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Fractal Approach for Researching Information Emergency Features of Technological Parameters

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ABSTRACT The use of a fractal-cluster theory apparatus is proposed to describe random information signals in the information space when technological parameters of a power plant unit deviate from standard specifications. It is found that when random information signals with warning signs are transmitted, the degree of filling of the three-dimensional phase information space changes, which is characterized by the informational fractal dimension as a decimal value. This demonstrates a clear connection between the degree of space filling and the changing quality of information in the information space. Analytical expressions are derived, allowing the establishment of a relationship between the increase in the amount of accidental information due to deviations from standard technological parameters and changes in the informational dimension of random fractal signals in space coordinates and real-time. This approach provides a robust tool for detecting potential failures by analyzing the behavior of the fractal dimension of the signals. Furthermore, it is determined that changes in the informational dimension of signals act as a sensitive indicator of the emergence of unstable system operating modes. This enables not only the identification of critical parameter deviations but also the assessment of potential accident risks at early stages.

KEYWORDS random fractal signal; data process space volume; fractal dimension; fractal structure.

I. INTRODUCTION

THE major role in power systems, which are complex technical power objects, is taken by their structure in the form of a dynamical system, which is characterized by its initial state and deterministic law, according to which the system changes from the initial state to another one, thus systems with discrete or continuous time emerge, they are accompanied by dynamic chaos (chaotic phenomena).

However, in such systems, unstable modes of operation may occur, which make it difficult to control and predict their behavior. It is especially relevant for energy objects where even minor deviations can lead to serious consequences as a power outages or emergencies.

At that, there emerges a phenomenon, characterized by random nonlinear system behavior, despite being determined by deterministic law, and actually being a nonlinear system with ongoing processes, depicted by nonlinear differential equations [1-7].

In scientific and technical literature [1, 5], Control Dynamic chaos systems problems were discussed and solved on the basis of Chua, Lorenz and Ressler models [12-14] describing chaotic random dynamic systems.

Although these models describe chaotic regimes well, their practical applications in energy systems have certain limitations. In particular, they are highly sensitive to initial conditions, making long-term prediction and management of such systems difficult.

In addition, as shown in works [15, 16], for chaos control the following methods are used: the method of analytical construction of aggregated regulators, which is based on introduction of states of synthesized systems of attracting (invariant) manifolds-attractors, where only natural properties (physical, chemical) of the object and the requirements of management tasks correlate; the method for detecting the mode of determined chaos, based on detection of deviations of angular frequency and stress from the nominal value and energy dissipation resulting from the presence of global chaotic dynamics at power objects.

As the analysis of the above examined methods [17-19] shows, they do not consider the inhomogeneous properties of their unstable structures with dynamic chaos in space and time (real time), which may cause loss of information on faults and accidents at power objects with chaotic dynamics of the process flow.

It means that the existing methods and models do not take into account spatial-temporal heterogeneities in the structure of chaotic processes. Ignoring these factors can lead to loss of information or receipt of false information about potential malfunctions or emergency conditions, which reduces the efficiency of diagnosis and control of the power plant.

Works [20-22] state that complex power systems are usually examined by showing the power objects as interrelated components, analyzing their functions and tasks for further study of interaction of all elements thereof. This approach considers the establishment of a developed mathematical apparatus for proper processing of available process data.

However, this approach has a significant disadvantage – it does not take into account the complex internal dynamics of subsystems, which may differ from the general behavior of the system.

However, as the theory of the synergetic approach with elements of fractal-cluster theory shows [23-25], the system functions and tasks are not always repeated in the parts thereof: subsystems and elements, causing loss of information in the process data space volume.

It means that the standard methods for analyzing energy systems may not take into account their complex fractal structure. As a result, the important information about the process inside the system may be lost which makes it difficult to identify potential emergency conditions.

In works [9, 10, 26], the authors studied the behavior of dynamic systems and obtained the results, proving the structures having fractal properties and depending on external control parameters. This reveals the cause of such phenomena as dynamic chaos, resulting in random processes (i.e., scenarios of emergency situations), leading to chaotic regimes. The purpose of the article is to develop methods of fractal detection of emergency signs in the process data area on the basis of the study of loss of energy of chaotic random signals using elements of fractal – cluster theory.

