UDC 628.517:622.691.4.052
DOI: 10.15587/1729-4061.2025.337736

DEVELOPMENT OF AN ANTI-SURGE PROTECTION SYSTEM FOR GAS PUMPING UNITS BASED ON HARDWARE AND SOFTWARE VIBRATION MONITORING TOOLS

Leonid Zamikhovskyi
Corresponding author
Doctor of Technical Sciences, Professor,
Head of Department*
E-mail: leozam@ukr.net

Olena Zamikhovska
PhD, Associate Professor*

Nataliia Ivanyuk
PhD, Associate Professor*

Oleksandra Mirzoieva
Assistant*

Mykola Nykolaychuk
PhD, Associate Professor*

*Department of Information and Telecommunication Technology and Systems
Ivano-Frankivsk National Technical University of Oil and Gas
Karpatska str., 15, Ivano-Frankivsk, Ukraine, 76019

This study's object is the non-stationary process of gas flow stall in the compressor of a gas pumping unit (GPU), accompanied by surge oscillations. The task relates to the need for a comprehensive approach to the design and operation of anti-surge protection systems based on improved procedures, algorithms, and unified hardware and software solutions.

A procedure has been devised for predicting surge oscillations during the sequential operation of two compressor stations. Its distinctive feature is the processing of data on the dynamics of technological parameters of an actual facility under pre-surge and surge modes to construct a corrected extrapolation model. The method ensures an acceptable prediction error with a root mean square deviation of 10–15%.

An anti-surge protection system for GPU with forecasting functionality has been designed, based on offset and vibration displacement parameters of the compressor's rear bearing support in vertical and horizontal directions. Hardware and software solutions were implemented using a PLC S7-1200, SM 1281 vibration module, as well as CMS2000 VIB-SENSOR. The system enables monitoring of rear bearing support vibration displacement in the range from 0 to 80 μm, with an «optimal» operating point of 40 μm. The permissible monitoring distance to the control object is up to 30 m without loss of vibration signal quality.

A dispatcher interface has been designed with functions for visualization, archiving, alarm signaling about technological parameters, and calculating the predicted moment of GPU surge onset.

A subsystem for controlling the station's anti-surge valve has been designed, with status indication, based on the developed FB1 «Program» algorithm with the vibration state parameters at the facility

Keywords: surge phenomenon, vibration monitoring, GPU automatic control system, extrapolation model, TIA Portal, anti-surge valve

Received 02.06.2025
Received in revised form 05.08.2025
Accepted date 15.08.2025
Published date 29.08.2025

How to Cite: *Zamikhovskyi, L., Zamikhovska, O., Ivanyuk, N., Mirzoeva, O., Nykolaychuk, M. (2025). Development of an anti-surge protection system for gas pumping units based on hardware and software vibration monitoring tools. Eastern-European Journal of Enterprise Technologies, 4 (2 (136)), 117–132. https://doi.org/10.15587/1729-4061.2025.337736*

1. Introduction

The reliability and efficiency of GPU operation depends on both its technical condition and operating modes. The phenomenon of surge is one of the most dangerous operating modes not only of GPUs, but also of a number of turbomachines operating with a compressible medium (aviation gas turbine engines, centrifugal compressors and superchargers, fans, etc.). Turbomachines are used in various industries (chemical, oil and gas, metallurgical, etc.) and are prone to surge under certain operating modes.

Surge is a non-stationary operating mode of a centrifugal compressor, characterized by periodic fluctuations in pressure and gas flow, which may be accompanied by strong noise, vibration, and thermal shock. It can lead to serious damage to equipment, downtime, and financial losses.

Among the many causes of surge, the main one is a decrease in gas flow below a critical level (surge limit). When the gas flow rate through the compressor becomes too low for its current parameters (pressure, rotor speed, etc.), the compressor loses stability.

The current state of methods and means for building anti-surge protection systems for GPUs indicates various approaches to preventing surge in the compressor. These include various methods and algorithms for determining the surge limit and comparing it with the operating point of the compressor characteristic. For their implementation, systems for diagnosing the GPU technical condition are used, in particular vibroacoustic, which are built on the basis of modern hardware and software tools, as well as its anti-surge protection systems. Taking into account modern signal processing methods, sensor characteristics and hardware and software tools, in most cases, attention is focused on the development of surge protection systems that make it possible to determine the compressor operating point. To this end, technological parameters are measured and processed using various sensors (flow rate, temperature, pressure, vibration, etc.). Next, the compressor surge limit is compared with the operating point of the system, and the control error is determined. Various algorithms are used to acquire a control signal to open the anti-surge valve.

The main method for preventing surge is to maintain the compressor operating point at a safe distance from the surge limit. To implement this method, automatic systems are used that constantly monitor the compressor operating parameters (pressure, flow rate, rotor speed). In the event of approaching the surge limit, the system opens the anti-surge valve or regulates the rotor speed of the axial compressor. If the GPU has guide devices, the system regulates them, which allows one to change the angle of attack of the gas flow on the working blades.

The most promising and relevant direction of preventing surge is constant monitoring of key GPU operating parameters (pressure, temperature, flow rate, vibration) using their control systems. Diagnostic systems are widely used, which make it possible to quickly detect defects in GPU units that are the cause of the initial stage of surge and take measures to prevent surge.

Therefore, scientific research into this area, in particular, devising a procedure for predicting the occurrence of surge phenomena and an anti-surge protection system for GPUs based on modern hardware and software vibration control tools, is relevant for surge prevention. The results are needed in practice because they could be used to prevent surge in turbomachinery operated in various industries.

2. Literature review and problem statement

Paper [1] briefly explains the phenomenon of surge in compressors. Methods for preventing surge in compressors implemented in modern surge control systems are described, as well as their applications. Existing methods for protecting compressors from surge are analyzed to highlight their advantages and disadvantages. Limited analysis of practical implementations; the paper is dominated by a theoretical overview but lacks a detailed analysis of real industrial implementations of ASC/FTC systems. At the same time, most of the solutions considered are based on idealized models that do not necessarily take into account unforeseen failures or changes in the dynamics of the system.

In [2], an ASC model is built; the discharge pressure is regulated in such a way as to avoid surges during various changes and noise in the pipeline using multivariate predictive control. The proposed controller can be used in related processes and can be implemented with the minimum possible information about the process. The main limitations of this system is the installation and maintenance costs, as well as the requirement for a large set of tuning parameters. At the same time, the paper does not provide a comparison of the simulation results with experimental data.

In [3], various models for ASC in compressors are discussed, as well as increased performance of control systems. It is indicated that the surge margin of 10% of the flow is based on the indecipherable interpretation of various standards and literature sources by users. At the same time, no recommendations are given for the selection of a specific anti-surge protection system and its controller.

In [4], a model predictive controller (MPC) was implemented for ASC and compared with an existing PID controller. The results show that MPC is more efficient than PID control, proving that the model could minimize the steady-state error and the percentage of overshoot. The disadvantage of MPC is its complex algorithm, which takes more time to implement than other controllers.

In [5], an existing PID controller is compared with a fuzzy logic PI controller. The simulation results show that the fuzzy logic PID controller responds to surge faster and the anti-surge valve is opened more efficiently than when using a PID controller. However, the efficiency of such a system is low since it depends heavily on fault information, while the efficiency of the fuzzy logic controller depends on the knowledge and skills of the human operator. Machine learning and neural networks are not recognized by such controllers.

In [6], the authors describe various causes of surge, which include unstable flow or gas flow disruption. Studies related to axial or radial compressors have shown that surges can be controlled in these units by moving the operating point in the operating range to the right of the surge boundary line. However, the work does not take into account modern information technologies and adaptive data processing algorithms and there are no experimental data. In addition, the work does not solve the problem of taking into account the dynamics of gas flow disruption under the surge mode during unstable and transient modes of GPU operation.

Paper [7] considers the detection and diagnosis of the initial surge (ISDD) of a centrifugal compressor based on the vibration signals of its bearings. For this purpose, adaptive feature fusion and a sparse ensemble learning approach are used to develop an intelligent diagnostic model based on data. At the same time, the paper does not provide the results of the testing of the model built.

In [8], a new spectral modeling method based on short-time Fourier transform (STFT) and time series analysis is reported, which was successfully applied to the detection of the initial surge of a centrifugal compressor. The paper does not justify the procedure for selecting, representing, and processing diagnostic information.

In [9], various potential methods for identifying the stall and initial surge of centrifugal compressors were devised, using various signal processing techniques, such as wavelet analysis and higher-order statistical analysis. The authors also found that the sum of all the moduli of the autobispectrum components in the subsynchronous range can be reliable for predicting unstable conditions. However, the implementation of wavelet algorithms requires significant computational resources, which limits their application under the "real-time" mode. The work focuses on control problems but does not offer direct solutions for their prevention.

In [10], turbocharger failures, including those that can be caused by surge, are analyzed using acoustic and vibration analysis. For this purpose, the vibration characteristic of the compressor is obtained by analyzing vibration signals measured on the turbochargers. In addition, sound pressure measurements are performed to estimate noise emission based on the acoustic wave decomposition method. Experimental results obtained for the vibration characteristic and noise generation from the turbocharger compressor make it possible to characterize operational malfunctions of the turbocharger. The work is focused on post-accident analysis and does not offer a real-time surge detection algorithm, which limits its application for forecasting tasks. The problems of integration with SCADA-based control systems are also unresolved.

In [11], a numerical model of the full surge cycle is presented. Based on the fact that surge is very difficult to model due to the large time scale and area of influence, the work uses a numerical method that makes it possible to analyze the physical processes of surge occurrence. The method considered in [11] makes it possible to obtain information about such characteristics as flow reversal areas, pressure distribution, pressure increase, cycle frequency, etc., which is important for the design of surge protection systems. It is indicated that the simulation results were compared with the results of the experiments but the conditions of the experiment and their adequacy to the real process of surge occurrence are not given.

The results of our review of related literature allow us to conclude that the task that needs to be solved is associated with the complexity of implementing an integrated approach for designing and operating GPU anti-surge protection systems.

3. The aim and objectives of the study

The purpose of our research is to design a system for GPU anti-surge protection based on modern hardware and software. This will make it possible to increase the efficiency of control over pre-surge phenomena in GPUs and prevent the occurrence of emergencies.

