is enthalpy; v is velocity vector; Q is the heat source; q is the heat flux.

The reactor emergency shutdown subcluster $C_{1,4}$ is designed to immediately stop the chain reaction in case of emergencies. The model is based on the introduction of pulsed negative reactivity (5)

$$\rho(t) = \rho_0 - \Delta\rho_{emer}, \tag{5}$$

where $\Delta\rho_{emer}$ is the instantaneously introduced reduction in reactivity by emergency lowering of absorbing elements or introduction of boric acid.

Within the framework of the system-cluster approach to modeling an NPP's power unit, the generalized state of the system at the macro level is denoted by aggregated variable $x_1(t)$, which reflects the reactor thermal power, neutron density, total reactivity, or other integral parameter. The dynamics of this variable are described by a differential equation, which takes into account both internal interactions between the system subclusters and the influence of external factors. Formally, it is given in the form of expression (6)

$$\frac{dx_1(t)}{dt} = f_1\left(x_1(t), \sum_{j=1}^{4} \alpha_j x_{1j}(t), u_1(t), \omega_1(t) \right), \tag{6}$$

where $x_{1j}(t)$ – state variables of the corresponding subclusters (power control, protection, heat carrier adjustment and emergency shutdown, etc.); α_j – weighting factors ($\alpha_j \in [0, 1]$); $u_1(t)$ – control influences; $\omega_1(t)$ – external disturbances.

In this case, each of the state variables of corresponding subclusters $x_{1j}(t)$ describes a specific physical or logical-dynamic subsystem, and their combination determines the behavior of the system as a whole. Weighting factors α_j establish the strength of influence of each subcluster on the general state of the nuclear reactor of an NPP's power unit. Their values can be determined both by engineering methods (expert estimates) and by statistical analysis of operational data, as well as by optimization in the process of model identification.

Control influences $u_1(t)$ come from the upper level of the information-control system of TP ASC STC and include setting the target power by the operator, changing operating modes, limiting the reaction speed, or activating certain protective scenarios. These signals can be both analog and discrete, which necessitates the inclusion of hybrid elements in the structure of function f_1.

External disturbances $\omega_1(t)$ are uncontrolled factors that affect the operation of the system from the outside. These include changes in electrical load, return heat carrier temperature, power grid failures, failures in auxiliary systems, or fluctuations in environmental parameters. Their influence is also taken into account in function f_1, which is nonlinear, multifactorial, and, in the general case, stochastic.

Function f_1 plays the role of an aggregate operator of the system's response to state changes and is built in the form of an empirical model as an affine combination of main influencing factors (7)

$$f_1 = \alpha_0 + \alpha_1 x_1 + \sum_{j=1}^{4} b_j x_{1j} + c_1 u_1 + c_2 \omega_1 + \varphi(t), \tag{7}$$

where α_0 is a constant component that describes the basic level of the system response in the absence of changes;

$\alpha_1 x_1$ is a term that takes into account the influence of the current state of the aggregated variable (for example, the thermal power of the reactor);

$\sum_{j=1}^{4} b_j x_{1j}$ is the weighted sum of the influences of the variable subclusters (power control, protection, heat carrier, and emergency shutdown);

$c_1 u_1$ is the influence of control signals from a higher level of control (SCADA, MES);

$c_2 \omega_2$ is the influence of external disturbances that are not directly controlled by the system;

$\varphi(t)$ is a stochastic residual error or noise that takes into account uncertainties, unformalized influences, and false alarms.

In a more general case, function f_1 may not have a fixed analytical form. It is built on the basis of fuzzy logic, artificial neural networks, or the application of system identification methods using historical operational data. This approach ensures the ability of the model to reflect complex behavior of the power unit not only in normal operation but also under transient or emergency modes. The proposed integrated system-cluster dynamic model of an NPP's power unit can be used as a basis for building a digital twin of the power unit, predictive analysis systems, and intelligent power plant safety management.

5. 2. Considering the hierarchical structure of an information-control system of the power unit for implementing the digital twin model algorithm

According to the fractal-cluster theory [7, 8, 11], each cluster of an NPP's power unit can be represented as a self-similar, scalable structure consisting of lower-level subclusters. The hierarchical structure of the NPP process control system based on the system-cluster approach is shown in Fig. 1.

