Dynamic Simulation for Processes as a Key Factor of Efficiency

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Abstract

The object of the research are the control systems for the turbomachinery equipment in the chain of processes of the largest oil refining companies in the existing economic realities. As a subject of research, the existing problems of transition to innovative technologies by the mentioned companies and the solutions were chosen. Research methodology: methods of comparative analysis, statistical observation, scientific dynamic simulation. The purpose of the study is to identify the dynamics of informatization and the objective possibility of introducing innovative technologies in the studied petrochemical plants. The article presents the results of the analysis conducted by the authors, which reflect low effectiveness of existing control systems for the turbomachinery components at refineries in Russia. The author's approach for turbomachinery control optimization based on the examination of global trends is justified. The factors affecting the quality of the turbomachinery control system functioning as well as challenges companies being faced with are identified. A set of measures for improving the control systems based on the author's complex method for all kind of rotating equipment is proposed. The approbation of the proposed method is implemented at the Omsk Refinery FCC unit (Fluid Catalytic Cracking). Scope of the research results: centrifugal compressors in the petrochemical industry processes. The results of the economic effect assessment after implementation of the author's model for the turbomachinery controls are presented.

Keywords: Control system, Turbomachinery controls, Compressor, Power consumption optimization, Anti-surge control, Safety.

I. INTRODUCTION

The fourth industrial revolution have been happening nowadays - the economy is becoming digital. Robots appear in large quantities at factories, computers increasingly control highly dynamic processes and integrate into human work. Considering the specifics of the Russian economy, mining and processing companies in the oil and gas industry should be the first in "digitalization". The Russian industry is in a difficult situation due to many factors, including sanctions restrictions on materials, components, partnership with foreign suppliers, export transactions; high volatility of world oil prices (figure 1);

the interrelationship of enterprises and banking structures experiencing a shortage of financial resources
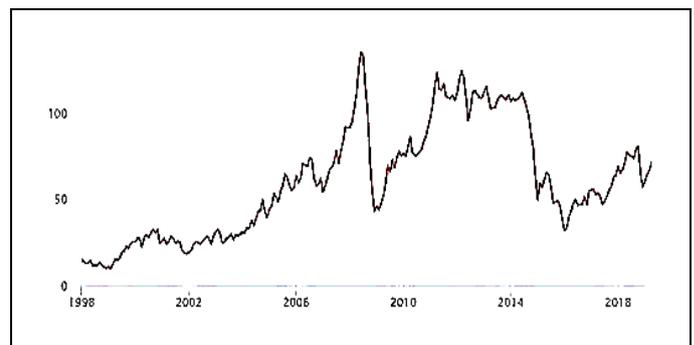
Fig. 1. Dynamics of prices for futures for Brent crude covering 1998-2018, $ / barrel

In September 2018, the 47th annual symposium on innovations in the field of turbomachinery and pumps was being held in Texas (USA) and one of the key topics was increasing the energy efficiency of existing turbomachinery equipment [1].

II. METHODOLOGY

The results of the author's research were approbated in the one the most modern refinery in Russia and one of the largest in the world, the «Gazpromneft-ONPZ», which has a capacity of 20.5 million tons of oil per year [2].The Omsk Refinery subsidary is the industry leader in refining efficiency: refining depth is more than 90%, the yield of light oil products of the Euro-5 ecological class is over 71%. «Gazpromneft-ONPZ» is an important link in the technologically related complex of subsidiaries of the oil company Gazprom Neft.

A) *The Object of Research*

For the time, the general development concept of «Gazpromneft-ONPZ» is aimed at improving the efficiency and profitability of production, maximizing profit, i.e. creation of economically highly efficient oil refineries. Medium-term and long-term tasks: the organization of production in the territory

of the Russian Federation of technology and the development of technologies that allow for the import substitution of fallen positions under sanctions; the creation of oil and gas processing and chemical facilities that provide deep processing of primary raw materials [3],[4].

Table 1. Link between Compressor Capacity and Energy Cost

№	Prime mover capacity MW	Consuming energy, KW/h	Expenditure, $
1	1,0	8760,000	438,000
2	5,0	43800,000	2190,000
3	25,0	2190000,000	10950,00

According to data presented in Table №1, we can see that dynamic compressor driven by 5 MW prime mover consumes 43,800 KW/h, which is in line with $2,190M, and compressor driven by 25MW prime mover costs $10,950M.