To achieve this aim, the following objectives were accomplished:

– to devise a procedure for predicting the occurrence of surge phenomena during the sequential operation of two CSs;

– to design the components of an GPU anti-surge protection system and conduct a detailed analysis of the trends in technological and vibration parameters registered by the standard SCADA system before the occurrence of surge oscillations in an GCU supercharger. To config. the hardware of the system, parameterize its signal modules, set up the communication environment, develop the operating algorithm and application software of the system;

– to design the upper level of the system under the GPU anti-surge protection mode with components of the human-machine interface and the structure of the mnemonic diagrams of the technological process;

– to develop a subsystem for controlling the station anti-surge valve.

4. The study materials and methods

The object of our study is the unsteady process of gas flow disruption from the blades of an impeller in the GPU supercharger, which is accompanied by surge phenomena that could lead to serious damage to the equipment.

The hypothesis of the study assumed that increasing the efficiency of control over GPU pre-pumping phenomena could be achieved if the designed system integrated an algorithm for predicting surge oscillations based on an extrapolation model with correction based on actual parameters from the control object in real time. In addition, such a model must take into account the vibration parameters of the GPU supercharger rear support, which are recorded by modern unified hardware and software tools. Such a comprehensive approach to the design of a GPU anti-surge protection system should provide timely forecasting, control over the pre-pumping state, and the function of automatic control over the station anti-surge valve with an acceptable error.

Before starting the study, the following assumptions were adopted: the technological parameters of vibration recorded by the standard SCADA are functionally dependent on the operating modes of GPU in terms of the occurrence of the surge phenomenon.

During the study, the following simplifications were accepted: the system response time to the dynamics of the surge phenomenon is acceptable for correct prediction, while the surge dynamics themselves require additional research.

The problem of surge occurrence was considered in [12], in which the authors noted that in the case of sequential operation of two CSs it is quite important to react in time to the approach of the operating point to the surge limit. Analysis of the sequential operation of CS-2 and CS-3 at the Dolynska site of the Bogorodchansky LVUMG TOV "Operator of Ukraine's GTS. Western Region" revealed that insufficient protection is provided for the centrifugal GPU superchargers at GTK-10-4 and GTN-10 type, mounted at CS-2.

Taking into account the above, the task of controlling and preventing the occurrence of surge phenomena during gas pumping is not fully solved, especially when several CSs are operated in cascade.

In most cases, to detect and diagnose the initial surges at GPUs, the transformation of technological parameters and vibroacoustic signals generated by the GPU units is carried out with further processing of the obtained data by various methods.

The approach proposed in our paper involves a detailed analysis of trends in technological and vibration parameters recorded by the standard SCADA before the occurrence of surge oscillations in the GPU supercharger. It is also necessary to determine the interpolation polynomial used to predict the GPU parameters.

When analyzing the changes in technological and vibration parameters before the occurrence of surge oscillations in the GPU supercharger, trends in technological parameters of the GPU-C-16S operating mode were used. Trends in changes in technological parameters of the GPU-C-16S that occurred during a surge event were recorded by the standard SCADA system of CS-3 at the Dolynska site at the Bogorodchansky LVUMG LTOV "Operator of Ukraine's GTS. Western Region".

When devising a procedure for predicting the occurrence of surge phenomena during sequential operation of two CSs, the use of an extrapolation model using Lagrange polynomials was justified.

The increasing level of automation of gas compression processes necessitates the need to give increasing importance to the issues of predicting the condition of equipment, both at the GPU and CS levels. Special importance is on predicting changes in GPU operating parameters, which makes it possible to increase the reliability of the anti-surge protection system as a whole and solve the problem of timely prevention of emergencies at CS.

There are a significant number of methods for predicting the technical condition of various objects (analytical, probabilistic forecasting methods, forecasting using statistical classification methods, etc.). Each of them involves the construction of a mathematical model of the process that changes performance indicators of GPU over time based on a priori information with subsequent extrapolation of the values of the model parameters over time using one or another mathematical apparatus [13, 14].

Therefore, before starting to predict the performance indicators of GPU, it is necessary to perform their interpolation, that is, to construct function $F(x)$, which takes at individual points values that coincide with the previously obtained values at these points of the unknown function.

Geometrically, this means that it is necessary to find curve $y = F(x)$ of a certain type, which passes through the system of points $M(x_i, y_i)$ $(i = 0, 1, 2,..., n)$ (Fig. 1).

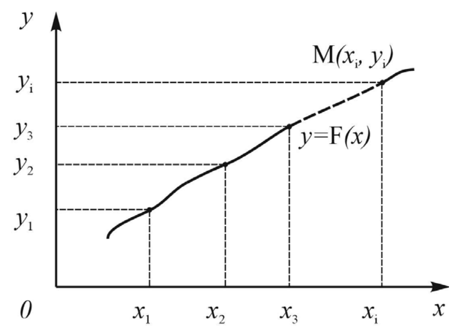


Fig. 1. Example of an interpolation function

In the forecasting process, several stages are typically distinguished [15]:

– accumulation of information about the process of changing the performance indicators of the object;

– construction of an extrapolation model for a given time interval;

– correction of the extrapolation model at a given time interval;

– extrapolation of the process of changing the state of the object to the forecasting area.

One of the tasks set in our work is to predict changes in selected technological parameters of the operating mode of GPU. These include pressure drop across the supercharger confuser, supercharger turbine speed, axial displacement of the supercharger, as well as vibration displacement of the rear supercharger support in the vertical and horizontal directions to the supercharger axis.

To solve this problem, simple extrapolation models of the process of changing the parameters of GPU can be used.

In such cases, the construction of models is usually carried out using numerical methods of approximation by extrapolation polynomials of Lagrange, Newton, or using power polynomials.

An important prerequisite for the use of analytical forecasting of GPU parameters is that during the GPU operation, the change in measured parameters over time occurs gradually with an explicitly or implicitly expressed trend.

For the purposes of forecasting diagnostic parameters of GPU, the time interval is divided into two intervals – T_1 and T_2 (Fig. 2). Time interval T_1 includes the time of accumulation of information about the process that is forecasted by measuring the values of its parameters, and time interval T_2 is the time for which the forecast is carried out.

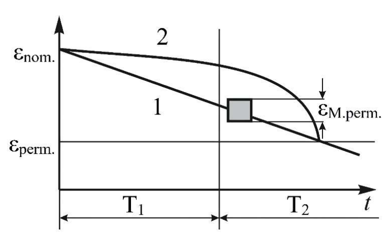


Fig. 2. Example of checking the accuracy of the extrapolation model: 1 — first-order model; 2 — second-order model: $\varepsilon_{nom.}$ and $\varepsilon_{perm.}$ are, respectively, the nominal and permissible values of the diagnostic parameter; $\varepsilon_{M.perm.}$ — permissible value of the model error

To improve the system for monitoring the vibration state of GPU and study its operation under the GPU anti-surge protection mode, the state-of-the-art software platform TIA Portal V14 SP1 (Totally Integrated Automation Portal) by "Siemens" was used. The project can be modified to the current version TIA Portal V20, intended for the design and testing of automated control systems for technological objects [16].

The TIA Portal software platform includes the following functions [17]:

– creation and management of projects for automation of technological objects;

– configuration of hardware for PLC-based control systems;

– parameterization of hardware for PLC-based control systems;

– creation and parameterization of communication environments for control systems;

– development of application software for PLC-based control systems;

– integration of SCADA functions into control systems for technological objects;

– simulation of PLC and SCADA operation for tasks of simulation modeling and testing of components of dispatch control systems for technological objects.

5. Results of development an anti-surge protection system for gas compressor units based on vibration control means

5. 1. Devising a procedure for predicting the occurrence of surge phenomena during sequential operation of two compressor stations

The first stage in the forecasting process is the accumulation of information. Information for solving the analytical forecasting problem is acquired as a result of measuring diagnostic indicators of GPU equipment, which can be carried out continuously and periodically. In practice, the measurement of forecasting parameters is mainly carried out discretely at time points t_0, t_1, ..., t_n.

In this case, the forecasting process is carried out at once for five gas compressor unit parameters to solve the problem of pre-surge warning, three of which are related to the vibration characteristics of the gas compressor unit GPU-C-16S.

These values can be measured by the control system [17].

Obtaining parameter values for predicting the state of the supercharger and preventing its surge is carried out using sensors and can be carried out at different time intervals.

But for forecasting purposes it is advisable to acquire information at equal time intervals Δt; therefore, extrapolation is carried out over a certain number of intervals k, $T_2 = k\Delta t$, which simplifies solving the problem.

The requirement for the size of the forecasting step follows from the features of the forecasting problem, its statement, the type of measured parameter, and the technical features of GPU.

However, some requirements can be formulated that make it possible to determine the size of the forecasting step before the surge occurs quite simply in a first approximation. Such requirements include:

– measurements at equal time intervals

$$\Delta t_1 = \ldots = \Delta t_{i-1} = \Delta t_i = \Delta t_{i+1} = \Delta t_{n-1}; \quad (1)$$

– the presence of a correlation between the measured values in the forecast interval

$$\Delta t = 2T/\tau,\ T = T_1 + T_2, \tag{2}$$

where t is the correlation time;

– uniform rate of change in the process.

In cases where information is not obtained at equal time intervals, the prediction step is determined using numerical interpolation methods and approximate functions.

At the stage of information accumulation, a smoothing process is performed, which makes it possible to isolate and significantly reduce the outflow of noise.

In cases where the amount of information is limited, a series of obtained values $\xi(t)$ without preliminary processing is used directly to build a model, correct it, and assess accuracy.

In the interval T_1, using known values, it is necessary to find such a function $F(t)$ that describes the process of changing the predicted parameter with the required accuracy, i.e., to perform interpolation. Extrapolation models based on interpolation polynomials of Lagrange and Newton have become widely used [18]:

1. An extrapolation model using Lagrange polynomials takes the following form

$$F(t)=\sum_{i=0}^{n}\xi_i\varphi_i(t)=\xi_0\varphi_0(t)+\xi_1\varphi_1(t)+\ldots+\xi_n\varphi_n(t), \tag{3}$$

where

$$\begin{aligned}&\varphi_i(t)=\\&=\frac{(t-t_0)(t-t_1)\ldots(t-t_{i-1})(t-t_{i+1})\ldots(t-t_n)}{(t_i-t_0)(t_i-t_1)\ldots(t_i-t_{i-1})(t_i-t_{i+1})\ldots(t_i-t_n)}\equiv\\&\equiv\prod_{j=0,j\neq i}^{n}\frac{(t-t_j)}{(t_i-t_j)},\end{aligned} \tag{4}$$

$i = 0, n$, ξ_i – value of $\xi(t)$, at time point t_i, $t_i \in T_1$.