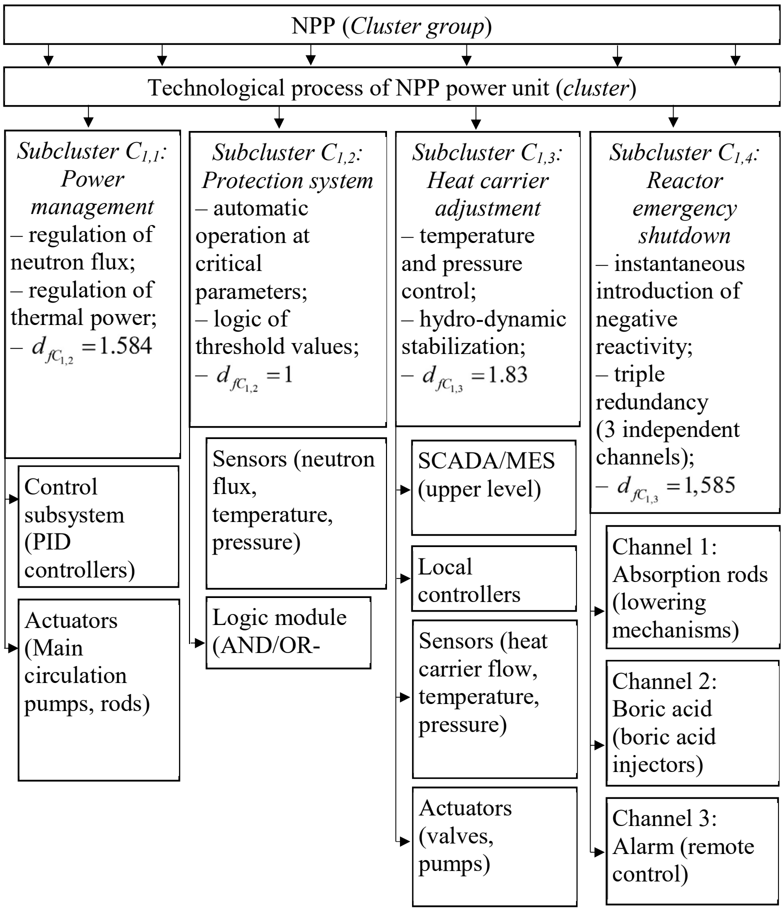


Fig. 1. Hierarchical structure of the nuclear power plant's power unit control system based on the system-cluster approach

Such structuring makes it possible to locally model controlled subsystems with subsequent aggregation of results from the micro- to the macro-level. In this context, the subcluster of level $C_{1,j}$ itself acts as a cluster that is subject to fractal decomposition into more elementary functional units (for example, reactor, turbine, generator, actuators, sensors, regulators, etc.).

The fractal approach to analyzing the structure of an NPP's power unit makes it possible to quantitatively characterize the degree of complexity of the organization of each functional subcluster. One of the key indicators of such complexity is the value of the fractal dimensionality, which is expediently calculated using the information space coverage method, which takes into account the scale invariance and hierarchical structure.

For a discrete structure with known levels of detail, fractal dimensionality d_f can be calculated using the following formula (8)

$$d_f = \frac{\log_{10} N(\varepsilon)}{\log_{10}(1/\varepsilon)}, \qquad (8)$$

where $N(\varepsilon)$ is the number of elements (nodes, subsystems); ε is the scale of division (for example, the fraction of the complete structure into which the object is divided).

Subcluster $C_{1,1}$, which is responsible for the continuous regulation of the thermal power of the nuclear reactor at NPP, is one of the key mechanisms that enables stable operation of the power unit under a given mode. The task of this subcluster is to maintain the set power value in accordance with changes in the load or instructions from TP ACS operator to higher levels of control (ACS dispatching).

Control over reactor thermal power parameters is one of the main functions of the automatic control system. Its dynamics can be described by a simplified first-order differential equation (9)

$$\frac{dx_{11}(t)}{dt} = -k_p \cdot \left(x_{11}(t) - r(t)\right) + u_{11}(t), \qquad (9)$$

where $x_{11}(t)$ is the value of the current thermal power; $r(t)$ is the value of the target power coming from the higher level; k_p is the proportional control coefficient; $u_{11}(t)$ is the parameter of the control signal to the actuators, which is measured in real time.

The model under consideration assumes that the deviation from the set power value is compensated by the corresponding corrective signal. In practical control systems, multi-level signal transmission occurs – from SCADA (upper level) to controlling elements.

To describe the fractal structure of the subcluster $C_{1,1}$ system, control hierarchy is divided into levels given in Table 1.

We calculated the fractal dimensionality for the level with maximum division using the covering method according to formula (8), which allowed us to obtain the value of fractal dimensionality $d_{fC_{1,1}} = 1.584$ and quantitatively describe the complexity of the subcluster structure.

