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## INFORMATIVE TECHNOLOGY OF EARLY DIAGNOSIS OF DEVIATED GAS COMPRESSION PROCESS FROM NORMAL GAS PROCESS

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## ІНФОРМАЦІЙНА ТЕХНОЛОГІЯ РАНЬОГО ВИЯВЛЕННЯ ВІДХИЛЕННЯ ПРОЦЕСУ КОМПРИМУВАННЯ ГАЗУ ВІД НОРМАЛЬНИХ РОБОЧИХ ХАРАКТЕРИСТИК

**Purpose.** To improve the technology of prompt detection of a deviated gas compression process in a gas compressor station of underground gas storage from a normal gas process within the context of improving the efficiency of its practical application to prevent accidents caused by the phenomenon of surging in system – “centrifugal supercharger of compressor units – pipeline”.

**Methodology.** Basic methods of this study are general scientific and special methods, techniques and approaches of knowledge of processes and phenomena, namely systematic approach to the analysis of a gas compression process and phenomena of surging in centrifugal superchargers of gas compressor units in underground gas storage compressor stations, the position of modern control theory, informative and production technologies.

**Findings.** The informative technology of early detection of a deviated gas compression process from a normal gas compression process, in particular, surging phenomenon based on the analysis of phase portraits of controlled parameters is proposed.

**Originality.** Based on multidimensional measuring, methodological approach how to identify a deviated gas compression process from a normal gas process associated with the phenomenon of surging, accompanied by uncertainty, imbalance, the presence of phase transitions is first done. It allows detecting the phenomenon of surging in the system “centrifugal supercharger of compressor units – pipeline” in time.

**Practical value.** The proposed informative technology of early detection of a deviated gas compression process from a normal gas process can be used to activate alarms, which gives the operator a certain time to make a decision on how to act further.

**Keywords:** *detection, surging, gas pumping units, phase trajectory*

**Introduction.** Detection of deviations of a gas compressor process (GCP) at a booster compressor station, natural gas storage (BCS, NGS) from the normal gas process is an important scientific and practical task and a way of auto emergency protection. With the use of it, the protection of equipment from damage and prevention of the normal process from falling outside the limits are done. Unfortunately, Ukraine operates outdated equipment at compressor stations because of being on the periphery of investment flows. It mostly entails the increasing of the accident rate of equipment damage. Considering this aspect the problem of formulation of scientific principles based on the modern method for detecting gas compression process deviations from the normal gas process adapted to international standards and taking into account national specifics has arisen.

**Analysis of the recent research and publications.** Issues related to the detection of technological

process deviations from normal working parameters are constantly in sight of scientists. Recently the scientific literature has been full of publications where the detection of technological process deviations is seen in the light of reducing process variability and bringing it closer to the optimal mode. Such native Ukrainian authors, exploring the issue of detection of various process deviations, as S. H. Hireenko [1], Y. Ye. Blyaut, M. O. Petesh [2], M. V. Becker, R. Ya. Shymk, A. V. Sukach, A. F. Repeta [3], as well as foreign scientists S. Yu. Borovik, B. K. Raikov, Yu. N. Senisov, O. P. Sobolev, Jeff Artli [4], A. P. Yastrebov, E. V. Dolgova [5], M. P. Tsygankov [6] and others must be mentioned.

The results of the mentioned above scientists' studies have scientific and practical value. However, issues related to the establishment of methods for early detection of technological process deviations from normal working parameters are still considered to be topical ones.

**Theoretical study.** Early detection of gas compression process deviation (EDD) from normal work-

ing parameters may be done in two ways – by using the historical data and monitoring on-line gas compression mode, while comparing current data with normal operating data and defining the moment of process deviations from the given value.

Some industries in western countries have already used such technologies. Nowadays, Shell/Station and AJM Consulting companies [4] are developing the latter ones.

Early detection of gas compression process deviation (EDD) is a complex monitoring application, based on the results of multidimensional measurements. Instead of taking into account a single variable, variable multidimensional measurements consider that the variables are correlated and this relationship should be taken while evaluating the results of the measurement process.