The results of economic effect achieved by optimizing control systems presented in Figure below.
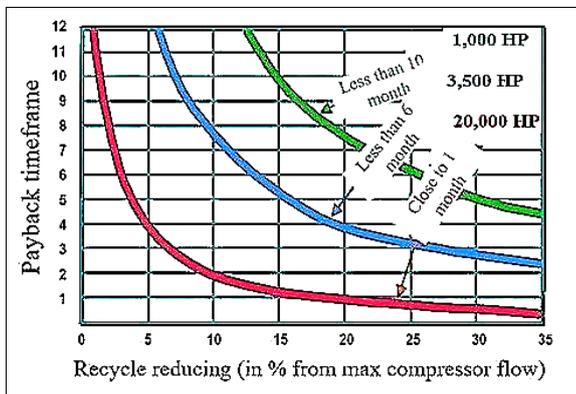
Fig. 2. The economic effect achieved with reducing of recycle through the anti-surge valve

The graph in the "Payback Timeframe" coordinates on the vertical axis and "Recycle reducing (in % from max compressor flow)" on the horizontal axis is a synthesis of more than 3,000 projects around the globe. It is clearly shown that in case of 15% reduction in consumption through an anti-surge valve, it is possible to achieve a quick return on investment (ROI), less than one year.

In 2018, Schneider Electric company, Process Automation entity, including the author of the article, implemented an anti-surge protection and control system for the compressors of the catalytic cracking unit (FCC) during the comprehensive program to increase the operating efficiency of production at «Gazpromneft-ONPZ», including compressors of the 43/103 unit [5],[6].

The compressors of the anti-surge protection and control system on the compressors of the catalytic cracking unit 43/103 were

designed for the specified parameters and operate in a specific performance range, while developing the design pressure and power.

B) *Compressor principal of operation*

Dynamic compressors operate by transferring torque to the gas through a high-speed rotor and have an open air-gas channel. When shaft is fixed, it is possible to blow it through in any direction, regardless of whether the compressor is axial or centrifugal. It compresses the gas by increasing its speed and then converting it into pressure in the diffuser. Positive displacement compressors lock part of the gas in the working chamber and compress it by reducing the volume of the chamber. The volumetric compressor has inside some mechanical part that blocks the flow path, so that such a compressor cannot be blown through. This part, be it a screw or a plunger, is used to reduce the volume of the gas and, thus, increase its pressure. The foregoing implies that the dynamic compressor can surge, and the positive displacement compressor does not. Surge is the development of a stalling phenomenon.

C) *Surge condition in compressor*

When a flow breakdown occurs in a dynamic compressor, it suddenly loses its ability to withstand the pressure drop that it created during previous work. At this moment, the gas begins to move in the direction dictated by the forces of nature, that is, from the high-pressure zone to the low-pressure zone. In this case, from the discharge to the suction. In turn, the volumetric compressor is not susceptible to stalling and contains a mechanical obstacle to the reverse flow of gas, so that it cannot surge.

When the compressor is operating, the mechanical energy of the rotating shaft is transferred to the gas in the form of kinetic energy, thus the blades accelerate the gas flow. In order to maintain energy exchange, the gas must move along the aerodynamic surface at a high speed, and in addition, the wing (or blade) must be located relative to the gas flow at a certain angle of attack [7]. If the gas begins to move slower than a certain critical velocity, or the angle of attack becomes too large, the flow separates from the aerodynamic surface and the exchange of energy between them stops [8]. A typical gas-dynamic characteristic of a turbocharger in the coordinates of the discharge pressure and productivity at a certain fixed speed is shown in Figure 2, 3.

It is easy to see that the pressure ideally should start to fall immediately when the flow crosses the surge line. But in real life, compressed gas pipe is screwed to the output flange of the compressor [9].