Table 1

Levels of the fractal structure of the $C_{1,1}$subcluster system

Level	System components	N_i	ε
1	Main control system (TP ACS)	1	1
2	Block regulation	3	1/2
3	Local regulators	9	1/4
4	Actuators (main circulation pump (MCP), rods)	27	1/8

The value of fractal dimensionality $d_{fC_{1,1}} = 1.584$ corresponds to a structure with a high degree of detail, but less than a planar one ($d_f < 2$), which is typical for systems that have a scaled, self-similar fractal-cluster structure. The value of fractal dimensionality $d_{fC_{1,1}} = 1.584$ also indicates the presence of a deep hierarchy with a high degree of control detail. According to the system-cluster methodology, the normalized (specified) range of fractal dimensionality is $d_f \approx 1.5 \div 1.7$, where:

– 1.5 is the lower limit, corresponding to a stable but simpler configuration with the minimum required number of levels;

– 1.7 is the upper limit, reflecting a fully engaged multi-level control loop.

A decrease in d_f below 1.5 may indicate a simplification of the structure, loss of control elements, or control functions (a sign of a pre-accident state). In turn, an excess of d_f above 1.75 is usually associated with system overload or duplication of functions.

The reactor plant protection system subcluster $C_{1,2}$ plays a critically important role in maintaining operational safety.

The main task of this subcluster is to promptly respond to exceeding the permissible power level or other emergencies.

Mathematically, the protection system operation logic model can be represented as a Boolean (two-valued) function (10)

$$x_{12}(t)=\begin{cases}1, \text{ if } x_1(t)>x_{thres},\\ 0, \text{ otherwise},\end{cases} \tag{10}$$

where $x_1(t)$ is the current value of the reactor thermal power; x_{thres} is a value exceeding which the system initiates protection; $x_{1,2}(t)$ is the activation signal of the protective mechanism (1 – activated, 0 – inactive). This is a simple but extremely important logic, which is implemented through a combination of sensors and a logic module for processing information signals (Table 2).

Table 2

Levels of the fractal structure of the $C_{1,2}$ subcluster system

Level	System component	N_i	ε
1	Central logic unit that makes decisions	1	1
2	Two detectors (e.g., neutron detectors or power meters) that provide data to the logic	2	1/2

To determine the complexity and structural depth of the control system, the fractal dimensionality is used, which gives an idea of the number of active elements of the system depending on scale: $d_{fC_{1,2}}=1$. The resulting value of fractal dimensionality $d_{fC_{1,2}}=1$ for subcluster $C_{1,2}$ reflects the most simplified, linear structure of the protection system, which fully corresponds to its functional purpose – instant response to emergencies without delays and logical branches. Within the framework of the system-cluster approach, the normalized (specified) range for this type of subcluster is $d_f \approx 0.9 \div 1.2$, where:

– 0.9 is the lower limit, signaling the potential shutdown of one of the detectors or degradation of signal transmission;

– 1.2 is the upper limit, which may be followed by excessive duplication of functions or complexity of logic.

A decrease in d_f below 0.9 may indicate a loss of reliability or partial unavailability of signal channels (pre-emergency condition), and an increase in d_f above 1.2 indicates a risk of response delays due to excessive structural complexity.

With increasing complexity or with the addition of additional levels of control and adaptive logic, the value of fractal dimensionality may increase. But in this case, simplicity is an advantage that provides high performance and reliability. In the reactor control system, an important function is to maintain the heat carrier temperature within the established standards (subcluster $C_{1,3}$). Changing the heat carrier temperature of an NPP's power unit directly affects the efficiency of heat transfer, reaction stability, and safety. Therefore, the heat carrier control system plays the role of a stabilizing element in the dynamic equilibrium of the reactor. Mathematically, behavior of the heat carrier temperature can be described by the following differential equation (11)

$$\frac{dx_{13}(t)}{dt}=-k_T\cdot\left(x_{13}(t)-T_{nom}\right)+u_{13}(t), \tag{11}$$

where $x_{13}(t)$ is the current heat carrier temperature; T_{nom} is the rated temperature value; $u_{13}(t)$ is the control signal on MCP, measured in real time; k_T is the thermal control coefficient, which determines the speed of the system's response to deviations.

The physical implementation of the control subsystem includes several levels of automation (Table 3).

Table 3

Levels of the fractal structure of the $C_{1,3}$ subcluster system

Level	System components	N_i	ε
1	SCADA (upper level)	1	1
2	Main controllers	2	1/2
3	Local controllers / subsystems	6	1/4
4	Sensors (temperature, pressure, etc.)	12	1/8
5	Actuators (MCP, valves)	24	1/16

The calculated value of fractal dimensionality according to formula (8) is equal to $d_{fC_{1,3}}=1.83$ for subcluster $C_{1,3}$, indicating a high functional complexity and branching of the structure, characteristic of systems with multi-level automation. Such a level of detail is typical for stabilizing subclusters that interact with both process variables (temperature, pressure) and controlling elements (MCP, valves).

Within the framework of the system-cluster approach, the normalized (specified) range of fractal dimensionality for temperature maintenance systems is $d_f \approx 1.7 \div 1.9$, where:

– 1.7 is the lower limit, indicating a decrease in the number of involved links or the loss of one of the control levels;

– 1.9 is the upper limit, indicating a full-fledged implementation of a multi-level SCADA architecture with redundancy.