The gas compression process also has a multidimensional character and system of early detection of gas compression process deviation must analyze the main components to detect abnormalities within the data related to multidimensional measurements. The most important informative parameters characterizing the phenomenon of surge in a centrifugal supercharger (CS) GCP are the following: a pressure drop on confuser supercharger, speed power turbine of gas turbine actuator and CS, vertical moving vibration of back CS pillars, horizontal moving vibration of back CS pillars, vertical moving vibration of front CS pillars, horizontal moving vibration of front CS pillars, CS axial displacement and acoustic signals [1–3].

Normal operation data GCP are used to create the model. Current values are compared with the model for determining whether current values are within or outside the range of the normal operation of GCP. Additional measurements being not required, but squared error between the current individual data signals and output model data can be used.

$$e = \sum_k [b_k(k) - b_m(k)]^2, \quad (1)$$

where  $b_k$  is on-line controlled parameter, object output;  $b_m$  is a parameter value as a result of a model solution;  $k$  is discrete time.

If this value is high, it means that the current operation differs from the standard model and it is not normal. An operator is reported to have a potential problem – in this case it is a surging phenomenon.

There are four steps to use early detection of gas compression process deviation (EDD) in the on-line control systems in the ASO TP GCP:

- the definition of measuring parameters, they are the main components characterizing the surging;
- the creation of the “norm-demand” model;
- the setting of communication channel;
- the setting of interface.

The most important step is to define the parameters to be measured to detect the surging phenomenon.

This problem was solved by means of expert evaluations [1] and the use of technology Data Fusion (merger, i.e. combining data).

The set of parameters characterizing the surge in CS GCP are given in Table.

Survey results are presented in a calculated rank of each option (Fig. 1).

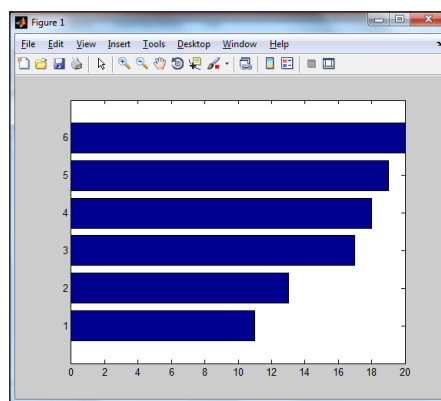
According to the sum of ranks for 10 parameters characterizing the surge phenomenon, the most important characteristics of the surge in CS is  $dP_{\text{конф.}}$ ,  $N_{\text{ст}}$ ,  $G_{gZON}$ ,  $G_{vZON}$ ,  $G_{gPON}$ ,  $G_{vPON}$ . Their values are respectively 11, 13, 17, 18, 19, and 20 points.

The example of factor ranking in order of gaining an informative surge phenomenon factor allows selecting the most important ones, taking into account that rank 1 has got the highest score while the lowest one is ranked  $k$ , where  $k$  is the number of factors (parameters).

As operators of compressor stations get graphical representation of current operations better, normal GCP operation phase portraits, available surge phenomenon state and surge for visual detection process gas compression deviations from normal GCP operation are proposed to use.

*Table*  
The set of parameters characterizing the surge in CS GCP

№	Denotation	Marking or coding
1	A pressure drop on confuser supercharger	$dP_{\text{конф.}}$
2	Pressure after CS	$P$
3	Gas temperature	$T$
4	The density of gas	$\rho$
5	Power turbine rotation velocity	$N_{\text{ст}}$
6	CS axial displacement	$G_{ZN}$
7	Horizontal moving vibration of front CS pillars	$G_{gPON}$
8	Vertical moving vibration of front CS pillars	$G_{vPON}$
9	Horizontal moving vibration of back CS pillars	$G_{gZON}$
10	Vertical moving vibration of back CS pillars	$G_{vZON}$
11	Acoustic signals	$A_k$



*Fig. 1. Sample of analysis of value of amount ranks specified by experts as to variables indicating the occurrence of surge in CS GCP*

Significant feature for dynamical systems with nonlinearities is known to be each new nonlinear problem that is at least slightly different from the previous one, and usually requires a dedicated study. This research includes the search for stability terms and the existence of possible movements characterizing the quality system.