II. MATERIAL AND METHODS

When studying the influence of fractal properties of information volume in the technological space on the changes in parameter characteristics of random information signal, the method of fractal detection of emergency signs with deviation of normalized values of technological process parameters is offered. This proposed method is based on the evaluation of the fractal properties of the volume structure of the phase information space when random information signals pass through it on the basis of quantitative and qualitative changes in fractal and information dimensions. In addition, it is shown that in the chaotic random system, the change in the volume of the information area is proportional to the change in signal energy in a given volume and to possible energy losses associated with the change in dimension in the fractal structures of cluster-cluster aggregations of three-dimensional phase space.

Let us examine how information volume V_0 changes depending on spatial coordinates in real time. In [8-10], the authors studied how data space signals change using fractal theory. It was found that in chaotic random systems the energy losses of random signal E_0 are possible; such a system (process) is considered to be dissipative, where a decrease in volume V_0 causes E_0 energy decrease, as shown in Fig.1. Figure 1 (b) shows that the degree of V_0 space data volume filling changes for ΔV , which is proportional to the change of ΔE signal energy in this volume. Therefore, the data volume change is identical to $\Delta V \approx \Delta E$ energy change.

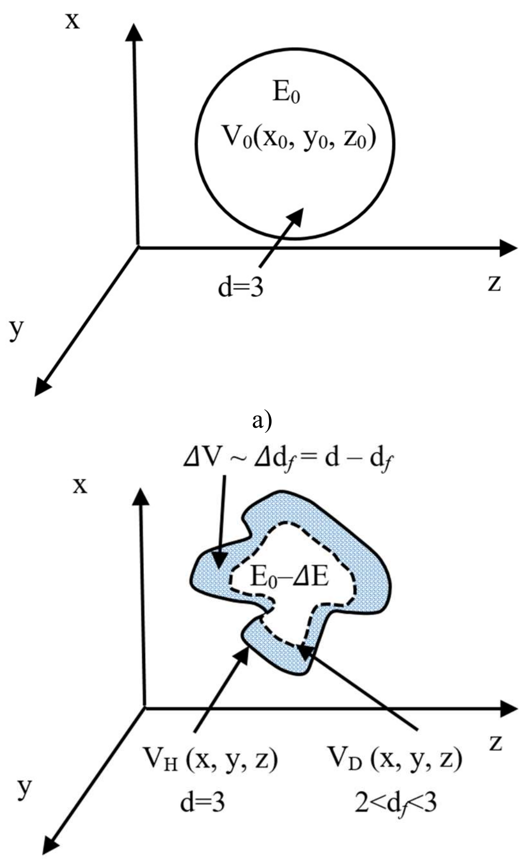

Figure 1. The process of energy change in the volume of phase three-dimensional data space: a) reference (initial volume of phase data space at baseline and the corresponding energy; b) the volume of phase space of Hamiltonian V_H and Dissipative V_D system at time and energy corresponding to it

The properties of heterogeneous structures with dynamic chaos in the information space of the technological process are of key importance for the analysis of information signals in information and control systems of software and hardware complexes (SHC) of automated process control systems (APCS) of power units in power plants. In this systems the informational local heterogeneity of spatial distribution of process parameters are observed. These parameters significantly affect the transmission and preservation of information about the state of electric power equipment. One of the characteristic features of chaotic systems is dissipativity, that is, the loss of energy when an information signal passes through a heterogeneous information space, which can lead to the loss of data on possible malfunctions of electric power equipment and accidents.

According to [8-10], V_f data space volume has fractal properties, and its filling degree is measured by the fractal dimension d_f .

Consequently, it can be concluded that ΔE change in random signal energy, passing through V_f fractal volume in real time, is also associated with d_f quantitative value, featuring the degree of V_f data space volume filling (DS). As it is known [3], and based on the aforementioned assumptions, we obtain an equation to determine the volume described by V_0 sphere:

$$V_0 = \frac{4}{3}\pi r_0^3, \tag{1}$$

where r_0 – radius. We must consider the fact that the change in V_0 Euclidean volume depends on the change in r_0 radius, particularly its degree index, which is known [3] as equal to three in Euclidean space r_0^3.

It follows from this, that study of ΔE change in random signal energy, passing through the V_f volume in real time, requires a connection of changes in Δr_{av} average correlation radius of V_f data space volume with Δd_f change in fractal dimension. As it is known, the authors [9] obtained the following dependence for changing Δr_{av} average value of correlation radius (2):

$$\Delta r_{av} = r_{2av.r.cl} - r_{1av.r.cl}, \tag{2}$$

where Δr_{av} – change in mean correlation radius; $r_{1av.r.cl}, r_{2av.r.cl}$ – average cluster radiuses.