In expanded form, the extrapolation model is written as follows

$$\begin{aligned}F(t)=&\frac{(t-t_1)(t-t_2)\ldots(t-t_n)}{(t_0-t_1)(t_0-t_2)\ldots(t_0-t_n)}\hat{\imath}(t_0)+\\&+\frac{(t-t_0)(t-t_2)\ldots(t-t_n)}{(t_1-t_0)(t_1-t_2)\ldots(t_1-t_n)}\hat{\imath}(t_1)+\ldots+\\&+\frac{(t-t_0)(t-t_1)\ldots(t-t_{n-1})}{(t_n-t_0)(t_n-t_1)\ldots(t_n-t_{n-1})}\hat{\imath}(t_n).\end{aligned} \tag{5}$$

2. An extrapolation model using Newtonian polynomials is of the form

$$\begin{aligned}F(t)=&c_0+c_1(t-t_0)+c_2(t-t_0)(t-t_1)+\ldots+\\&+c_n(t-t_0)(t-t_1)\ldots(t-t_{n-1})\equiv\sum_{i=0}^{n}c_i\prod_{j=0}^{i-1}(t-t_j),\end{aligned} \tag{6}$$

where coefficients c_i are calculated as follows:

$$\xi_0 = c_0; \tag{7}$$

$$\begin{aligned}\xi_i=&c_0+c_1(t_i-t_0)+\\&+c_2(t_i-t_0)(t_i-t_1)+\ldots+\\&+c_{i-1}(t_i-t_0)(t_i-t_1)\ldots(t_i-t_{i-2})+\\&+c_i(t_i-t_0)(t_i-t_1)\ldots(t_i-t_{i-1}),\end{aligned} \tag{8}$$

Hence

$$c_i=\frac{\xi_i-c_0-\sum_{j=1}^{i-1}c_j\prod_{k=0}^{j-1}(t_i-t_k)}{\prod_{k=0}^{j-1}(t_i-t_k)}. \tag{9}$$

After selecting the interpolation polynomial, the extrapolation model is corrected for a given time interval. The order of the model significantly affects the prediction error. Analysis of the processes of changing the performance of various elements and devices reveals that they can be described mainly by extrapolation models of the second and third order. The error of the extrapolation model is determined on the interval of its construction and is calculated from the following formula

$$\varepsilon_M=\left|\xi(t)-F(t)\right|=\frac{\sup\left|\xi^{(n+1)}(t)\right|}{(n+1)!}(t-t_0)\ldots(t-t_n). \tag{10}$$

Model construction begins with a first-order polynomial (Fig. 2) for an acceptable error value $\varepsilon_{M\,perm}$.

If the model error does not satisfy the specified ε_M, (curve 1), then the model order is increased by one, and the parameters of the new model are calculated again.

The model construction procedure ends when inequality $\varepsilon_M < \varepsilon_{M\,perm.}$ holds.

If the obtained third-order polynomial does not satisfy the condition, then a conclusion is drawn about the impossibility of building a model with the required accuracy [18].

The next step is to evaluate the forecasting results.

With individual forecasting, the expected forecast error can be estimated. The expected forecast error is calculated and corrected when additional information is received during the extrapolation process.

The expected forecast error is determined by the error of the specified technological parameters of the extrapolation model, which is built on interval T_1 (Fig. 2).

To do this, first the absolute error of the extrapolation model is calculated for each measurement point in the $(0, T_1)$ interval, then the average value of the error is determined, and its relative value is calculated; the variance of the error is calculated, and its standard deviation is found.

The originality of our proposed procedure is fairly simple, in the first approximation, determining the prediction step before the surge occurs, which is subsequently implemented by the designed anti-surge protection system for GPU.

5. 2. Design of components of the anti-surge protection system for gas compressor units

The problem of surge occurrence was considered in [12], in which it was noted that in the case of sequential operation of two CSs, it is quite important to respond in time to the approach of the operating point to the surge limit. Analysis of the sequential operation of CS-2 and CS-3 at the Dolynska site of the Bogorodchansky LVUMG TOV "Operator of Ukraine's GTS. Western Region" revealed that insufficient protection is provided for the centrifugal superchargers of the gas compressor units of the GTK-10-4 and GTN-10 types, mounted on CS-2.

Taking into account the above, the task of controlling and preventing the occurrence of surge phenomena during gas pumping is not fully solved, especially when several CSs operate in cascade.

In order to design a system for anti-surge protection of GPU, the GPU-C-16S vibration state control system was adopted as its basis, the structure of which included an analog signal module [19].

For visualization of the technological process and operational control, an operator panel (Simatic HMI Comfort Panel) or built-in WEB servers of the PLC Simatic S7-1200 [20] and the SIPLUS SM 1281 technological module [21] can be used as an HMI (Human Machine Interface).

The WEB server makes it possible to design custom WEB pages with binding of control process variables to project tags. Standard WEB technologies (HTML, Java-script, and AJAX) are used to design pages.

This approach is more flexible since in the case of using a WEB server, there is no need for additional equipment and software.

Access to the WEB server is carried out locally or remotely, using mobile communication devices (tablets, computers, smartphones, as well as standard browsers for viewing WEB pages – Mozilla Firefox, Microsoft Internet Explorer 10/11/, Microsoft Edge, etc.).

However, it should be borne in mind that the WEB server is not a fully-fledged replacement for the classic human-machine interface.

The functional diagram of the GPU anti-surge protection system is shown in Fig. 3.

Fig. 4 shows the window of technological parameters under the operating mode of GPU-C-16S No. 3 during a surge situation at CS-3, registered by the regular SCADA.

It was noted above that by using a mathematical model based on interpolation polynomials, it is possible to predict the process of changing the selected parameters over time.

Fig. 4 shows a mnemonic diagram of the compressor shop, which displays technological parameters and their trends, in particular, the vibration displacement of the shaft on the rear support of the supercharger and the axial displacement of the supercharger with a fixed mode of surge of the supercharger. The vibration displacement of the shaft on the rear support of the supercharger are displayed by blue and purple trends with the corresponding parameters (archive value, range, current value, units of measurement). The axial displacement of the supercharger is displayed by a red trend with similar parameters. As can be seen from Fig. 4, before the surge occurs, an increase is observed for 7.5 min. the level of vibration displacement of the rear support of the supercharger in the vertical and horizontal directions. At the same time, the level of axial displacement of the supercharger drops sharply. Thus, the informative parameters for the occurrence of surge oscillations in the supercharger are the value of the vibration displacement of the shaft on the rear support of the supercharger and its axial displacement.

After a detailed analysis of trends in the technological and vibration parameters of GPU operating mode, a list of them with measurement ranges was compiled for predicting the GPU pre-pumping state. It includes the following parameters:

1) pressure drop across the confuser dPk (Fig. 3) – measurement range from 0 to 1 kgf/cm^2, "optimal" operating point – 0.2 kgf/cm^2, significant change within 10–15%;

2) supercharger turbine speed (nST) – measurement range from 0 to 5200 rpm, "optimal" operating point – 5000 rpm, significant change within 10–15%;

3) supercharger axial displacement "VIB" – measurement range from –500 μm to +500 μm, a total of 1 mm, "ideal" operating point – 0 mm, significant change within 10%;

4) vibration displacement of the rear support of the supercharger "VIB2", "VIB3" (in vertical and horizontal directions to the supercharger axis) – measurement range from 0 to 80 μm, the "ideal" operating point – 40 μm, significant change within 10%.

The concepts of "ideal" and "optimal" operating points mean the following: "ideal" – parameters that can be obtained during the operation of the unit in the absence of defects, damage, etc.; "optimal" – parameters at which maximum performance of the unit is ensured.

All the above parameters are used by the centralized GPU control and management system. These data are entered into the PLC Simatic S7-1200 for their further processing. Therefore, the first-order Lagrange interpolation polynomial was used to predict the change in the required parameters, since Lagrange polynomials can be used for interpolation, as well as numerical integration [18].

The first stage of forecasting is the accumulation of information about the change in the value of GPU parameters.

In the developed program, this is achieved by saving the measured parameter values in the appropriate array, in which the initial values are stored for the possibility of their further prediction.

Moreover, for a more correct construction of the extrapolation model, several values are measured for one indicator of GPU operation at discrete points in time, after which their average value is found.