A drop in d_f below 1.7 potentially indicates a simplification of the structure, decommissioning of part of the equipment, or a violation of signal transmission (a sign of a pre-accident state). A d_f value above 1.9 indicates a risk of excessive complexity, which could lead to a decrease in performance or difficulty in synchronizing control signals.

The normalized (set) value is an optimal indicator that provides a balanced interaction between stability, adaptability, and flexibility of heat carrier temperature control under conditions of dynamic reactor operation.

Subcluster $C_{1,4}$ plays a critical role in ensuring the nuclear safety of an NPP power unit. The main purpose of the system is to promptly reduce the reactor power to a minimum level in the event of an accident caused by exceeding control parameters or receiving an emergency stop signal from the dispatcher or automation.

The functioning of this subcluster is described by a logical conditional construction

$$x_{14}(t)=\begin{cases}1, \text{ if } x_{1,2}(t)=1 \text{ or signal } MES,\\ 0, \text{ otherwise},\end{cases} \tag{12}$$

where $x_{14}(t)$ is the activity of the emergency stop function; $x_{1,2}(t)$ is the signal from subcluster $C_{1,2}$ (protection system).

In practical implementation, according to the requirements for nuclear safety, the emergency stop is designed with triple redundancy (independent channels, signal duplication, several physical actuation circuits). Thus, the structure becomes branched, although it remains shallow.

With three independent actuation channels with the same scale (depth – level 2, ε = 1/2), the total number of elements at this level is 3, i.e., $d_{fC_{1,4}}=1.585$. The calculated value of fractal dimensionality $d_{fC_{1,4}}=1.585$ for subcluster $C_{1,4}$ indicates a structurally simple but reliably redundant architecture that provides instant emergency response. The presence of three independent channels with the same depth ($\varepsilon = 1/2$) indicates a purposeful duplication of critical functions in accordance with safety requirements. Within the system-cluster approach to modeling, the normalized (specified) range of d_f for emergency stop subclusters is $d_f \approx 1.4 \div 1.6$, where:

– 1.4 is the lower limit allowed for the simplest scheme with $2N$ redundancy;

– 1.6 is the upper limit covering architectures with triple redundancy and minimal logical delays.

A decrease in d_f below 1.4 may indicate a failure of one of the emergency response channels or loss of logic independence (a sign of a pre-emergency state), and an excess of 1.6 is a potential overload of the logic, which may complicate the synchronization of operation. This value of fractal dimensionality is typical for emergency logic systems of safety class 1, which must have a simple but redundant architecture, high performance, and fault tolerance.

Within the framework of the system-cluster approach to modeling the information-control system of TP ACS STC in a nuclear power plant power unit, functional modules can be represented in the form of hierarchically organized subclusters. Each level of this hierarchy implements separate control or executive functions. The fractal dimensionality d_f assesses how hierarchically branched the structure of the subcluster is. For this purpose, the logarithmic ratio between the number of active elements N_i at each level i and the corresponding decomposition scale ε_i is used. The summary parameters of the fractal structure of subclusters are given in Table 4.

Table 4 demonstrates that the heat carrier control system has the greatest fractal complexity, due to the need for flexible, multi-level temperature control. On the other hand, the protection system implements a simple two-stage triggering logic without a complex hierarchy.

Each value of fractal dimensionality determines the degree of complexity of the subcluster and its ability to maintain control in the event of a connection failure or loss of elements. For dynamic assessment of changes in the parameters of the technological process in an NPP power unit, the fractal dimensionality of the subclusters is constantly updated, based on data from controllers, sensors, actuators, etc. The algorithm for implementing the model of the digital twin of the technological process of an NPP power unit (Fig. 2) should include:

– identification of active elements at each level;

– estimation of the depth of the hierarchy in real time;

– calculation of the current value of fractal dimensionality $d_{f_{real}}(t)$;

– comparison with the given dimensionality $d_{fC_{i,j}}(t)$ for each subcluster.

For each of the subclusters in the normal state of the system, a threshold value of fractal dimensionality $d_{fC_{i,j}}(t)$ has been calculated that is stored in the data memory cells of the information-control system of an NPP power unit's control and monitoring system. During operation, the current values may change due to the dynamics of changes in the parameters of subsystems, reserves, or violations of the signal transmission logic.