It should also be noted that at change in Δr_{av} average correlation radius, the degree of data volume filling changes for $\Delta V = V_0 - V_f$ (V_f – data space volume with fractal properties), therefore, $d_3 = 3$. Euclidean dimension by Δd. Whence it follows, that the degree of data space volume filling is characterized by d_f fractal dimension, which is defined by expression (3):

$$d_f = d_3 - \Delta d, \tag{3}$$

where d_f – fractal dimension; d_3 – Euclidean dimension; Δd – change in information space filling degree.

It follows from expression (3) that the change in Δr_{av} correlation radius is identical to alteration of Δd degree of data space volume filling in real time, i.e., $\Delta r_{av} \equiv \Delta d$. Consequently, in contrast to the Euclidean volume r_0^3, the radius for V_f fractional data space volume may vary with change in fractal dimension in the range of $2 < d_f < 3$, thus, expression (1) can be represented as follows:

$$V_f = \frac{4}{3}\pi r_f^{d_3-\Delta d} = \frac{4}{3}\pi r_f^{d_f}, \tag{4}$$

where d_f – fractal dimension. The works of authors [1-6] show that cluster-cluster aggregation (CCA) of V_f data space fractal volume with local data inhomogeneity (LDI) has fractal properties, i.e., geometrical distances ℓ_{cca}^{geom} (average distance between the clusters of different CCA) and ℓ_{ca}^{geom} (average distance between the clusters of CCA) differ from Euclidean ones for $\Delta\ell$ and are fractal dimensions ℓ_{fcl} and ℓ_{fccl} correspondingly, as shown in Fig.2.

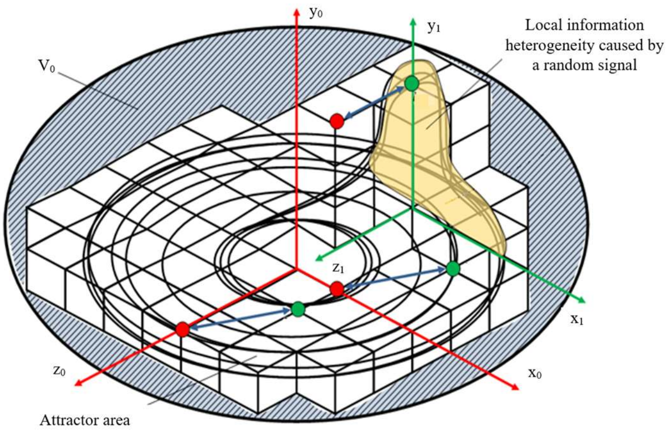

Figure 2. The architecture of physical model structure of the three-dimensional phases of the data space volume

As Fig.2 shows, the change in $\Delta\ell_x, \Delta\ell_y, \Delta\ell_z$ fractal dimensions is equivalent to spatial coordinates Δx, Δy, Δz. Variation, hence it can be assumed that the change in r_f radius for fractal of V_f data space volume is approximately equal to the change in l_f fractal dimensions of V_f fractal volume, that is $r_f \approx l_f$, and, consequently, r_f radius can be expressed through the change in $\Delta\ell_x, \Delta\ell_y, \Delta\ell_z$ fractal dimensions, and expression (1) can be represented as follows (5):

$$V_f = \frac{4}{3}\pi\left(\sqrt{(\ell_{x1}-\ell_{x0})+(\ell_{y1}-\ell_{y0})+(\ell_{z1}-\ell_{z0})}\right)^{d_3-\Delta d} = \frac{4}{3}\pi\left(\sqrt{\Delta\ell_x+\Delta\ell_y+\Delta\ell_z}\right)^{d_f}. \tag{5}$$

It follows from expression (5) that V_f fractal volume of data space depends on the change in $\Delta\ell_x, \Delta\ell_y, \Delta\ell_z$ fractal dimensions, as shown in [10], $\Delta\ell_x, \Delta\ell_y, \Delta\ell_z$ dimensions are related to ℓ_d average distance between clusters of different

CCA and ℓ_{cl} average distance between clusters of CCA, that is $\ell_{fcl} = \ell_{cl} + \Delta\ell_{cl}$, and $\ell_{fcca} = \ell_{cca} + \Delta\ell_{cca}$.