ACS GCP is a multifunctional, multi-channel system for long-term use, managing the work of GCP without the constant presence of staff.

This work involves the development of applications for phase trajectories method for early detection of process deviations of GCP, being classified as nonlinear systems due to the presence of non-linear input-pressure characteristics.

To construct the phase portrait of the second-order anti-surgung regulation system (AR) the following procedure is used [7].

As coordinates, we take the deviation  $x$  of an output value from its value which is equal to the established regime of AR system, and its first derivative  $y = \frac{dx}{dt}$ . Pre-description of AR leads to a system of two first order equations in the form of

$$\left. \begin{aligned} \frac{dy}{dt} &= Q(x, y) \\ \frac{dx}{dt} &= P(x, y) \end{aligned} \right\}, \quad (3)$$

where  $y = \frac{dx}{dt}$ ;  $Q, P$  are non-linear functions of the output value  $x$  and its derivative  $y$ ;  $x$  and  $y$  are coordinates of the system, being dealt with at any time  $t$ , completely determine the state of AR system at this time.

Since the phase portrait method remains unchanged for any autonomous second-order systems (linear or nonlinear), thus the system is supposed to be non-linear and non-linear equation systems, being studied, is in the form

$$\frac{d^2x}{dt^2} = F\left(x, \frac{dx}{dt}\right), \quad (4)$$

where  $F$  is a certain nonlinear function, and using the notation  $y = \frac{dx}{dt}$ , we obtain a system of equations in the following form

$$\left. \begin{aligned} \frac{dy}{dt} &= F(x, y) \\ \frac{dx}{dt} &= y \end{aligned} \right\}. \quad (5)$$

Having divided the first equation of the system (3) or system (5) for the second one, we obtain the equation of phase trajectories in the form of non-linear differential first order equation

$$\frac{dy}{dx} = \frac{Q(x, y)}{P(x, y)} \quad \text{or} \quad \frac{dy}{dx} = \frac{F(x, y)}{y}, \quad (6)$$

where  $x$  is an independent variable and  $y$  is a dependent variable.

Thus, by eliminating the time we simplified the problem and moved from the second order equations to the first order equation.

Further, having divided variables  $x$  and  $y$  and integrated equation (6), the equation of phase trajectories can be obtained in this form [7]

$$y = f(x) + c_0, \quad (7)$$

where  $c_0$  is integration constant which depends on the initial conditions.

However, the equation (6) cannot determine the direction of the phase trajectory in the case when an indefinite result is received by means of it; in other words, when both the numerator and denominator of the right side of the equation are equal to zero (2)

$$Q(x, y) = 0; \quad P(x, y) = 0, \quad (8)$$

that is there is no definite direction of the tangent to the trajectory at this point. They are singular points being correspond to equilibrium. Indeed, if equality is valid for any point (8), then putting them in equation (2), we obtain the formula

$$\frac{dx}{dt} = 0; \quad \frac{dy}{dt} = 0. \quad (9)$$

This means that the rate of change of coordinates of the point  $M$   $x$  and  $y$  at this point is zero, i.e. the system is in the state of equilibrium.

If this state of linear systems totals one only, then the non-linear systems, presented by the ACS GCP, can be few in number, and, thus, the phase portrait may have a few special points  $M1, M2, M3, \dots$

Since the nature of the phase trajectory around the singular point of a nonlinear system determining its type depends on the nature of the roots of the characteristic equation. We are going to analyze their types.

There are six types of special points of nonlinear systems [7]:

- a special "center" – like point;
- a special "stable focus" – like point;
- a special "unstable focus" – like point;
- a special "stable node" – like point;
- a special "unstable node" – like point;
- a special "saddle" – like point.

As for surging phenomena in the "centrifugal supercharger compressor units – pipeline" system, phase trajectory is in the form of a spiral spinning, and depicting point  $M$  moves from the origin, thus, a singular point is "unstable focus".