D) *Surge Consequences*

Surge is extremely dangerous for the compressor. The sudden pressure fluctuations inside the compressor caused by surging create shock axial loads of up to several tons on the rotor,

bearings, compressor housing, pipelines. When the surge reaches a critical level, vibration and axial displacement of the rotor reach, and the inlet temperature increases sharply.
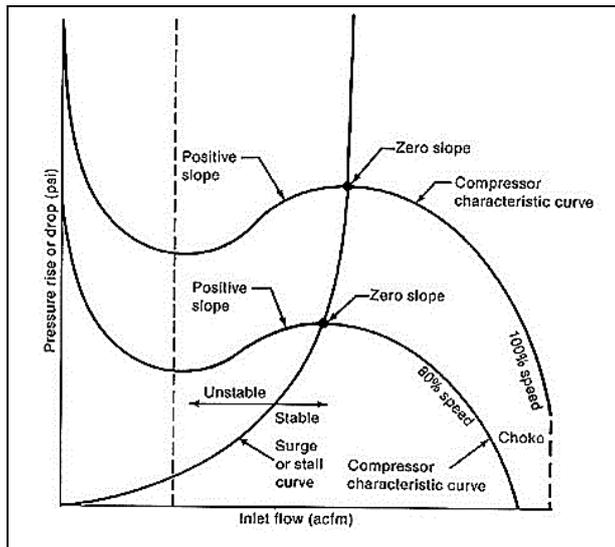
Fig. 3. Typical gas-dynamic map of a centrifugal compressor
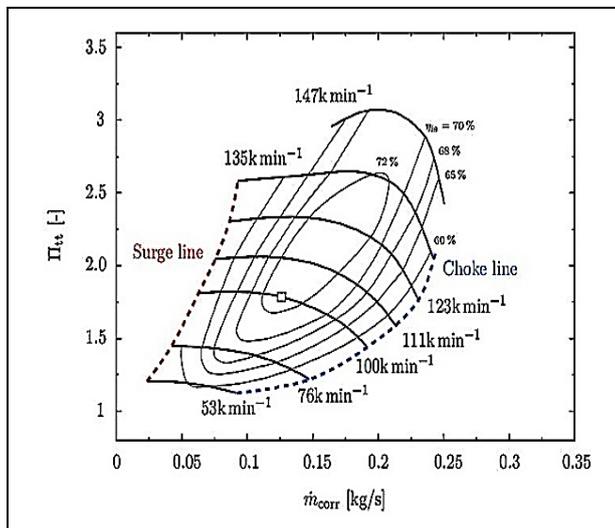
Fig. 4. Gas-dynamic map of a specific model of centrifugal compressor

E) Methodology for Power Optimization

The following engineering solution for anti-surge control has been proposed to ensure safe operation with significant load fluctuations. 43/103 compression unit consists of two types 340-81-3 and 340-81-4 electric drive compressors designed to supply the catalytic cracked compressed hydrocarbon gas to the absorption unit, and three electric drive centrifugal compressors of types 900-31-1 and 900-31-4, designed to supply compressed atmospheric air for catalyst regeneration. When the plant is operating in the normal process mode, two air compressors are in operation, one of which is redundant.

The total capacity of two air compressors is approximately 120,000 Nm3 / h. At the same time, the total need for installation in the air on the technology currently is approximately 105,000 Nm3 / h. Prior to the implementation of the anti-surge protection and control system, the necessary air consumption for the technology was regulated by discharge of excess air to the candle and, if necessary, slight throttling of the compressor suction [10]. Compressors were equipped with only shut-off motorized valves with manual doubles installed at the suction side, in the discharge and bypass line. Air flow control was performed by covering / opening the corresponding dampers using handwheels. In this case, the excess air, approximately 10,000 ÷ 15,000 Nm3 / h, was discharged into the atmosphere through a bypass line. The Schneider Electric solution for optimizing electricity consumption is based on satisfaction with all the parameters required by the technology, while at the same time minimizing consumption through the compressor [11].
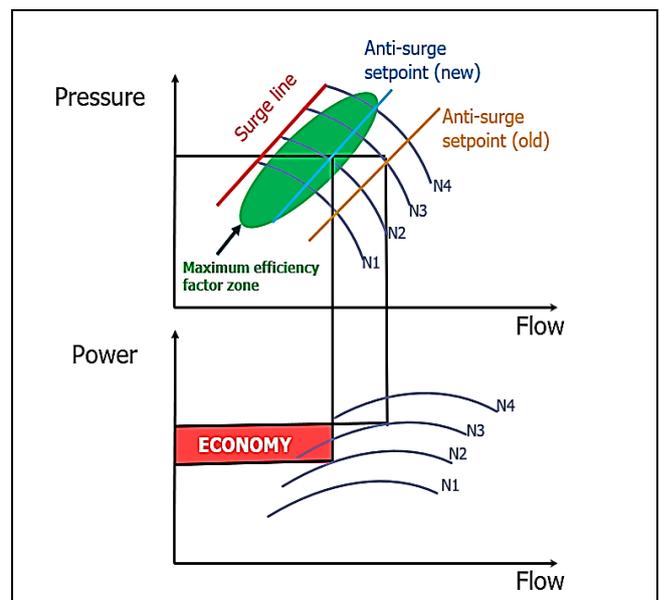
Fig. 5. Compressor energy optimization graph

The authors recommend the most effective approach to ensure safety and efficiency: the use of anti-surge control algorithms by moving to the surge line as close as possible with minimal opening of the recirculation line.