Further to paper [8], this circumstance allows for detection of signs of the signals passing through the fractal volume of space three-dimensional phases, namely: no signals with failure signs at V_0 full volume filling of DS at $\ell_{\kappa\kappa a} = \ell_{f\kappa\kappa a}$ and $\ell_{\kappa d} = \ell_{fkd}$, that is, if there is no $\Delta\ell_x, \Delta\ell_y, \Delta\ell_z$; accident signs at $\Delta\ell_x, \Delta\ell_y, \Delta\ell_z$. Since the data signals alteration process has been studied within the space and time, there is a good reason to consider r_0 change in radius within time not in the form of $\Delta\ell_x, \Delta\ell_y, \Delta\ell_z$ change in fractal dimensions, but in the form of Δx, Δy, Δz, i.e. $x_0...x_1, y_0...y_1, z_0...z_1$ spatial coordinates variation, that $r_0 = \sqrt{(x_1 - x_0) + (y_1 - y_0) + (z_1 - z_0)}$.

Taking into account Δx, Δy, Δz spatial coordinates variation, V_f fractal volume can be defined by expression (6):

$$V_f = \frac{4}{3}\pi\left(\sqrt{(x_1 - x_0) + (y_1 - y_0) + (z_1 - z_0)}\right)^{d_3 - \Delta d} = \\ = \frac{4}{3}\pi\left(\sqrt{\Delta x + \Delta y + \Delta z}\right)^{d_f}, \qquad (6)$$

Expression (6) shows that the fractal volume V_f of data space depends on d_f the exponent of spatial coordinate variation Δx, Δy, Δz.

On the other hand, it should be noted that V_f fractal volume of data space is characterized by a quantitative value – d_I data dimension, which, as shown in work [2] for many standard strange attractors, coincides with d_{cor} correlation and d_c capacitarian dimensions of data space. It follows that any change in correlation quantities (r_{cor} – correlation radius, ℓ_{cor} – correlation dimensions) and changes in geometric dimensions of the cross-sectional area of S_{atr} strange attractors, have a significant influence and cause changes in correlation dimension d_{cor}. These attractors are a geometric measure, considering ω_{sig} frequency of random signal passing the movement pattern in the three-dimensional phase volume of data space V_f.

The studies have shown that the fractal structure of informational area in the information control systems of software and hardware complexes of automated process control systems of power units of power plants allows us to characterize the degree of its filling with the help of information fractal dimension. The change in the information fractal dimension is associated with a change in the average value of the correlation radius of the information space, which in turn affects the change in the energy of the information fractal signal about the state of electric power equipment. Thus, decreasing in volume of the informational area of technological process is the equivalent to reduction in information fractal signal energy. In the existing information and control systems of software and hardware complexes of automated process control systems of power units in power plants, this may complicate the detection of signs of malfunctions, because a decrease in the information volume leads to the receipt of inaccurate information about the state of electric power equipment.

It has a significant impact and causes alteration of d_{cor} correlation dimension, and, as it is known [2] d_{cor} for standard strange attractors, which in our case are CCA, limit the data capacity in V_f volume and $d_{cor} \approx d_I$. As it is well known [5], at S_{atr} small cross sectional area of strange attractors of CCA, d_I data space is related to I amount of data volume of data space with the following expression (7):

$$I_{S_{atr}} \approx d_I \log_2(1/S_{atr}), \qquad (7)$$

It follows from expression (7) that $I_{S_{atr}}$ amount of data, passing through the section of a strange attractor S_{atr}, depends on d_I data dimension alteration and changes in S_{atr} attractor area, while, at smaller S_{atr} area there are small ΔE energy losses and $I_{S_{atr}}$ data amount increases. Thus, ΔE energy alteration in the volume of amount of V_f data space depends on S_{atr} section of strange attractor of CCA, which determines the data loss amount.

According to works [5, 11], different dimensions (d_f, d_I, d_{cor}) are represented by the same problem and the same LIN of information's space's volume V_f, which is non-uniform Poincare display in fact (with attractor's area S_{atr}). Therefore, accepting the following assumptions in work [11]: $d_f \approx d_I \approx d_{cor}$. According to [11], the fractal dimension d_f of volume V_f is counted by formula (8):

$$d_f = d_3 \cdot 2^{\lambda(T_f - T_c)}, \qquad (8)$$

where $\lambda = \ln 2\left|\overline{\Delta I}\right|$ – Lyapunov's index; T_f – fractal's time; T_c – time of cycle.