As for ACS GCP phase portrait as a whole, it has a single stable singular point 0 (Fig. 2), so the system is stable.

However,  $M1, M2$  limit cycle is unstable as usual trajectories are off of it both inside and outside. The point  $M$  approaches the singular point 0 only if its initial position is in the shaded area bounded by the  $M1, M2$  limit cycle.

If the initial position of depicting point  $M$  is not in shaded region of the phase plane, then the point  $M$

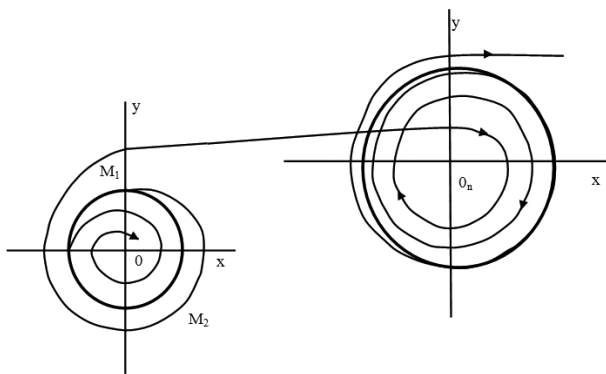


Fig. 2. Phase portrait of ACS GCP with particularly accurate point at the origin and two limit cycles

will move away from limit cycle and point 0. Therefore the “gravity attractor” area of singular point 0 is limited and does not cover the entire phase plane. Thus, phase portrait system (Fig. 2) is stable in a small amount while  $M1, M2$  marginal cycle is unstable. It is the boundary separating one type of phase trajectories from the other – it is describing the surge phenomenon.

**Phase portrait modeling.** We should note that the phase portraits give some idea of the dynamics of non-linear second-order systems while deterministic disturbances take place, including precision, stability and quality processes. Controlled deflection values  $x$  given in Table, from their values corresponding to the established regime of ACS GCP, and their first derivatives  $y_i = \frac{dx_i}{dt}$  were used as the coordinates of phase portraits.

To simulate the phase portraits of the studied on-line parameters, Matlab Simulink and the diagram (Fig. 3) were used.

Having analyzed obtained phase portraits, we revealed that the established regime corresponded to phase trajectories converged to the focus, being the average value of the controlled parameter. Unstable process is equal to trajectory going from the origin.

Since the EDD task is to find limit cycles depending on the parameters of the system, then the limit cycles can be analyzed only by using the construction of several phase trajectories.

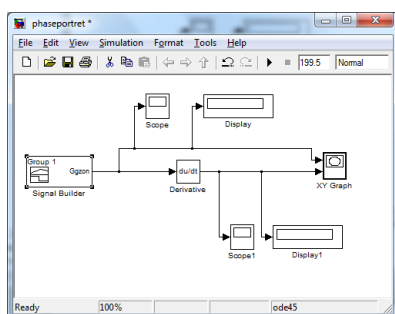


Fig. 3. Modeling of phase portraits using the system Simulink

Phase portraits graphed in the coordinates  $\frac{dx}{dt} = f(x)$  where  $x$  is the controlled parameter, are compared with the so-called ellipse reliability or reliable data. If the current data are located within this ellipse reliability,  $ax^2 + by^2 = 1$  then the submission process gas compression is classified as a “norm”. If the point of phase portrait goes beyond the ellipse, it is classified as “available surging phenomenon” or “anomaly”.

The investigated process is unstable because in a hard surging phase portraits go away from the ellipse reliability (attractor) and create another attractor. Attractor allows defining two parameters of oscillatory cycle – the frequency and the amplitude.

Since the study is a nonlinear process, there are several areas with different phase trajectories (Fig. 4).

Let us note that if later the data were found out not to characterize the available surge GCP condition, they can be included in the normal data model to improve the latter and avoid potential false alarms. The possibility of data re-classification is important to prevent false protection GCP system. The logic detection of the available surge condition of the “centrifugal supercharger compressor unit – piping” system being complicated, a complex analysis of taking decision on necessary actions must be done to clear up the final causes of the abnormal situation. In this regard, any new analysis should be conducted by an experienced engineer or automation specialist.