The second recommended method - control of compressor capacity - manipulation of the rotor speed of the compressor.

The figure below schematically reflects the influence of the driven prime mover speed control on the achievement of the desired energy consumption and, consequently, the fast achievement of return on investment (ROI). If the process needs a stable pressure or compression ratio of the gas to be compressed, then when the network resistance changes (point number 1), the control point will tend to position number 2. There are two options to meet the required parameters of the technology: the opening of the bypass recycling line (anti-surge valve), without achieving economic effect, because the anti-surge valve spends energy compressing or moving the control

point to position number 3, manipulating the speed of the driven prime mover, which saves steam from the boiler, electricity from a driving motor, or fuel gas in the case of a gas turbine.

After implementation of the new control system, each air compressor was fitted regulating dampers FV2101, FV2201, FV2301, mounted on the suction compressors B-2, B-2a and B-2b, respectively, and fast-acting regulatory FV2102, FV2202, FV2302 anti-surge valves installed in parallel with discharge valves for discharge lines for compressors B-2, B-2a, B-2b, respectively.

The installation of regulating dampers on the compressor's suction made it possible to reduce the air flow through the compressors by covering the suction dampers, i.e. put compressors into deep throttling mode [12]. Thus, the introduction of the APSA system of air compressors allowed in the automatic mode to regulate the necessary air flow for the technology, which led to the almost complete cessation of the discharge of compressed air into the atmosphere through the discharge line.

Fig. 7. Gas Dynamic Characteristics for FCC compressors

Fig. 6. Compressor energy savings by driven prime mover speed control

The total air flow through the compressors decreased by 10,000 ÷ 15,000 Nm3 / h, and, consequently, the power consumed by the compressors decreased [13]. The real gas-dynamic map for the specific compressor is presented below.

G) Dynamic and Math Model of the Object

The Dynsim Sim Sci dynamic simulation software package by Schneider Electric was used to accurately estimate the economic effect and the amount of gas recycling. Based on the initial data, a dynamic model of the technological process was built (Fig. 8). Based on the model, the field devices and Triconex Tri-GP software and hardware complex manufactured by Schneider Electric were selected [14]. The gas-dynamic map of the compressor was "digitized" in a dynamic model, technological procedures and main parameters of the technological process were imposed, which require limitation. The anti-surge mathematics was worked out, the main technological parameters were calculated, including the maintenance of the compression rate specified by the technology. The mathematical model proposed by the authors is presented in Figure 10 & Figure11.

$$Si = tg\alpha_i = \frac{h_{p,red,i}}{q^2_{s,red,i}} \qquad (1)$$

$$S_{sp} = tg\alpha_{sp} = \frac{1}{K} = const \qquad (2)$$

$$Ss,a = \frac{S_A}{S_{sp}} = \frac{k \cdot (R^\sigma - 1)/\sigma}{\Delta P_o/p_s} \qquad (3)$$

$$S = \frac{S_A}{S_{sp}} = 1 \tag{4}$$

$$S_s = \frac{f\left(\frac{R_e^{\sigma} - 1}{\sigma}\right)}{\Delta p_o / p_s} \tag{5}$$

$$d = 1 - S_s \tag{6}$$

$$de\vartheta = d - b \tag{7}$$

$$\sigma = \frac{\log \theta_c}{\log R_c} \tag{8}$$
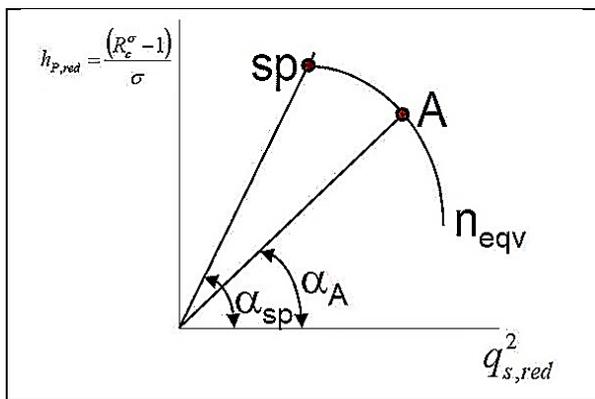
Fig. 8. Mathematical model for reducing flow through a compressor