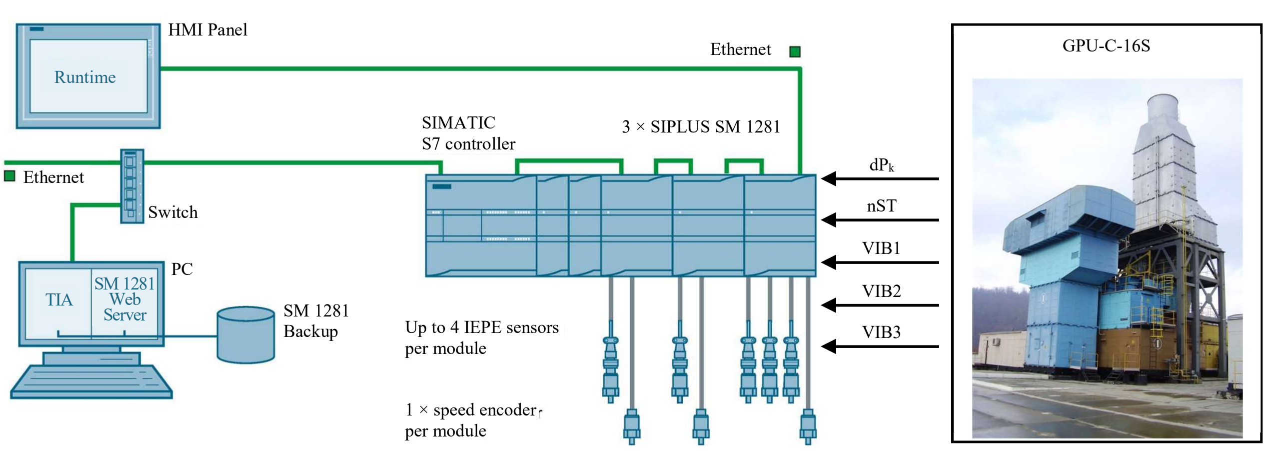


Fig. 3. Functional diagram of the anti-surge protection system

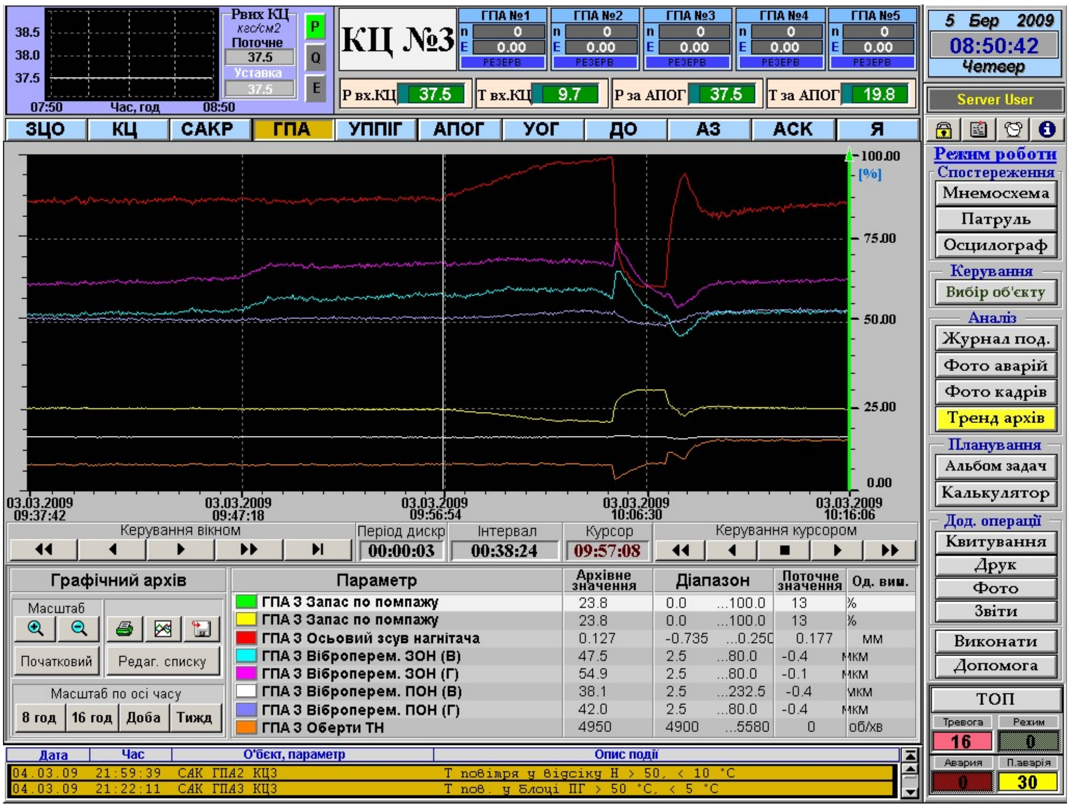


Fig. 4. Trend of technological parameters under the GPU-C-16S operating mode during a surge event at CS-3

The hardware of the system under development includes the following components: PLC S7-1200 with CPU 1212C AC/DC/Rly, vibration module monitoring the condition SIPLUS SM 1281, communication equipment.

Additionally, an analog signal input/output module for connecting sensors with a unified 4–20 mA output signal and controlling actuators (machine and station pneumatic converters for controlling anti-surge valves) (Fig. 5).

At the same time, it is necessary to configure the system hardware, parameterize signal modules, and set up the communication environment. Based on analysis of trends in the technological and vibration parameters registered by standard SCADA before the occurrence of surge oscillations in the GPU supercharger, one must develop algorithms for the functioning and application software of the system and test them at a technological facility.

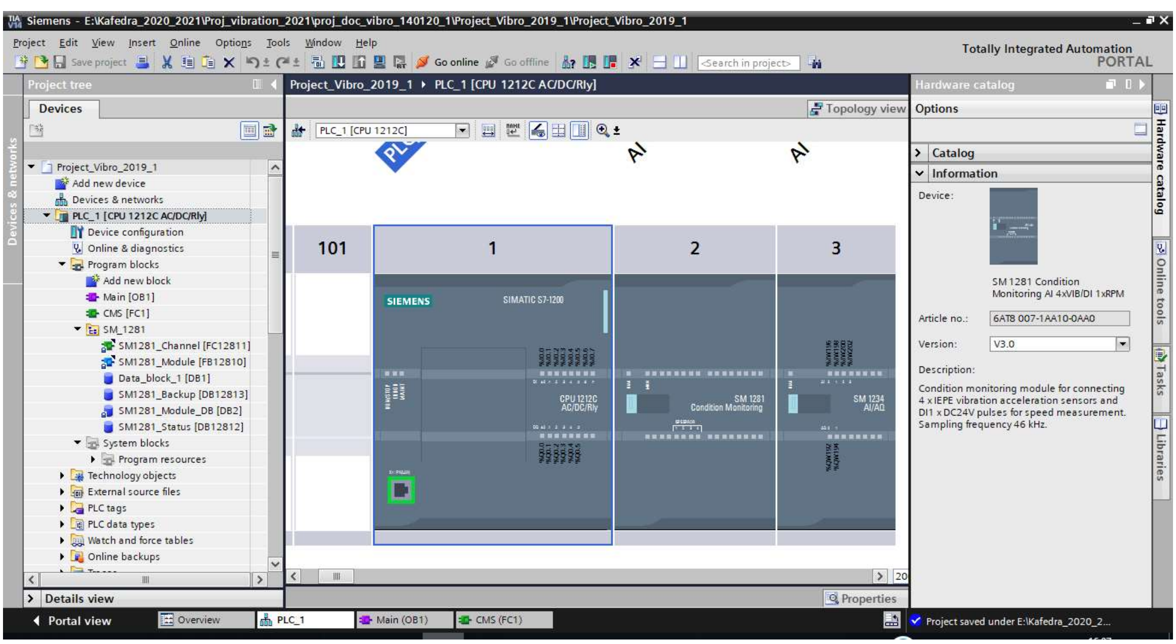


Fig. 5. Hardware support for the anti-surge protection system in a gas compressor unit:
1 — PLC S7-1200; 2 — SIPLUS SM 1281 — 4-channel vibration signal processing module;
3 — SM 1234 AI4/AQ2 — analog signal input/output module)

The project structure in the TIA Portal V14 environment takes the form shown in Fig. 6.

Among the important modules that are connected to the project as an external library for the SIPLUS SM 1281 vibration module, we can highlight "SM1281_Channel [FC12811]", "SM1281_Module [FB12810]", "SM1281_Status [DB12812]".

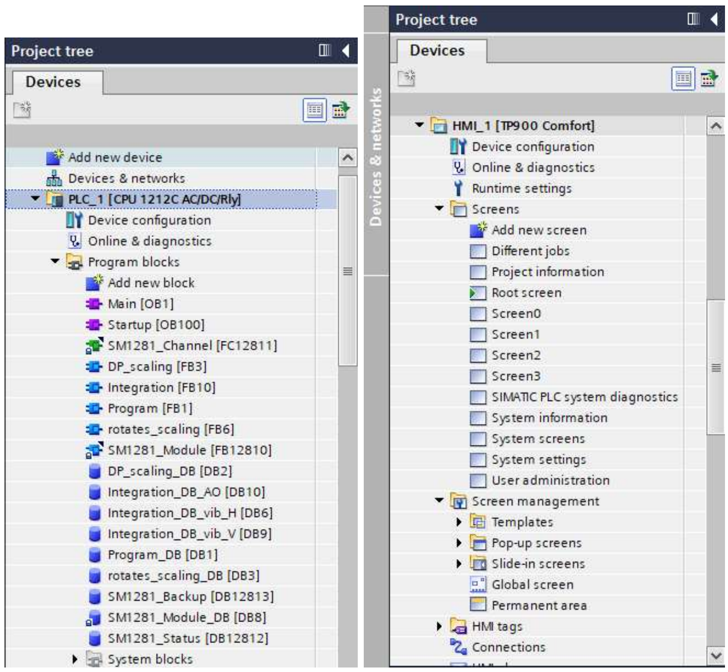
The parameterization of the SM 1281 vibration module is carried out using a special FB12810 function block "SM1281_Module". The settings of FB12810 "SM1281_Module" are shown in Fig. 7.

The main parameters of the input and output signals of the "SM1281_Module" function block are given in Tables 1–3.

Next, one needs to configure the "SM1281_Channel" function module, which is used to set the parameters of the vibration measurement channel (there can be no more than four per module).

An example of configuring the FC12811 "SM1281_Channel" function module is shown in Fig. 8.

Thus, to continue the project with the SIPLUS SM 1281 module, it is necessary to enter the necessary parameters into the functional modules considered.



a *b*

Fig. 6. System project structure in the TIA Portal environment: *a* — structure at the PLC level; *b* — structure at the Human Machine Interface level

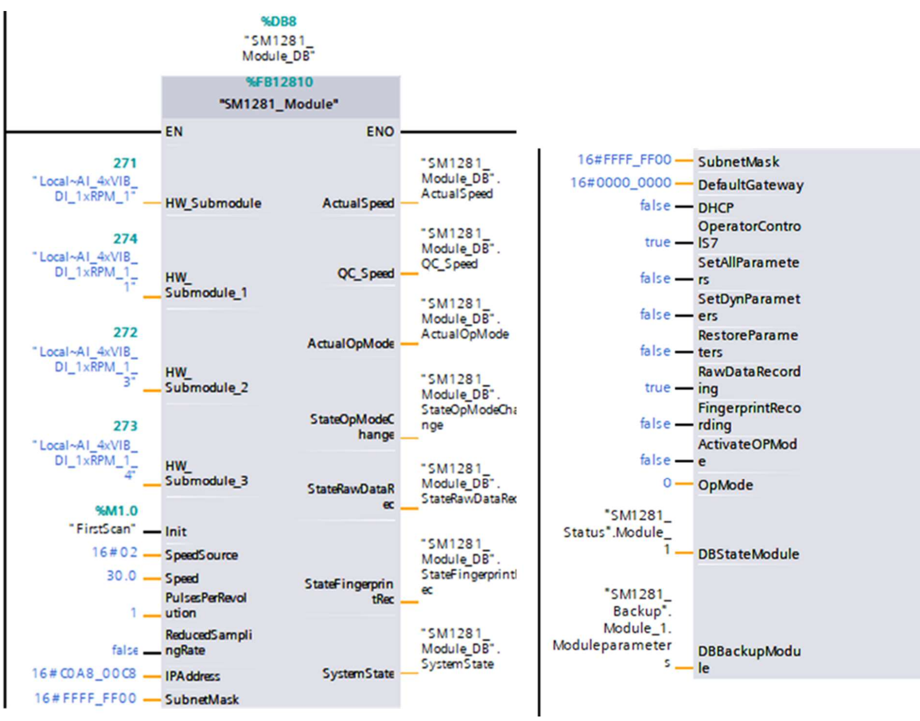


Fig. 7. Function block parameters FB12810 "SM1281_Module"