The change in fractal dimension d_f in the area of strange attractor S_{atr} in dissipative chaotic system in the level dependence on the change in the amount of informational ΔI_f on the time's interval $\tau + \Delta T$ is observed.

There are the fractal amounts $\Delta T = T_f - T_c$. In order to physically understand the change in quality of informational ΔI_f, the assumption is introduced that the return time τ is actually fractal time T_f and is quantified by fractal time dimension t_f.

In this case characteristics parameters can take the normed value $\Delta I_f = 0$ or irregular value $\Delta I_f = 1$ and given the time $T_c = \tau$ – the normed value, $T_c > \tau$ – irregular value. It can be concluded that the conditions of appearing the emergency indications in the information area (9):

$$\left| \begin{array}{l} \Delta I_f = 1 \rightarrow T_c > \tau; \\ \Delta I_f = 0 \rightarrow T_c = \tau. \end{array} \right. , \quad (9)$$

According to this material, the expression of fractal dimension d_f for volume V_f is as follows (10):

$$d_f = d_3 \cdot 2^{\ln 2 \left|\overline{\Delta I}\right| (\tau + \Delta T)}, \quad (10)$$

where $d_3 = 3$ – Euclidean's dimension, $\left|\overline{\Delta I}\right| = [0,1]$

Thus, substituting formula (10) into (6), we derive equation (11) for the fractal volume V_f.

Formula (11) shows that the change in volume informational space with the fractal quality V_f depends on the change in the space coordinates $\Delta x + \Delta y + \Delta z$ in the level dependence on the level of filling Euclidean's volume V_0 with the quality of information which goes through area of strange attractor sections S_{atr} during the time's interval $\tau + \Delta T$ and is characterized by the information dimension d_I (11):

$$V_f = \frac{4}{3}\pi \left(\sqrt{\Delta x + \Delta y + \Delta z} \right)^{d_3 \cdot 2^{d_I |S_{atr}| (\tau + \Delta T)}} \quad (11)$$

Thus, formula (11) makes it possible to look for the emergency indications of information signal in the divergence from the standards features of the technological parameters of the technological process in the real time.

Another important aspect is the formation of cluster-cluster aggregations with local information heterogeneities. In such structures, the average distances between clusters have information fractal dimensions that differ from Euclidean. At the same time, the change in spatial coordinates can be equivalent to the change in fractal dimensions of the information space of the technological process. Loss of information or receipt of false information about the emergency signs of the technological process in the information and control systems of the software and hardware complexes of automated process control systems of power units in power plants can be caused by an excessive decrease in the section area of the attractor, which leads to energy losses and an increase in the volume of transmitted data, and at the same time complicates the separation of information signals with signs of accident in real time.

Furthermore, it follows from the above statement, that the change in the volume of information space ΔV is proportional to the change in signal energy ΔE at a given volume. We can make a conclusion that in the chaotic random system, possible energy losses E are connected with the changes in different dimensions (d_f, d_I, d_{cor}) in the fractal three-dimensional phase space.

Thus, the spatio-temporal local information heterogeneities of such chaotic structures are critical to ensure reliable monitoring and diagnostics of technical processes using modern information and control systems of software and hardware complexes of automated process control systems of power units in power plants. Using the information fractal model allows not only to describe the behavior of unstable chaotic heterogeneous structures, but also to identify potential emergency signs by analyzing deviations of the characteristics of information fractal signals from normal values.

III. DISCUSSON OF RESULTS OF STUDYING INFORMATION IN ICS FOR STC IN APCS

When developing a dynamic fractal-cluster model of the structure of the information space to increase the reliability criteria of the information, the software and hardware complexes of automated process control systems for controlling the power plant were considered to be a successful application of fractal-cluster theory.

Based on the developed fractal-cluster model of the structure of the information space volume, presented as a set of cluster-cluster aggregates, it is found that random information signals passing through this space change the degree of its filling.

This process is due to the variation of energy and power of fractal information signals, which in turn influences the structure of distribution of information within the system.

It is found that among the dimensions characterizing the degree of filling of information space (correlative, capacitive, point), the most appropriate is the use of information fractal dimension. In the standard operating mode of the system, the information fractal dimension coincides with the Euclidean and is equal to 3, which corresponds to the complete filling of the three-dimensional phase space of the system.