$$(\Delta P_{oi})eq, i = C_3 \cdot \Delta P_{oi} \cdot f(R_{c1}) + C_4 \cdot \Delta P_{os} + C_5 \cdot \sqrt{\Delta P_{01} \cdot \Delta P_{05} \cdot f(R_{c1})} \tag{9}$$

$$(\Delta P_{oi})eq, i = C_3 \cdot \Delta P_{oi} \cdot f\left(\frac{P_d}{P_{s3}}\right) + C_4 \cdot \Delta P_{os} - C_5 \cdot \sqrt{\Delta P_{od} \cdot \Delta P_{05} \cdot f\left(\frac{P_d}{P_{s3}}\right)} \tag{10}$$

$$S_s \frac{k \cdot f(h_p)red, i \cdot P_{s,i}}{(\Delta P_{oi})eq} \tag{11}$$

$$(\Delta P_{oi})eq, i = C_3 \cdot \Delta P_{oi} \cdot f(R_{c1}) + C_4 \cdot \Delta P_{os} + C_5 \cdot \sqrt{\Delta P_{01} \cdot \Delta P_{05} \cdot f(R_{c1})}$$

Where, S is invariant parameter,

Hp, red, I – polytropic head, K is the Boltzmann constant, P is the pressure in suction or discharge,

q is a flow through the compressor and

C is closed invariant parameter [16].

Based on that we can build a math model covering load sharing between machines at the object of research.
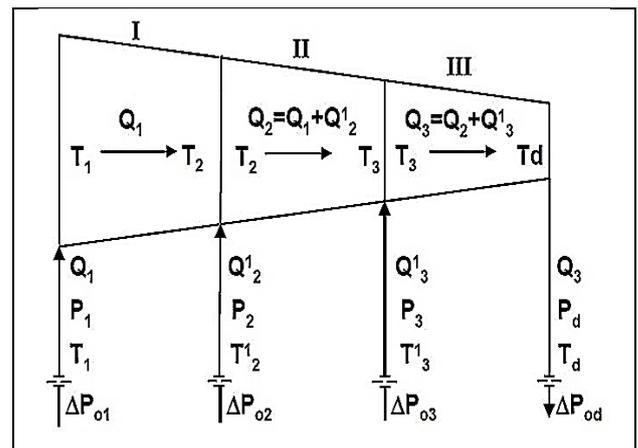
Fig. 10. Mathematical model of the load distribution between the compressors

The operating parameters of compressor B-2b during the test are shown in figures below. As a result of the test, it was found that when the pressure at the compressor inlet was reduced by about 4 kPa, from -20 kPa to -24 kPa, the active power consumed by the compressor decreased by about 160-200 kWh. A similar picture was observed when testing the compressor B-2a.

The main parameters of the compressor during the tests remained in the normal range [15]. Changes in the level of vibration, axial displacement, temperature rise of the support-thrust bearings during the tests were not observed [16]. Thus, reducing the air pressure at the compressor intake (throttling the flow through the suction) is one of the most effective ways to achieve energy savings.

The anti-surge protection and control system was platform (SIL2) by Schneider Electric with integration to existing control system network. Figure 11 demonstrates how we combined math model with dynamic model and integrate them into the one engineering suite for further tests.

At the same time, the control system monitors the position of the operating parameters of the compressors and protects the compressors from surge by adjusting the air flow through the compressors using anti-surge valves [17]. To determine the possibility of stable operation of air compressors with a