Table 1

Input parameters for FB12810 "SM 1281_Module"

Parameter	Data type	Description
HW_Submodule	HW_SUBMODULE	Identifier of the first vibration measurement channel for the SM 1281 module
HW_Submodule_1	HW_SUBMODULE	Identifier of the second vibration measurement channel for the SM 1281 module
HW_Submodule_2	HW_SUBMODULE	Identifier of the third vibration measurement channel for the SM 1281 module
HW_Submodule_3	HW_SUBMODULE	Identifier of the fourth vibration measurement channel for the SM 1281 module
Init	Bool	Initialization bit. The SM 1281 module is initialized via the "Init" bit during CPU restart. It is linked to the "FirstScan" system bit
IPAddress	DWord	Setting the IP address for the SM 1281 module Example: IP address 192.168.0.1: 192 → Hex C0 168 → Hex A8 0 → Hex 00 1 →Hex 01 ⇒ IPAddress = C0A80001
SubnetMask	DWord	Setting the subnet mask for the SM 1281 module. Example: Subnet mask 255.255.255.0: 255 → Hex FF 255 → Hex FF 255 → Hex FF 0 → Hex 00 ⇒ DWord Subnet = FFFFFF00
DefaultGateway	DWord	Gateway SM 1281 Example: IP 192.168.0.1: 192 → Hex C0 168 → Hex A8 0 → Hex 00 254 → Hex FE ⇒ DWord DG = C0A800FE
DHCP	Bool	Using a DHCP server
OperatorControlS7	Bool	Write protection of the SM 1281 web interface. True: The S7-1200 has control priority. False: This means that SM 1281 can no longer be controlled by program blocks. This parameter is cyclically transferred to SM 1281
SetAllParameters	Bool	All module and channel parameters are transferred to SM 1281 with a positive edge
SetDynParameters	Bool	All dynamic parameters are transferred to SM 1281 with a positive edge
RestoreParameters	Bool	Restore the last valid parameter set with a positive edge and transition to SM 1281
RawDataRecording	Bool	Request to record raw data
FingerprintRecording	Bool	Request to record "parameters"
ActivateOpMode	Bool	Activate the selected operating mode in the OpMODE parameter
OpMode	USInt	Selecting the SM 1281 operating mode.0: STOP: System is waiting 1: RUN: Monitoring 2: RUN: Monitoring deactivated 3: RUN: Measuring 4: RUN: System diagnostics Values > 4 are interpreted as "0", i.e. - "STOP: System waiting"

Table 2

Input/output parameters for "SM1281_Module"

Parameter	Data type	Description
DBStateModule	Struct	Link to the module structure in DB "SM 1281_Status"
DBBackupModule	SM 1281_Type_Moduleparameters	Link to the module parameter structure in DB "SM 1281_Backup"

Table 3

Output parameters for functional "SM1281_Module"

Parameter	Data type	Description
ActualSpeed	Real	Current speed in revolutions per minute
ActualOpMode	USInt	Current operating mode of the SM 1281 module
StateOpModeChange	USInt	Operating mode change status
StateRawDataRec	USInt	Raw data recording status
StateFingerprintRec	USInt	"Parameters" recording status
SystemState	DWord	Current system status

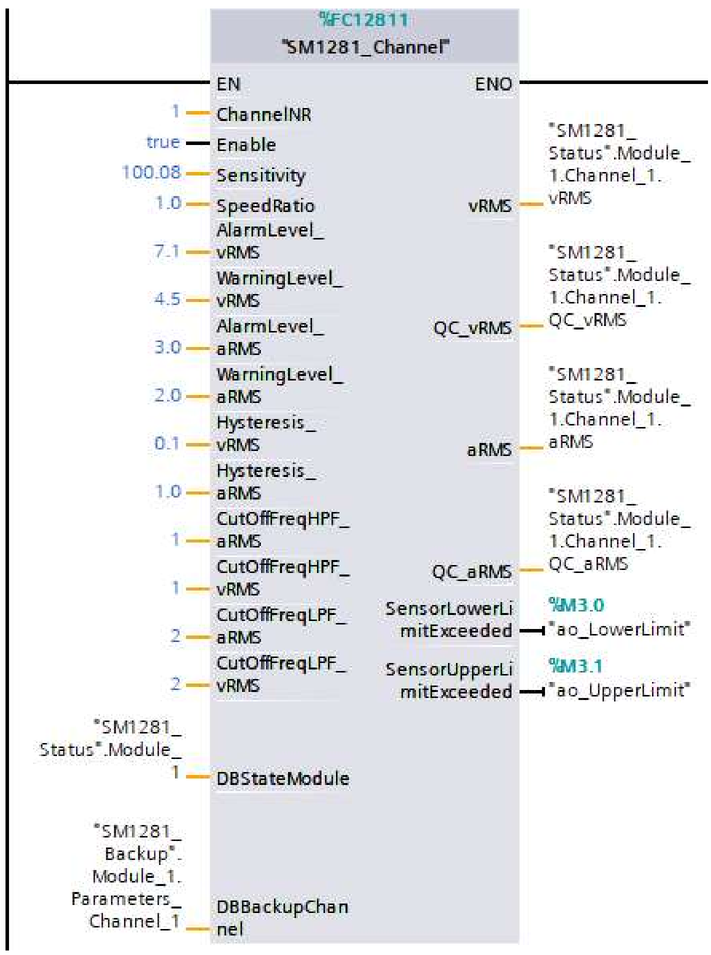


Fig. 8. FC12811 "SM1281_Channel" function module for parameterizing the vibration measurement channel

The configured module "SM1281_Channel" returns the measured root mean square value of vibration acceleration or vibration velocity; therefore, to determine the vibration displacement, the received signal must be integrated.

It should be noted that the SIPLUS SM 1281 technology module can act under several operating modes, therefore, to enable the measurement mode of values, it is necessary to explicitly set the number "3" in the "OpMode" parameter in "SM1281_Module".

After the initial values of the parameters for prediction have been calculated, an extrapolation model can be built using the Lagrange interpolation polynomial to determine the values of the parameters for the future period. In this case, one can also check the prediction error, and if it is within acceptable limits, make a prediction according to the model built to determine the probability of surge occurrence.

Thus, it will be possible to prevent surges by using the prediction of the main performance indicators of the centrifugal supercharger.

Let us consider in more detail other functional modules of the project. First of all, the module with the implementation of the algorithm for calculating the predicted values of GPU performance indicators – "Program [FB1]".

This functional module is cyclically called in the main organizational module of the project "Main [OB1]" (Fig. 9).

It makes it possible to set the value of Δt, i.e., to specify the time intervals at which data should be saved for further extrapolation.

In addition, one can set permissible values for axial displacement, pressure drop across the supercharger baffle, supercharger turbine speed, and horizontal and vertical vibration displacement of the supercharger rear support. In the process of setting permissible values for these parameters, one can also assign a limit value of absolute error to each of them.

To save the measured values in the array, an incremental counter with a selected frequency is used, in this case 2 Hz. Fig. 10 shows a fragment of the algorithm for finding the average value from a set of measured data over a given time interval. In this case, if the average value from the set of measured data reaches a predetermined value, the parameter from the sensor is written to the array. Then the current index for the data array is increased, and the countdown starts from zero to repeat the procedure described above.

As a result of such actions, the same time interval between the stored measured values is ensured, since the measurement of the prediction parameters must be carried out discretely at times t_0, t_1, ..., t_n (Fig. 11).

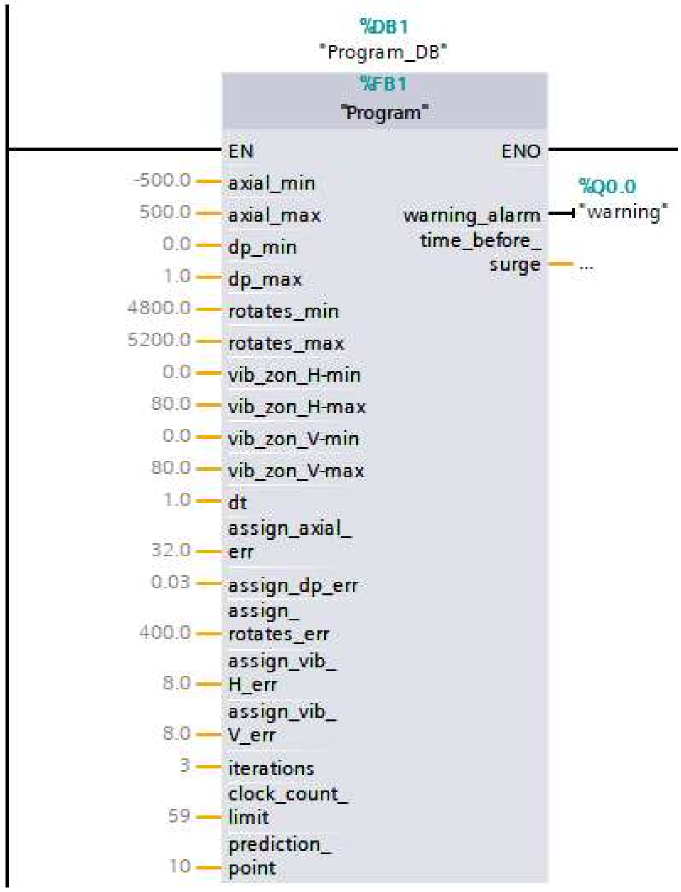


Fig. 9. The FB1 "Program" functional module developed to predict the pre-pumping state of a gas compressor unit