However, when there are signs of an accident, the fractal dimension decreases, indicating a partial loss of order in the system and the possible occurrence of unstable processes.

The results of the analysis show that a decrease in information fractal dimension below 2.85 can indicate the beginning of the occurrence of unforeseen situations related to the deterioration of the information reliability and possible errors in the transmission of signals. Further reduction of the dimension to 2.6-2.7 indicates a critical state of the system, with pronounced signs of chaos, information flows become heterogeneous and the probability of accidents increases significantly.

The practical application of the results obtained is the possibility to compare the information fractal dimension of a random information signal with parameters of a known useful signal. The use of comparison method allows us to quantify the degree of deviation of an unknown random signal, which helps to analyze more precisely the structure of information flows in the system and timely detection of unreliable data.

Analysis shows that when the fractal dimension is reduced, the probability of false responses increases by 30-35% because the signals become less structured and more difficult to classify. This indicates a critical state of the system, where false alarms or delayed response to real-world emergency situations are possible. Therefore, monitoring of information fractal dimension change allows us to detect potential violations in a timely manner and correct the system operation in real time.

From the theoretical point of view, the study of fractal-cluster model of structure of information space makes it possible to obtain new analytical dependencies for existing dynamic spatial-temporal models. The application of this approach allows us to establish a quantitative relationship between the amount of information containing signs of accident and the change in parameters such as energy, power, amplitude, frequency and phase of the random fractal information signal. In particular, studies have shown that when the information fractal dimension is reduced by 0.15, energy losses of up to 10% are possible, which has a significant effect on the system's stability.

In practice, this means that the system can work in real time, analyzing incoming signals and determining their reliability. The introduction of this methodology makes it possible to increase the reliability criteria of operation of information control systems of software and hardware complexes in automated process control systems in power plant by reducing the probability of false starts and failures, as well as by timely response to emergency signs. The introduction of the proposed method allows increasing the accuracy of monitoring of emergency situations by 20-25%, which significantly improves the performance of the system.

In the future, it is intended to conduct in-depth studies aimed at clarifying the parameters of information fractal dimension, as well as developing algorithms for adaptive signal correction taking into account the dynamic characteristics of the information space.

Further improvement of the model may include integration with machine learning and artificial intelligence methods for more accurate accident prediction.

IV. CONCLUSION

In the course of the study, a fractal method for detecting the accident signs arising from the deviation in normalized values of the characteristics of the technological process parameters of the power plant is proposed. The method is based on the analysis of fractal properties of the volume structure of the phase information space, which is formed when random information signals pass through it. It is established that in the process of normal operation of electric power plant equipment, in the information control systems of software and hardware complexes of automated process control systems fractal dimension of the information space remains unchanged, and its structure is characterized by a high degree of organization.

However, when the process parameters are deviated, the fractal dimension begins to change, which indicates the appearance of chaotic processes and instability of the robot of the power plant equipment. Reaching the critical change threshold indicates a high probability of an emergency state, which allows for early detection of potential threats and preventive measures.

In addition, the study confirmed the existence of a relationship between the change in the volume of information space and the change in the energy of the information signal. The analysis of chaotic random systems shows that the amount of information space of a technological process changes proportionally to the energy characteristics of the input signals, since any information flows have a certain energy, which influences the structure of the information space in the information control systems of software and hardware complexes of automated process control systems in power plant unit. Under the standard operating conditions of the system, energy redistribution occurs within the permissible values, but significant energy losses are possible when chaotic processes are intensified, which leads to a change in the fractal structure of the cluster-cluster aggregations in three-dimensional information space.

This in turn can lead to destabilization of the information control systems of software and hardware complexes of automated process control systems and decrease its reliability. Thus, the change in the fractal dimension and volumetric characteristics of the information space can be considered as an indicator of potential accident and used to predict the development of non-emergency accident situations.

The proposed approach allows not only to identify the signs of the accident states, but also to evaluate random information signals by comparing them with known parameters of useful signals. By analyzing the dynamics of change in fractal characteristics, it is possible to determine the degree of deviation of unknown signals from normalized values, which contributes to a more precise control of the system's operation, and reduce the number of false responses.

The introduction of this method in the information control systems of software and hardware complexes of automated process control systems can improve system reliability, minimize the loss of information and energy, as well as respond to emerging risks in a timely manner, preventing accidents in the early stages of their formation.

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