decrease in suction pressure from -20 kPa to -24 kPa and an assessment of the reduction in power consumption by the compressor, a series of tests on compressors B-2a and B-2b was performed during the commissioning works.
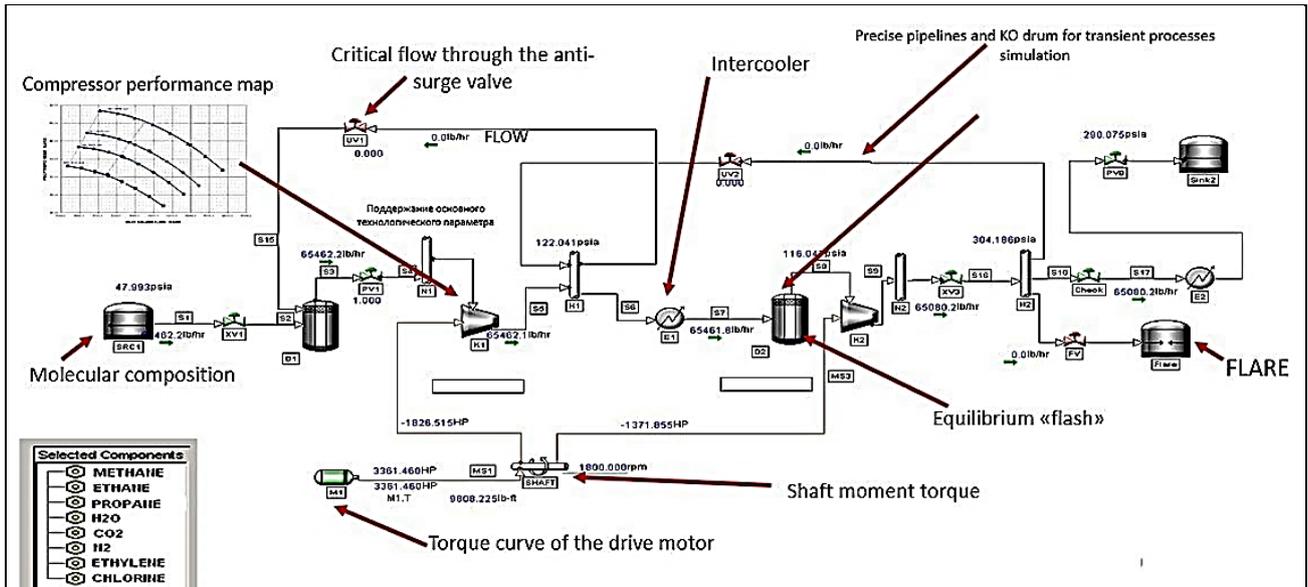
Fig. 9. Dynamic model for the FCC process including compressors
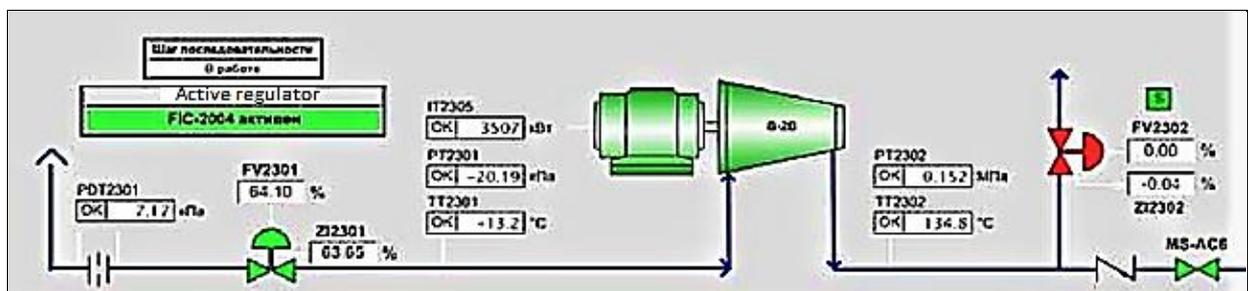
Fig.11. Testing the modified compressor
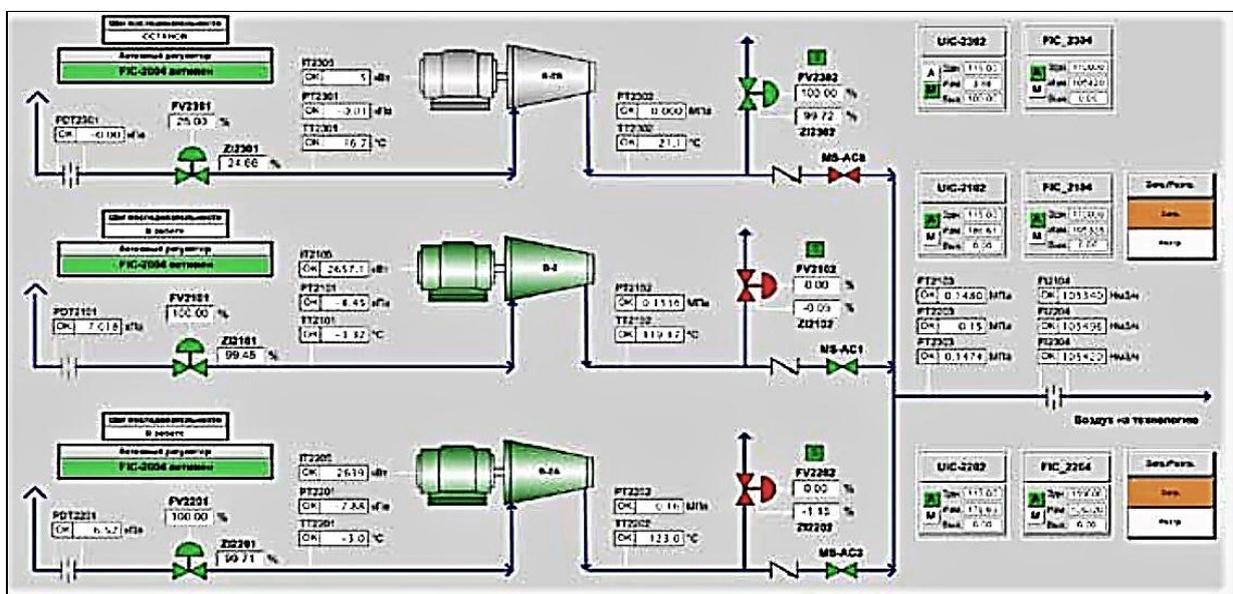
Fig 12. Diagram of air compressors at 43/103 unit