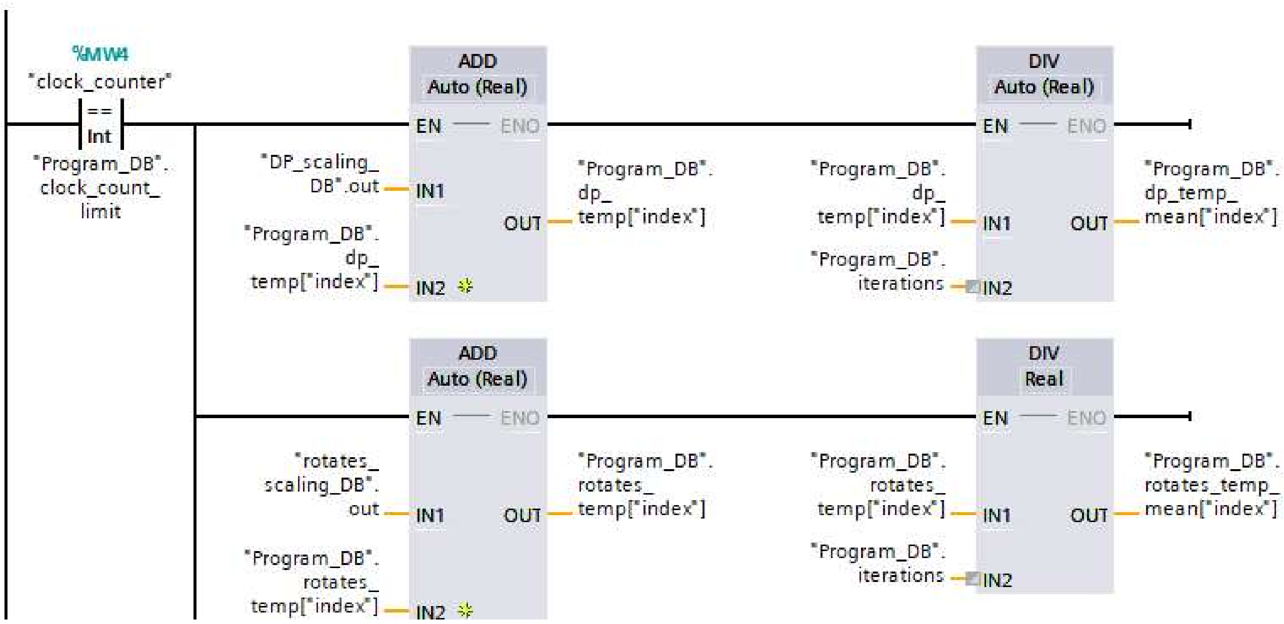


Fig. 10. Fragment of an algorithm for finding the average value from a set of measured data

If, as a result of the forecast, the values of GPU performance indicators, after a time equal to 5Δt, go beyond the specified permissible limits, and the forecast error does not exceed 10–15%, an alert signal is generated. This signal warns of the possibility of a supercharger surge (the time for setting the Δt value can be reset depending on the task).

Otherwise, a conclusion is drawn about the correctness of supercharger operation; the previously saved values are reset, and the forecasting process starts again for the next time points.

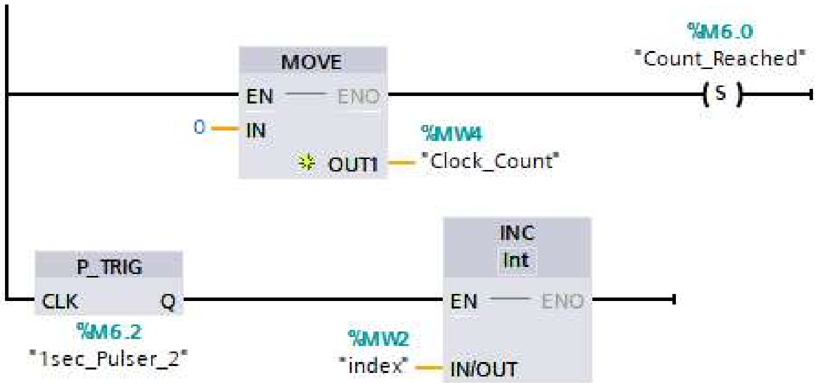


Fig. 11. Fragment of the algorithm for resetting the counter after saving data

5. 3. Design of the upper level of the anti-surge protection system for gas compressor units

To visualize the technological process, the Siemens TP900 Comfort HMI panel with a 9-inch TFT display was used.

As a result, a new device was added to the project – HMI_1 [TP900 Comfort] (Fig. 12).

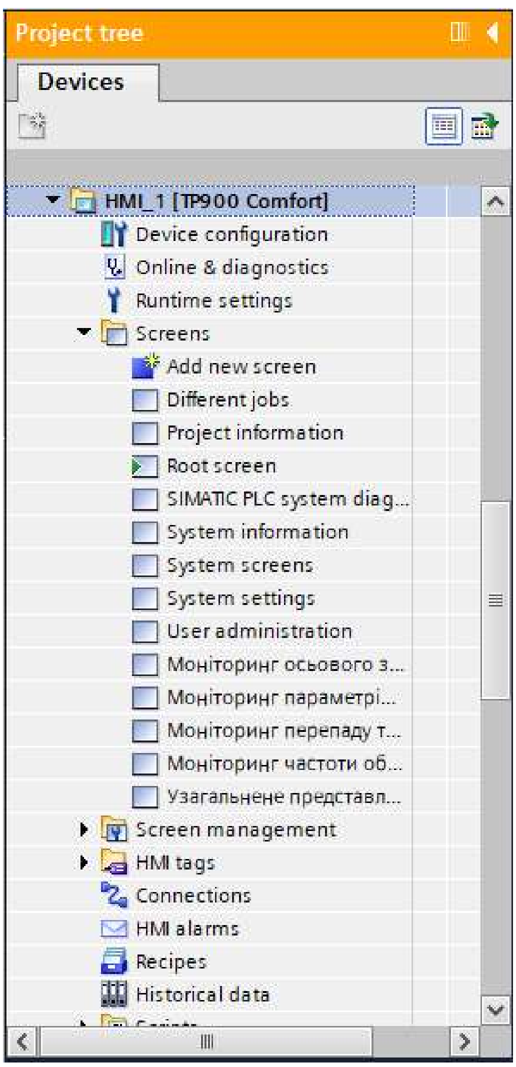


Fig. 12. New device HMI_1 [TP900 Comfort] in the project tree window

The main HMI screen displays a navigation menu that makes it possible to obtain information about the monitored parameter, display time trends, and calculate its predicted value before the onset of surges (Fig. 13).

Let us take a closer look at the window for monitoring the vibration displacement indicators of the rear support of the supercharger horizontally and vertically.

This parameter has a measurement range from 0 to 80 µm; the "optimal" operating point is 40 µm. Data from the object is measured using piezoelectric sensors, which are connected to the SIPLUS SM 1281 module and stored in the controller for further processing (Fig. 14).

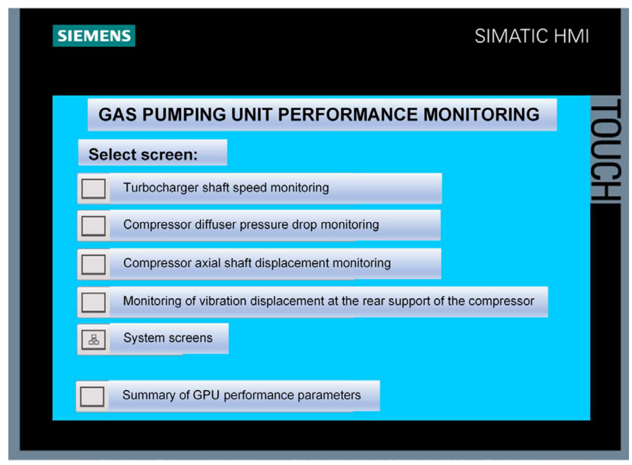


Fig. 13. Human Machine Interface – "Main Screen"

The window for monitoring the indicators of all the parameters of the supercharger operation is more meaningful since it provides complete information about the state of the supercharger and the possibility of a surge situation.

This window is shown in Fig. 15. The current value from the sensor is shown on the left, and the predicted value according to the developed algorithm is on the right.

The time for which the prediction is performed is set separately in the PLC program settings.

According to the previously conducted analysis of trends in the GPU-C-16S, when a surge event occurs, several tens of seconds pass before the indicators of the vibration displacement of the rear support of the supercharger increase horizontally and vertically, as well as the axial displacement of the supercharger before the surge occurs.

In the case when the values of GPU operation indicators exceed the permissible limits, a signal is generated about the occurrence of a surge event on GPU-C-16S.

Such a signal can be used to further open the anti-surge valve in a time that will avoid a surge event (Fig. 16).

Thus, using the prediction of the main indicators of the centrifugal supercharger operation, the occurrence of surge in the GPU supercharger can be prevented.