Table 4

Levels of the fractal structure of the $C_{1,3}$ subcluster system

Subcluster	ID	Level	N_i	ε	d_f
$C_{1,1}$	Power management	4	27	1/8	1.584
$C_{1,2}$	Protection system	2	2	1/2	1
$C_{1,3}$	Heat carrier adjustment	5	45	1/8	1.83
$C_{1,4}$	Emergency stop	2	3	1/2	1.585

Therefore, the system constantly monitors the value of fractal dimensionality in real time, determining deviations according to formula (13)

$$\Delta d_f(t) = d_{fC_{i,j}}(t) - d_{f_{real}}(t), \qquad (13)$$

where $d_{fC_{i,j}}(t)$ is the threshold (set) value of the fractal dimensionality of a subcluster; $d_{f_{real}}(t)$ – current calculated dimensionality of subcluster at time t.

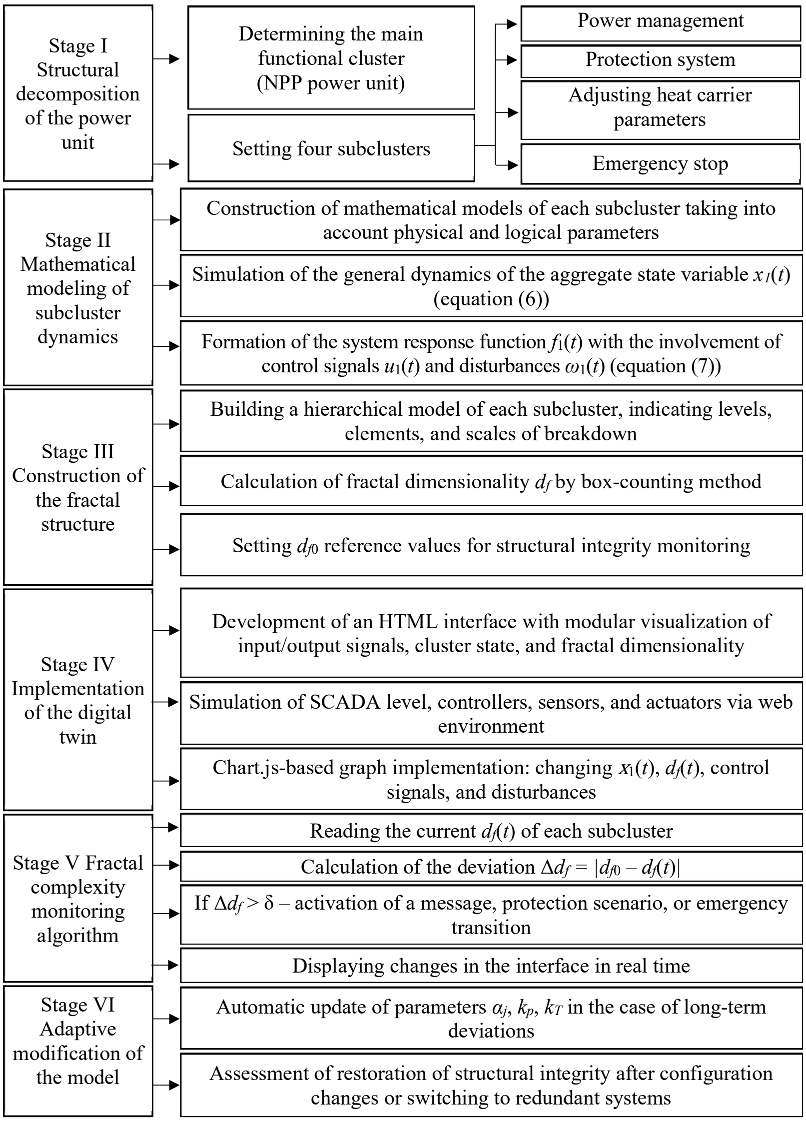


Fig. 2. Algorithm for implementing a digital twin model of the technological process of a nuclear power plant's power unit

For the purposes of monitoring the state of an NPP power unit in the information-control system within STC of TP ACS, the fractal dimensionality of each subcluster can be used as an indicator of the integrity of the structure. Under a normal mode, fractal dimensionality remains close to the threshold value $d_{fC_{i,j}}(t)$. If, as a result of degradation, damage, loss of communication channels, or functional failure, any subcluster starts to function with a smaller number of active levels or elements, this causes a decrease in fractal dimensionality.

This approach makes it possible to detect pre-accident situations when the control structure is simplified (for example, a signal transmission link or control level is lost) and to perform control actions in time. If $\Delta d_f(t)$ exceeds the permissible threshold, a warning or execution mechanism is activated, and in some cases – an emergency stop or switching to a backup system.

Thus, fractal dimensionality is not just a mathematical indicator but a structural diagnostic parameter that makes it possible to detect hidden violations in the architecture of control system even in the absence of functional failures.

5. 3. Practical implementation of the system-cluster model using a digital twin of an NPP's power unit technological process

Within the framework of the system-cluster approach, the implementation of a digital twin of the NPP power unit technological process is based on multi-level modeling of the interaction of functional subclusters, monitoring their structural integrity, and assessing fractal dimensionality in real time. This makes it possible not only to reflect the current state of the system but also predict its behavior based on changes in structural characteristics.