Table 2. Comparision of the compressor characteristic before and after

N п/п	Month	Flow, million nm3 2016-2017 гг	2018	Energy consumption, MW*h 2016-2017 гг	2018
1	January	71,42	77,35	5267,02	4531,02
2	February	65,67	69,43	4762,72	4068,97
3	March	72,99	77,74	4878,94	4531,71
4	April	70,56	75,04	4652,58	4283,62
5	May	73,55	76,57	4711,74	4410,20
6	June	71,35	71,91	4488,67	4416,69
7	July	63,34	74,05	4652,39	4559,40
8	August	73,10	76,04	4736,27	4606,20
9	September	65,48	74,77	4361,61	4559,07
10	October	44,91	49,39	2867,96	3048,41
Total		**672,38**	**722,29**	**45379,89**	**43015,29**

III.   ASSESSMENT OF ACHIEVING TARGETS AND ECONOMIC EFFECT

Using the proposed by authors methods, including control system and dynamic load balancing for two active compressors helps to reduce energy costs by selecting the optimal load distribution of the compressors. [18] The overall reduction in electricity consumption achieved as part of the implementation of the anti-surge protection and control system for 43/103 air compressors was 11.76% with a target of at least 3.5%.

Table 2. Comparison of the Compressor Characteristic before and after of about 5.21% of the figures for the same periods of 2017/2018. At the same time, the total consumption of compressed air of the installation 43/103 increased in 2018 in absolute terms by 49.9 million Nm3, which represents an increase in the volume of compressed air by 7.42% (equivalent to the energy consumption of 2,971.9 MWh the average value for compression 1 nm3) of the indicators for the same period of 2017/2018 [19].

The average value of electricity consumed for the compression of 1 Nm3 of air after the introduction of the new control system decreased to 59.55 W in 2015 compared to 67.49 W in the same periods of 2016-2017.

IV.   CONCLUSIONS

Compressors operation safety is provided by the modified control system. Practical implementation of the model of anti-surge protection and control proposed by the authors allows not only to increase the safety and reliability of operation of compressor equipment at oil refineries and chemical enterprises, but also to obtain an economic effect by reducing energy consumption, which is extremely important for modern financial condition of enterprises [20]. Thus, the practical application of the proposed solutions will achieve specific results:

-    new technology at the site with an approved amount of funding;

-    increasing the competitiveness of products, entering new markets;

-    improving the efficiency of enterprises.

Russia has set goals for developing a knowledge society in the country, increasing the availability of the quality of goods and services that will be produced using digital economy technologies. The construction of the digital economy in the country is designed to reduce the backlog of high technologies in Russia from the most developed countries, allow domestic companies to become more competitive, give a powerful impetus to development and strengthen the overall economy.

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