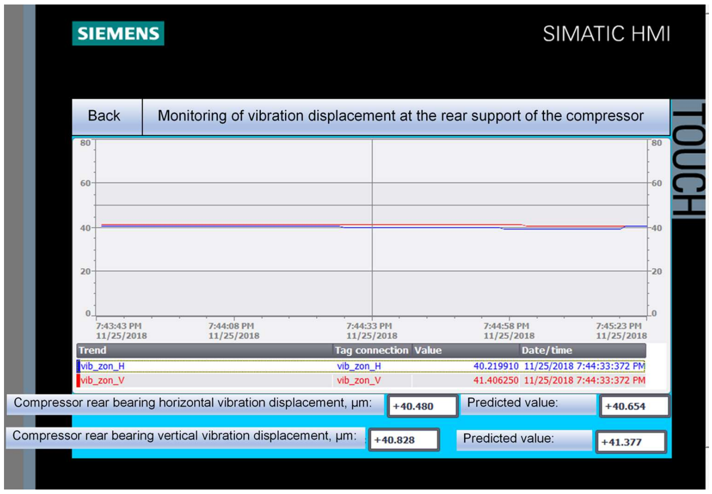


Fig. 14. Window "Monitoring the parameters of vibration displacement of a rear support in the supercharger"

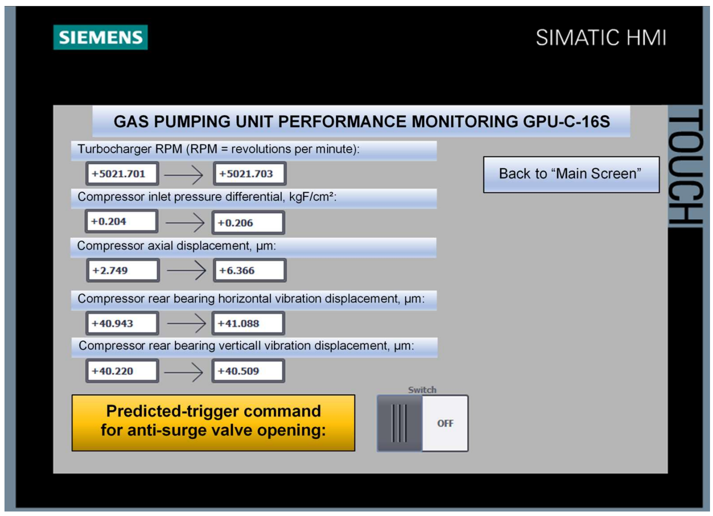


Fig. 15. Window "Monitoring the GPU-C-16S performance indicators"

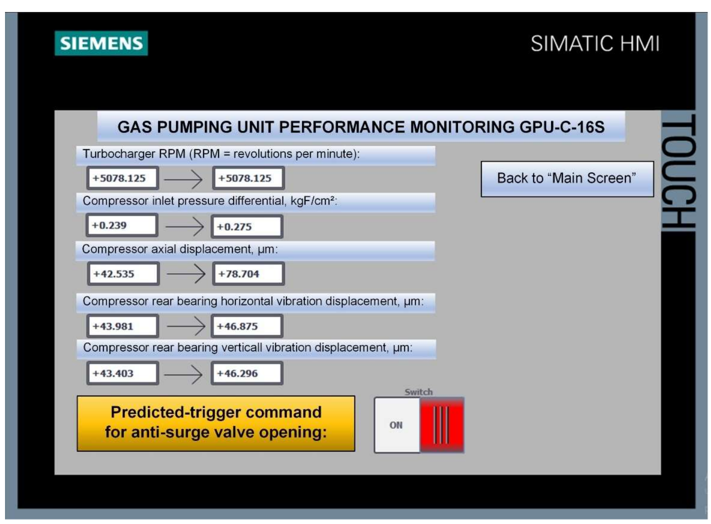


Fig. 16. Parameters exceeding permissible limits as a result of forecasting

5. 4. Design of a control subsystem for a station anti-surge valve

To implement the task of processing input analog signals from the pressure drop sensors on the condenser and the speed of the supercharger turbine, two input channels of the SM 1234 signal module with current measurement ranges of 4–20 mA (Fig. 17) at addresses "IW96" and "IW98" and one output signal of the SM 1234 module [22] with a range of 4–20 mA at address "QW192" were used.

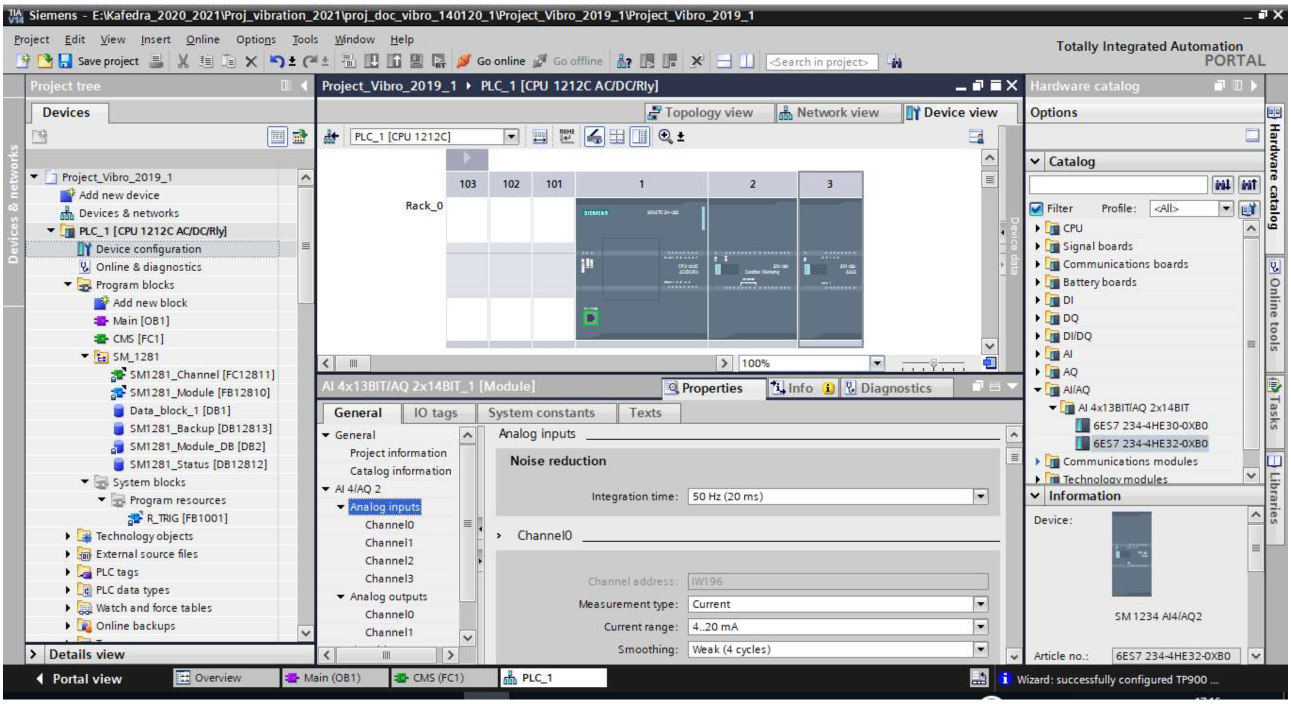


Fig. 17. Setting the parameters for a SM 1234 analog input signal processing module

The output signal for controlling the pneumatic converter ay the station anti-surge valve is formed on the basis of the output discrete signal "Q0.0" of the developed FB1 "Program" function module (Fig. 9).

The discrete signal "Q0.0" activates the analog output at address "QW192" of the SM 1234 signal module with the following parameters:

– closing time of the station anti-surge valve – up to 3 seconds;

– opening time of the station anti-surge valve – up to 10 seconds.

In addition, to indicate the state of complete closing or opening of the station anti-surge valve, signals are received from the valve limit switches on PLC S7-1200 at addresses "I0.6" and "I0.7".

The devised method and the designed system for monitoring the vibration state of GPU blade apparatus have undergone industrial testing at CS-3 of the Dolynska site and CS-39 "U-P-U" at the Bogorodchansky LVUMG TOV "Operator of Ukraine's GTS. Western Region".

6. Discussion of results related to designing an anti-surge protection system for gas compressor units based on vibration control devices

The main criterion in designing an anti-surge protection system for gas compressor units was a comprehensive solution to the tasks set on the basis of the devised procedures for predicting surge oscillations, an extrapolation model with correction, unified hardware and software tools, and a dispatcher interface. Additionally, when correcting the extrapolation model and developing a prediction and control algorithm, the vibration parameters of a real object under the pre-pumping and surge modes, which are recorded and processed in real time, were taken into account. Such a comprehensive approach ensured timely prediction and prevention of the surge mode of the gas compressor unit by automatically controlling the station anti-surge valve with an acceptable error to increase the indicators of effective and safe operation of technological equipment.

Devising the forecasting procedure involves the construction of a mathematical model for the process of changing the performance of GPU over time based on a priori information with subsequent extrapolation of values of the model parameters over time [13, 14]. At the same time, the accumulated information was subjected to a smoothing process to isolate and significantly reduce the outflow of interference for further construction of an extrapolation model.

The extrapolation model was built based on the Lagrange interpolation polynomial, taking into account the possibility of using it for interpolation and numerical integration (5); the model error on the interval of its construction (10) was determined.

The expected forecast error is determined by the error of the technological parameters of the extrapolation model, which is built on the interval (Fig. 2) with reduction to its standard deviation.

The extended functionality of the designed GPU anti-surge protection system is explained by the fact that in addition to monitoring the main technological parameters of GPU operation, the vibration parameters of its nodes are additionally monitored and taken into account (Fig. 3). Vibration parameters are also used to diagnose the technical condition of GPU nodes. This makes it possible to quickly detect deviations in the technological and vibration parameters of GPU from nominal values, take into account the technical condition of its components [19, 22], and take measures to prevent the surge phenomenon, especially in the case of sequential operation of two CSs (Fig. 4).

The structure of the designed system includes a hardware configuration based on PLC_1 [CPU 1214 AC/DC/Rly] and a dispatcher interface based on the operator panel HMI_1 [TP900 Comfort] (Fig. 6). At the same time, a unified

CMS2000 VIB-SENSOR and SM 1281 "Siemens" (Fig. 3) are used, which provide 16-bit depth and an error of ± 0.3% of the measuring range, which is acceptable for basic vibration measurements [21].

The application software has been developed in the LAD (Ladder diagram) language of the IEC 61131-3 standard. Parameterization of the SM 1281 PLC S7-1200 vibration module was performed using a special function module "SM 1281_Module [FB12810]" (Fig. 7). Parameterization of the function module "SM1281_Channel" provides setting of parameters for up to 4 vibration measurement channels (Fig. 8). To directly implement the algorithm for calculating the predicted values of GPU performance indicators, the function module "Program [FB1]" has been designed, which is cyclically called in the main organizational unit of the project "Main [OB1]" (Fig. 9). At the same time, the permissible values for axial displacement, pressure drop across the supercharger baffle, supercharger turbine speed, and vibration displacement of the supercharger rear support horizontally and vertically are parameterized (Fig. 4). In the process of setting permissible values for the specified parameters, it is also possible to assign a limit value of absolute error to each of them.

Based on our research, a subsystem for controlling the station anti-surge valve of the GPU operating modes was additionally designed by means of simulation modeling and full-scale tests (Fig. 17) [12, 19].

The results of research into the operating modes and practical implementation of the GPU anti-surge protection system based on hardware and software vibration control tools ensured an increase in the technical and economic indicators of the system during its operation due to improved procedures for monitoring and controlling technological equipment.

The limitations of our study include the maximum allowable cable length for CMS2000 VIB-SENSOR vibration sensors – up to 30 m, without compromising signal quality [21].