The digital twin is implemented in the form of a software-hardware complex that integrates with the existing information-control system of TP ASC STC in an NPP's power unit. Its architecture includes:

– a module for acquiring data from technological sensors, actuators, and controllers;

– a structural identification module that calculates the current values of the fractal dimensionality;

– a comparison module with normalized threshold values to determine deviations;

– a visualization and diagnostics module that displays the current state of the system and reports on potential structural failures;

– a predictive analysis module that uses accumulated statistics to identify patterns in deviations of technological parameters.

In order to monitor the state of an NPP's power unit, an adaptive interface was designed that provides visualization of the main technological parameters in real time, as well as performs system-cluster analysis based on input data.

The digital twin is built taking into account the principles of adaptive design. The main layout is carried out using a two-dimensional layout construction system that makes it possible to place elements in a two-column format: the left control panel and the right visualization panel.

For flexible configuration of the visual appearance, global variables were used that determine the color palette, radius of curvature, shadows, etc. This makes it possible to quickly adapt the interface to the user's needs.

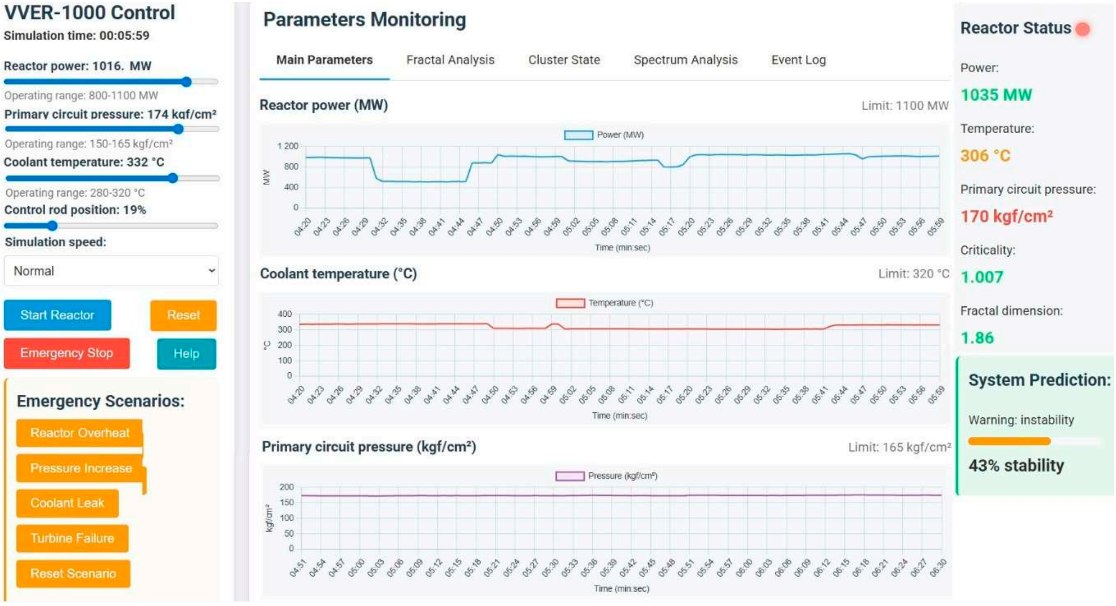
As shown in Fig. 3, the right part of the interface implements a system of tabs, where the following modules are displayed:

– basic parameters: reactor power, heat carrier temperature, pressure in the primary circuit;

– fractal analysis: a plot of changes in fractal dimensionality in dynamics (Fig. 4);

– cluster state: radar chart of cluster structure across five technical subsystems.

For visualization, an interactive plot construction library was used, which makes it possible to build high-quality interactive plots. All plots are initialized when the page loads, store the state in the global object of current values, and are automatically updated when the input data changes. Each plot has separate stylized settings for color, borders, markers, axis ranges, etc. Due to the modularity of the implementation, the code structure provides for further expansion of the functionality, in particular, connecting new plots, data processing algorithms, analytical functions, and integration with SCADA systems.