The second step is to use informative EDD technology namely the creating of the “norm-demand” model. To identify predisposing variables by means of which the surge phenomenon is determined, archival data were used in the form of chart of principal components  $P(t), N_{pr}(t), dP_{conf}(t), Gg_{zon}(t), Gv_{zon}(t), Gs_{zsu}(t), Gg_{spon}(t)$ . To view the data, the parallel coordinate visualization (PCV) is proposed, to be very useful and determine any causes of available surge phenomena.

Fig. 5 is a basic parameter viewer giving information about the surging to the operator. PCV is one-dimensional scheme, but it is a very useful tool to view all the data. However, one-dimensional analysis is unlikely to determine the causes of GCP disruptions completely and any one-dimensional reason is likely

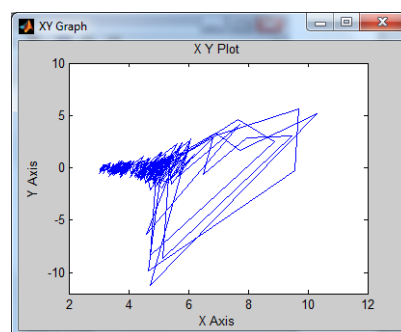


Fig. 4. An example of a phase portrait of the acoustic signal

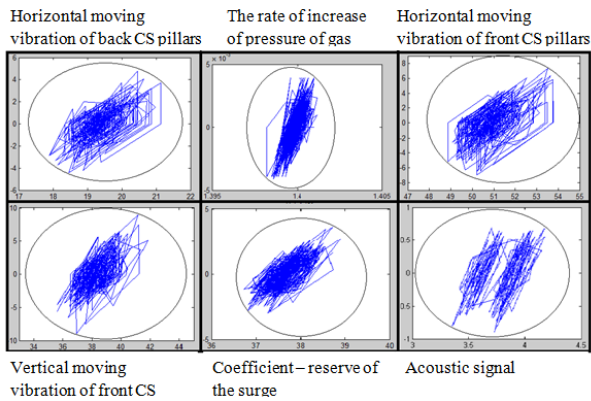


Fig. 5. Phase portraits

to be detected by viewing other data analysis techniques such as time-domain variables.

For multivariate analysis, to be necessary to identify causes of the surging, principal component analysis (PCA) is used to find the variables predisposing to abnormal GCP function.

The expert must select the number of principal components (PC), characterizing the variability of the process and contributing to the measurement. It is also carried out offline. To select the number of PC is an important way to obtain effective data analysis. The analysis could be deteriorated while using too many computers, which can slow down the performance

analysis, but the use of a very small number of computers, can fail the important information. The analysis allows using automatically [4] other graphics for the final determination of the causes of malfunction: straight segments trends, cusum trends, variable values schemes, multiple schemes and others.

Straight segments trends show the variable values of time series, cusum schemes reflecting the values of variables. Accuracy of straight segment analysis can be selected to evaluate the major points of changes and to compare them with a point of change of the measured parameter. Analysis of the straight segments is a powerful tool in assessing the range of values changes and variables

For rapid analysis the current values of the process, having been determined for parameter measure, are compared with the tested models to identify variables in this model range (Fig. 6).

The next step is to create a communication channel for data transmission in online mode and having them for analysis. The data are fully transmitted to the operator of workstation by means of standard data in real time (OWS).