The disadvantages of the work include the fact that the designed system of anti-surge protection of GCUs based on hardware and software means of vibration control when integrated into existing ACS at GPU s requires additional coordination. When modernizing existing ACS at GPUs, such coordination must be performed at the level of communication protocols and SCADA components.

Further research in this area may involve the design of new, more promising systems for anti-surge protection of gas compressor units. In this case, methods and hardware and software, algorithms and application software could be improved, including on the basis of practical testing of research results, implementation, and operation of such systems.

7. Conclusions

1. According to the extrapolation model, which is based on Lagrange interpolation polynomials, a procedure for predicting the occurrence of surge phenomena during the sequential operation of two compressor stations has been devised. Its feature is the accumulation of information about the process of changing the operating parameters of the control object by registering such parameters on a real object under the pre-pumping and surge modes of operation. Additional correction of the extrapolation model at a given time interval is provided by a step-by-step increase in the order of the model to a third-order polynomial, which provides an acceptable prediction error.

2. When designing the components of an anti-surge protection system for gas compressor units, the GPU-C-16S vibration state control system was taken as the basis, the structure of which included an analog signals module. A detailed analysis of the trends of technological and vibration parameters registered by the standard SCADA system before the occurrence of surge oscillations in the GPU supercharger was carried out. The key parameters were chosen as the pressure drop across the confuser, the speed of the supercharger turbine, its axial displacement, and the vibration displacement of the rear support in the vertical and horizontal directions to the supercharger axis. The hardware of the anti-surge protection system of the supercharger was designed taking into account the vibration parameters based on the Simatic S7 equipment by configuring, parameterizing, and debugging the communication environment. An algorithm and application software of the system were developed that makes it possible to predict the values of supercharger performance indicators. At the same time, if after a time equal to $5\Delta t$ the parameters go beyond the specified permissible limits, and the prediction error does not exceed 10–15%, a warning signal is generated about approaching the surge mode. Otherwise, a conclusion is drawn about the normal operation mode of the supercharger; the previously saved values are reset, and the prediction process is restarted.

3. The upper level of the GPU anti-surge protection system has been designed based on unified means and technologies for organizing the human-machine interface with visualization, archiving, and alarm functions. The main HMI interface displays a navigation menu that makes it possible to obtain information about the controlled parameter, for example, vibration acceleration, display time trends and calculate its predicted value until the moment of surge oscillations. Additionally, this parameter is used for the algorithm for opening the anti-surge valve in time, which makes it possible to avoid a surge event. Thus, using the prediction of the main technological and vibration parameters of the GPU operating mode, it is possible to avoid surge of its supercharger.

4. Based on our studies of the operating modes of CS technological equipment, a subsystem for controlling the station anti-surge valve with an indication of the state of complete closure (up to 3 seconds) or opening (up to 10 seconds) has been designed. The output signal of control over the pneumatic converter of the station anti-surge valve is formed on the basis of the output discrete signal from the designed functional module FB1 "Program" in accordance with the algorithm of operation of GPU ACS. Thus, when implementing the control algorithm for one of the main elements of the GPU anti-surge protection, the parameters of vibration state of the control object are additionally taken into account, which improves the efficiency of the anti-surge protection system as a whole.

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.

Funding

The study was conducted without financial support.

Data availability

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

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Alsuwian, T., Amin, A. A., Iqbal, M. S., Maqsood, M. T. (2023). A review of anti-surge control systems of compressors and advanced fault-tolerant control techniques for integration perspective. Heliyon, 9 (9), e19557. https://doi.org/10.1016/j.heliyon.2023.e19557
2. Bentaleb, T., Cacitti, A., De Franciscis, S., Garulli, A. (2015). Model Predictive Control for pressure regulation and surge prevention in centrifugal compressors. 2015 European Control Conference (ECC), 3346–3351. https://doi.org/10.1109/ecc.2015.7331051
3. Mirsky, S., Jacobson, W., Tiscornia, D., McWhirter, J., Zaghloul, M. (2012). Development and design of antisurge and performance control systems for centrifugal compressors. Proceedings of the Forty-Second Turbomachinery Symposium. Available at: https://core.ac.uk/download/pdf/147258448.pdf
4. Daniarta, S., Wardana, A. N. I., Rosita, W. (2016). Performance evaluation of compressor anti-surge control based on model predictive in ammonia plant. 2016 International Seminar on Application for Technology of Information and Communication (ISemantic), 75–79. https://doi.org/10.1109/isemantic.2016.7873813
5. Chetate, B., Zamoum, R., Fegriche, A., Boumdin, M. (2013). PID and Novel Approach of PI Fuzzy Logic Controllers for Active Surge in Centrifugal Compressor. Arabian Journal for Science and Engineering, 38 (6), 1405–1414. https://doi.org/10.1007/s13369-013-0601-6
6. Kolnsberg, A. (1979). Reasons for Centrifugal Compressor Surging and Surge Control. Journal of Engineering for Power, 101 (1), 79–86. https://doi.org/10.1115/1.3446465
7. Hou, Y., Wang, Y., Pan, Y., He, W., Huang, W., Wu, P., Wu, D. (2023). Vibration-based incipient surge detection and diagnosis of the centrifugal compressor using adaptive feature fusion and sparse ensemble learning approach. Advanced Engineering Informatics, 56, 101947. https://doi.org/10.1016/j.aei.2023.101947
8. Dietel, F., Schulze, R., Richter, H., Jakel, J. (2012). Fault detection in rotating machinery using spectral modeling. 2012 9th France-Japan & 7th Europe-Asia Congress on Mechatronics (MECATRONICS) / 13th Int'l Workshop on Research and Education in Mechatronics (REM), 353–357. https://doi.org/10.1109/mecatronics.2012.6451032
9. Niccolini Marmont Du Haut Champ, C. A., Silvestri, P., Ferrari, M. L., Massardo, A. F. (2020). Signal Processing Techniques to Detect Centrifugal Compressors Instabilities in Large Volume Power Plants. Journal of Engineering for Gas Turbines and Power, 142 (12). https://doi.org/10.1115/1.4048910
10. Sandoval, O. R., Machado, L. H. J., Hanriot, V. M., Troysi, F., Faria, M. T. C. (2022). Acoustic and vibration analysis of a turbocharger centrifugal compressor failure. Engineering Failure Analysis, 139, 106447. https://doi.org/10.1016/j.engfailanal.2022.106447
11. Liśkiewicz, G., Kulak, M., Sobczak, K., Stickland, M. (2020). Numerical Model of a Deep Surge Cycle in Low-Speed Centrifugal Compressor. Journal of Turbomachinery, 142 (12). https://doi.org/10.1115/1.4048328
12. Hurinenko, V. M., Ivanyshyn, V. P. (2012). Pidvyshchennia efektyvnosti ekspluatatsiyi kompresornoi stantsiyi KS "Dolyna". Naukovi visti: Halytska akademiya, 2 (22), 29–36.
13. Hrudz, Ya. V. (2012). Prohnozuvannia tekhnichnoho stanu hazoperekachuvalnykh ahrehativ. Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch, 4 (45). Available at: http://nbuv.gov.ua/UJRN/rrngr_2012_4_19
14. Bliaut, Yu. Ye. (2013). Avtomatychna identyfikatsiya pompazhnykh kharakterystyk hazoperekachuvalnykh ahrehativ z hazoturbinnym pryvodom dlia efektyvnoho rehuliuvannia. Ivano-Frankivsk: Ivano-Frankivskyi nats. tekh. un-t nafty i hazu, 20. Available at: https://www.library.nung.edu.ua/katalog-avtoreferatiiv-disertatsiii-zakhishchenikh-v-iifntung-z-fondu-ntb.html
15. Zamikhovska, O. L., Zamikhovskyi, L. M., Ivaniuk, N. I. (2021). Rozrobka protsedury prohnozuvannia vynyknennia pompazhnykh yavyshch pry poslidovniy roboti dvokh kompresornykh stantsiy. X Naukova konferentsiia "NAUKOVI PIDSUMKY 2021 ROKU". Kharkiv, 21. Available at: https://entc.com.ua/download/%D0%97%D0%B1%D1%96%D1%80%D0%BA%D0%B0_%D0%BD%D0%B0%D1%83%D0%BA%D0%BE%D0%B2%D0%B8%D1%85_%D0%BF%D1%80%D0%B0%D1%86%D1%8C_%D0%9D%D0%B0%D1%83%D0%BA%D0%BE%D0%B2%D1%96_%D0%BF%D1%96%D0%B4%D1%81%D1%83%D0%BC%D0%BA%D0%B8_2021.pdf
16. SIMATIC STEP 7 Basic/Professional V17 and SIMATIC WinCC V17. Available at: https://support.industry.siemens.com/cs/document/109798671/simatic-step-7-basic-professional-v17-and-simatic-wincc-v17?dti=0&lc=en-UA
17. Zamikhovskyi, L., Nykolaychuk, M., Levytskyi, I. (2024). Organizing the automated system of dispatch control over pump units at water pumping stations. Eastern-European Journal of Enterprise Technologies, 5 (2 (131)), 61–75. https://doi.org/10.15587/1729-4061.2024.313531
18. Adasovskyi, B. I., Zamikhovskyi, L. M. (2014). Diahnostuvannia system. Ivano-Frankivsk: IFNTUNH, 116.
19. Zamikhovskyi, L. M., Zamikhovska, O. L., Ivaniuk, N. I., Pavlyk, V. V. (2020). Improvement of the automatic control system of gas-pumping units taking into account their technical condition. Oil and Gas Power Engineering, 2 (34), 84–95. https://doi.org/10.31471/1993-9868-2020-2(34)-84-95
20. PID Control with PID_Compact for SIMATIC S7-1200/S7-1500. Available at: https://support.industry.siemens.com/cs/document/100746401/pid-control-with-pid_compact-for-simatic-s7-1200-s7-1500?dti=0&lc=en-US
21. Condition Monitoring Systems. SIPLUS CMS1200. SM 1281 Condition Monitoring. Operating Instructions. Available at: https://cache.industry.siemens.com/dl/files/490/109481490/att_885698/v1/cms1200_sm1281_operating_manual_en-US_en-US.pdf
22. Zamikhovskiy, L., Ivanuyk, N. (2017). Control system of operation of gas pumping unit taking into account its technical condition. PEN Conference Systems, Innovative Ideas in Science.