VVER-1000 Control

Simulation time: 00:05:59

Reactor power: 1016. MW

Operating range: 800-1100 MW

Primary circuit pressure: 174 kgf/cm²

Operating range: 150-165 kgf/cm²

Coolant temperature: 332 °C

Operating range: 280-320 °C

Control rod position: 19%

Simulation speed: Normal

Parameters Monitoring

Reactor power (MW) Limit: 1100 MW

Coolant temperature (°C) Limit: 320 °C

Primary circuit pressure (kgf/cm²) Limit: 165 kgf/cm²

Reactor Status

Power: 1035 MW

Temperature: 306 °C

Primary circuit pressure: 170 kgf/cm²

Criticality: 1.007

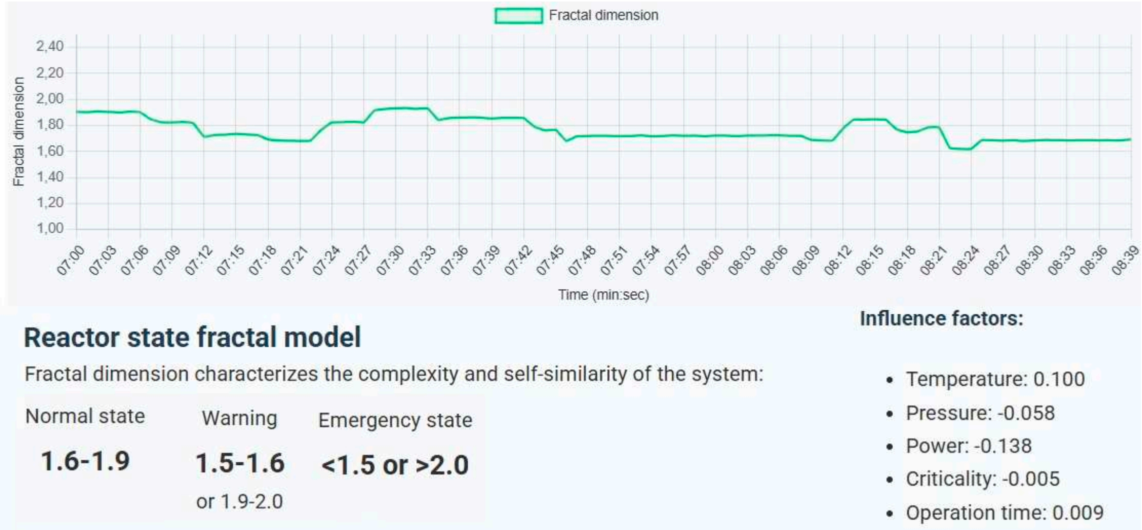
Fractal dimension: 1.86

System Prediction:

Warning: instability

43% stability

Fig. 3. Interface of the digital twin of the technological process of the power unit of a nuclear power plant with a VVER-1000 reactor



Reactor state fractal model

Fractal dimension characterizes the complexity and self-similarity of the system:

Normal state	Warning	Emergency state
1.6-1.9	**1.5-1.6** or 1.9-2.0	**<1.5 or >2.0**

Influence factors:

- Temperature: 0.100
- Pressure: -0.058
- Power: -0.138
- Criticality: -0.005
- Operation time: 0.009

Fig. 4. Dynamics of change in fractal dimensionality

6. Discussion of results related to the construction of a digital twin model of the technological process in an NPP's power unit

Our results demonstrate that the goal to build a digital twin model of the technological process in an NPP's power unit has b achieved within the framework of the current study. A system-cluster approach was applied, according to which the technological process of the power unit is represented in the form of a hierarchical structure with a cluster organization. The main cluster of the power unit (C_1) was divided into four sub-cluster subsystems: power control ($C_{1,1}$), protection system ($C_{1,2}$), heat carrier adjustment ($C_{1,3}$), and emergency shutdown ($C_{1,4}$). Each of the subsystems was modeled on the basis of the corresponding physical or logical-structural apparatus. For example, the $C_{1,1}$ model was based on point neutron equations with delayed neutrons (equations (1) to (2)), while the $C_{1,2}$ subcluster was implemented through discrete-logic mechanisms with threshold activations (3). The heat carrier parameters control ($C_{1,3}$) was described by the thermohydraulic equation (4), and the emergency shutdown system was described by pulse reactivity (5).

The state of the system was described by an aggregate variable $x_1(t)$, which combined the influence of all subclusters (6). The system response function f_1 (7) took into account the influence of the current state of the subclusters, control influences $u_1(t)$ and external disturbances $\omega_1(t)$. That allowed us to model the behavior of the power unit under both normal and emergency conditions, which is confirmed by the data in Table 1 and the results in Fig. 1, 2.

The state of the technological process was assessed based on fractal analysis. Subcluster subsystems were considered as self-similar structures, and their complexity was estimated using fractal dimensionality d_f, which was calculated by the covering method (8). For subcluster $C_{1,1}$ the value of $d_f = 1.584$ was obtained, which corresponds to a high degree of detail and a deep hierarchy of power control. The protection subcluster $C_{1,2}$ was characterized by a value of $d_f = 1$, indicating a simplified structure inherent in high-speed reactive systems. Subcluster $C_{1,3}$, responsible for heat carrier adjustment, had the highest fractal dimensionality of $d_f = 1.83$, indicating multi-level complexity and the need for precise regulation. The emergency shutdown system $C_{1,4}$ showed a value of $d_f = 1.585$, confirming a simple but redundant architecture with high reliability.