The operation, to be further evaluated as a desirable one, is easily introduced into the model to prevent unwanted messages in the future. After formation of the communication channel the way of warning the operator about available surge phenomenon is necessary to be done. Notification of faults can be

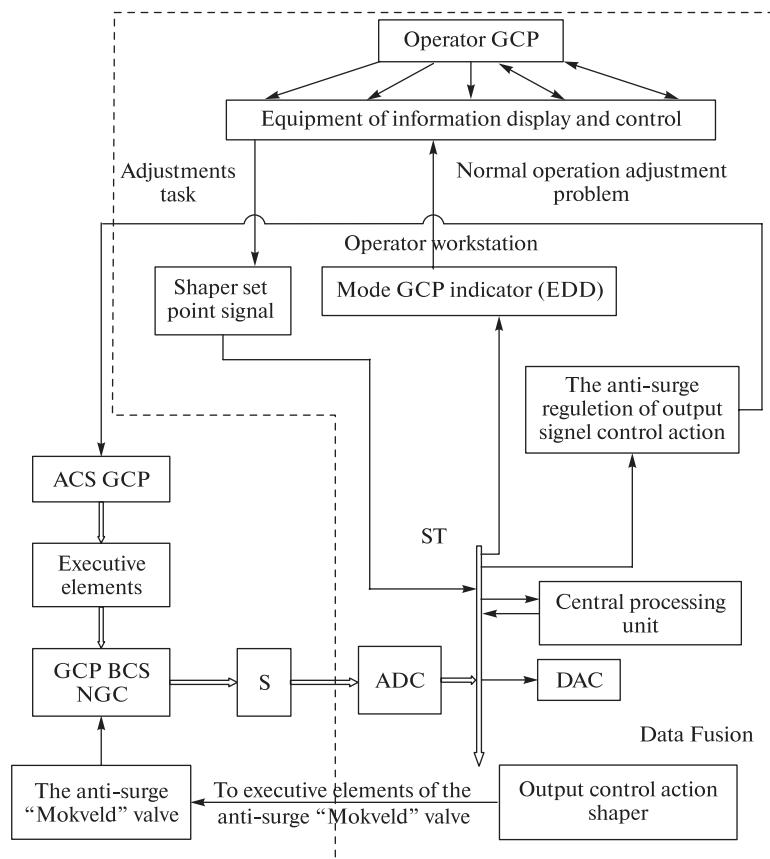


Fig. 6. The functional structure of anti-surge protection and regulation:  
*S* – sensors; *ST*– systemic tire; *ASV*– anti-surge valve

created through sms-messages on a mobile phone of an engineer being in charge of the process, or on the duty engineer's PC, or as a text message to the workstation operator. When the process is approaching to the surge warning zone, a warning as an alarm or by means of changing the color graphics on a workstation operator is sent to alert the operator about measure to be different from the desired value. This message appears before alarms are operated, to provide early detection of extraordinary situation – available surge phenomenon. For example, it may be a limited histogram causing discoloration when the value is high.

Having seen the warning, the operator can investigate various graphs to confirm the message authenticity. In addition, if the obtained information was analyzed before and the reason was found out and configured for the control system, the established diagnostic message for the operator about actions performed to remedy the problem can be written.

**Functional ACS GCP structure.** We improved the functional structure of ACS GCP to realize the proposed technology of early detection of performance deviations from the normal GCP process based on the phase trajectories construction.

In the functional structure of anti-surge protection system and control system (Fig. 5) the following relationship between elements of the system are established. The outputs of sensors are connected to the certain ADC inputs, the outputs of which are connected to the systemic tire (ST), which is also connected to input of output control action shaper, input mode GCP indicator and early detection of abnormalities process system, input and CP output and DAC input, the output of which is connected to the anti-surge Mokveld valve by forming the output of anti-surge protection.

The sensor group provides a parameter measurement of the compressor and the parameters of the gas inlet and the vibration of front and back pillars of centrifugal supercharger.

The processor implements the system algorithm, the generator of output control signal produces the signal for ACS GCP to increase or decrease the rotational speed of the compressor, generator of input signal transforms discrete control signal in digital form. This group of elements of antisurge regulator can be realized using programmable logic controller (e.g. GE Fanuc, "General Electric" company (USA)).

Anti-surge protection circuit performs two main tasks: ensuring the normal operation of GCP and early detection of disorders of GCP efficiency (available surge state) on the basis of early detection of abnormalities GCP performance technology.