We have practically implemented a digital twin as a software and hardware complex integrated into the information-control system of the power unit's process control system TP ASC STC. The architecture is implemented in the form of an interface that provides visualization of the basic technological parameters (Fig. 3), a plot of fractal dimensionality dynamics (Fig. 4), plots of subcluster status and analysis of deviations. The key component is an algorithm that monitors fractal dimensionality in real time, compares it with threshold values, and generates control actions in the case of deviations (13).

Our model allows for a comprehensive consideration of the physical, logical, and structural characteristics of the power unit's technological process, and its fractal-cluster structure provides high potential for diagnostics, forecasting, and adaptive control. The results given in Tables 2–4 clearly demonstrate that each subcluster has a characteristic range of fractal dimensionality, which can serve as a structural indicator of the subsystem's state. A digital twin, implemented on the basis of this model, could become an important component of modern intelligent control TP ASC STC systems in NPP power units, capable of providing both an increased level of automation and overall safety of the nuclear facility.

Despite the achieved results, our study has a number of limitations that determine the applicability of the constructed model of the digital twin of an NPP's power unit. The model used generalized mathematical representations, which limits the accuracy of the simulation under conditions of complex dynamic changes, especially during transient processes or emergencies with spatial heterogeneities. Although fractal analysis provided valuable information about the complexity and hierarchy of systems, the interaction between subclusters was modeled by a linearly aggregated variable $x_1(t)$. This may not be sufficient to take into account the nonlinear interdependence between subsystems in real scenarios. The model took into account external influences in a generalized manner. That does not allow us to fully simulate scenarios related to environmental anomalies, human errors, or complex external threats. The system-cluster approach is focused on the specific architecture of the power unit. This limits the possibility of directly transferring the model to other types of power units without re-analyzing their structural features.

Practical implementation requires high reliability of the hardware base. The use of a digital twin in real time imposes requirements on computing power, the speed of data acquisition systems, as well as continuous updating of the information model. The implementation conditions must be strictly observed, otherwise the expected efficiency may not be justified. Despite the correlation between fractal dimensionality and structural characteristics of subclusters, it is necessary to conduct a larger volume of empirical research to verify the stability of this indicator under real operating conditions.

To improve the accuracy and practical significance of the digital twin, further research should be focused on the following areas:

– expansion of physical models, including distributed parameters, local thermal effects, and three-dimensional neutron-physical calculations for modeling transient regimes with spatial consideration;

– integration of machine learning to detect anomalies, adapt model parameters based on real data, and predict failures based on behavioral characteristics;

– development of a universal technological solution for digital twins that would make it possible to adapt the model to power units of different types using a configuration description of the structure and processes;

– analysis of the impact of non-standard scenarios (cyberattacks, personnel errors, extreme external conditions) on the behavior of the model and its ability to generate adequate control effects.

7. Conclusions

1. We have modeled the technological process in a power unit at a nuclear power plant based on the system-cluster approach, which combines functional subcluster control structures and takes into account the influence of control signals and external disturbances through an aggregated state variable. This modeling allows for a formal description of the dynamics of the power unit both under normal, transient, and emergency modes. Unlike isolated physical models, the proposed scheme provides a comprehensive approach to control by combining logical, thermohydraulic, and neutron-physical processes. Its defining advantage is its ability to be flexibly integrated into a digital twin, which expands the functionality of NPP control systems.

2. The hierarchical structure of the information-control system of the power unit was considered for implementing the digital twin model algorithm. In particular, the highest fractal dimensionality of 1.83 was observed in the heat carrier control subcluster, which indicates a complex hierarchical structure, in contrast to the simple structure of the protection system with a fractal dimensionality equal to one. An algorithm for detecting changes in structural complexity based on comparing current values with preset values has been developed, which makes it possible to quantitatively detect losses of hierarchical levels or degradation of elements even before functional failures occur. Thus, fractal dimensionality acts as a diagnostic parameter that exceeds the capabilities of conventional complexity assessments.

3. We have practically implemented the system-cluster model by using a digital twin of an NPP technological process power unit with a monitoring mechanism, analysis of structural deviations, and adaptive control in response to a change in fractal dimensionality. This allowed us to implement a fractal dimensionality monitoring mechanism in the digital twin of an NPP power unit, which makes it possible to automatically detect deviations from the reference structural characteristics. An example is the loss of one control level in a subcluster, which leads to a decrease in fractal dimensionality from 1.83 to 1.60, signaling a possible degradation of the SCADA level. This approach makes it possible to implement a proactive control strategy that ensures the detection of hidden threats at the structural level and activates protective scenarios before the occurrence of emergency conditions, which is significantly superior to functional diagnostic methods.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

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