The use of the system can compensate heavy losses caused by reduced gas pumping volume or loss while replacement of critical equipment such as CS GCP BCS NGC is done.

**Conclusion.** To optimize the reliability and performance of gas pumping units of booster compressor stations of natural gas storage and to achieve the big-

gest efficiency by means of timely detection of surge phenomena, informative technology for early detection of gas compression process deviation from normal process based on the of phase portraits controlled parameters analysis is proposed. These changes can be used to activate alarm, giving the operator some time for taking control actions. For effective use of early detection surge phenomenon, it must be independent from ACS GCP and other gas pumping units.

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**Мета.** Удосконалення технології оперативного виявлення відхилень процесу компримування газу на дотискувальній компресорній станції підземного сховища газу від нормальних робочих характеристик у контексті підвищення ефективності його практичного застосування для запобігання аварійних ситуацій, викликаних явищем помпажу в системі „відцентровий нагнітач газоперекачувального агрегату – трубопровід“.

**Методика.** Методологічну основу даної роботи становлять загальнонаукові та спеціальні методи, прийоми та підходи пізнання процесів і явищ, а саме: системний підхід до аналізу процесу компримування газу та явища помпажу у відцентрових нагнітачах газоперекачувальних агрегатів дотискувальних компресорних станцій підземних сховищ газу, положення сучасної теорії керування, інформаційних та виробничих технологій.

**Результати.** Запропонована інформаційна технологія раннього виявлення відхилення процесу компримування газу від нормальних характеристик, зокрема явища помпажу, що основана на аналізі фазових портретів контрольованих параметрів.

**Наукова новизна.** Уперше розроблена, побудована на основі багатомірних вимірювань, інформаційна технологія виявлення відхилень процесу компримування газу від нормальних робочих характеристик, зв'язаних з явищем помпажу, які супроводжуються невизначеністю, невірноваженістю, наявністю фазових переходів, що дає змогу своєчасно виявити явище помпажу в системі „відцентровий нагнітач газоперекачувального агрегату – трубопровід“.

**Практична значимість.** Розроблена інформаційна технологія раннього виявлення відхилень процесу компримування газу від нормальних робочих характеристик може бути використана для активізації сигналізації, що дає оператору певний час для прийняття рішення стосовно

керуючих дій.

**Ключові слова:** виявлення, помпаж, газоперекачувальний агрегат, фазові траєкторії

**Цель.** Совершенствование технологии оперативного выявления отклонений процесса компримирования газа на дожимной компрессорной станции подземного хранилища газа от нормальных рабочих характеристик в контексте повышения эффективности его практического применения для предотвращения аварийных ситуаций, вызванных явлением помпажа в системе „центробежный нагнетатель газоперекачивающего агрегата – трубопровод“.

**Методика.** Методологическую основу данной работы составляют общенаучные и специальные методы, приемы и подходы познания процессов и явлений, а именно: системный подход к анализу процесса компримирования газа и явления помпажа в центробежных нагнетателях газоперекачивающих агрегатов дожимных компрессорных станций подземных хранилищ газа, положения современной теории управления, информационных и производственных технологий.

**Результаты.** Предложена информационная технология раннего обнаружения отклонения процесса компримирования газа от нормальных характеристик, в частности явления помпажа, основанная на анализе фазовых портретов контролируемых параметров.

**Научная новизна.** Впервые разработана, построенная на основе многомерных измерений, информационная технология выявления отклонений процесса компримирования газа от нормальных рабочих характеристик, связанных с явлением помпажа, сопровождающихся неопределенностью, неуравновешенностью, наличием фазовых переходов, что позволяет своевременно выявить явление помпажа в системе „центробежный нагнетатель газоперекачивающего агрегата – трубопровод“.

**Практическая значимость.** Разработанная информационная технология раннего выявления отклонений процесса компримирования газа от нормальных рабочих характеристик может быть использована для активизации сигнализации, что дает оператору определенное время для принятия решения относительно управляющих действий.

**Ключевые слова:** выявление, помпаж, газоперекачивающий агрегат, фазовые траектории

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