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Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
НАУК РЕСПУБЛИКИ
КАЗАХСТАН
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Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

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LINEAR MONITORING OF THE MAIN PIPELINE BY MEANS OF WIRELESS DIGITAL TECHNOLOGY

Abstract. Linear monitoring of technological and technical parameters of oil and gas pipelines based on intelligent wireless pressure, temperature and seismic sensors is considered, which allow monitoring anomalies of these parameters in order to optimize them in the main pipeline and detect cases of damage. A complete architectural monitoring diagram is proposed, which also allows detecting oil or gas leakage in the main pipeline and localizing it at the point of leakage. The possibility of integration on the example of WirelessHART wireless technology into a digital high-voltage frequency-controlled electric drive on intelligent power modules with microprocessor control is given. At the same time, it is shown that the replacement of the synchronous drive of pumping units with an asynchronous one has a number of technical and technological advantages. The optimal configuration of the elements of the technological and technical monitoring system of the main pipeline has been developed, regardless of the type of medium being pumped (oil or gas), with the transmission of measured data via a radio relay communication line in real time with the localization of abnormal disturbing effects by a digital invariant frequency-controlled asynchronous electric drive of compressor or pumping stations under any operating conditions. The monitoring system also allows you to detect cases of leaks and damage to the main pipeline.

Key words: linear monitoring, main pipeline, oil - and gas pipeline, pressure, temperature, vibration, wireless intelligent sensor, pumping unit, compressor station, frequency-controlled electric drive.

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СЫМСЫЗ ЦИФРЛЫҚ ТЕХНОЛОГИЯ ҚҰРАЛДАРЫМЕН МАГИСТРАЛЬДЫҚ ҚҰБЫРДЫҢ ЖЕЛІЛІК МОНИТОРИНГІ

Аннотация. Магистральдық құбырдағы оңтайландыру және оның зақымдану жағдайларын анықтау мақсатында осы параметрлердің ауытқуларын бақылауға мүмкіндік беретін зияткерлі сымсыз қысым, температура датчиктері мен сейсмикалық датчиктер негізінде мұнай және газ құбырларының технологиялық және техникалық параметрлерінің желілік мониторингі қарастырылуда. Магистральдық құбырдағы мұнай немесе газдың ағып кетуін анықтауға және оны ағып кету нүктесінде оқшаулауға мүмкіндік беретін толық архитектуралық бақылау диаграммасы ұсынылған. Сымсыз WirelessHART технологиясының мысалын қолдана отырып, микропроцессорлық басқарылатын зияткерлі қуат модульдеріндегі сандық жоғары вольтты жиілікті реттелетін электр жетегіне интеграциялау мүмкіндігі келтірілген. Бұл жағдайда айдау қондырғыларының синхронды жетегін асинхрондыға ауыстыру бірқатар техникалық және технологиялық артықшылықтарға ие екендігі көрсетілген. Айдалатын ортаның кез келген жұмыс режимдерінде компрессорлық немесе сорғы станцияларының сандық инвариантты жиілікті реттелетін асинхронды электр жетегінің шамадан тыс ақаулардың әсерлерін шектей отырып, нақты уақыт режимінде радиорелелік байланыс желісі бойынша өлшенген деректерді бере отырып, (мұнайдың немесе газдың) түріне қарамастан магистральдық құбырдың технологиялық және техникалық мониторингі жүйесі элементтерінің оңтайлы конфигурациясы әзірленді. Мониторинг жүйесі сонымен қатар магистральдық құбырдың ағып кетуі мен зақымдану жағдайларын анықтауға мүмкіндік береді.

Түйінді сөздер: желілік бақылау, магистральдық құбыр, мұнай және газ құбыры, қысым, температура, діріл, сымсыз зияткерлі өлшеуіш, сорғы қондырғысы, компрессорлық станция, жиілікті реттейтін электр жетегі.

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ЛИНЕЙНЫЙ МОНИТОРИНГ МАГИСТРАЛЬНОГО ТРУБОПРОВОДА СРЕДСТВАМИ БЕСПРОВОДНОЙ ЦИФРОВОЙ ТЕХНОЛОГИИ

Аннотация. Рассматривается линейный мониторинг технологических и технических параметров нефте- и газопроводов на базе интеллектуальных беспроводных датчиков давления, температуры и сейсмических датчиков, позволяющих контролировать аномалии этих параметров с целью их оптимизации в магистральном трубопроводе и обнаружения случаев его повреждения. Предложена полная архитектурная диаграмма мониторинга, позволяющая также выявлять утечку нефти или газа в магистральном трубопроводе и локализовать её в точке утечки. Приводится возможность интеграции на примере беспроводной технологии WirelessHART в цифровой высоковольтный частотно-регулируемый электропривод на интеллектуальных силовых модулях с микропроцессорным управлением. При этом показано, что замена синхронного привода перекачивающих агрегатов на асинхронный, обладает рядом технических и технологических преимуществ. Разработана оптимальная конфигурация элементов системы технологического и технического мониторинга магистрального трубопровода независимо от вида перекачиваемой среды (нефти или газа), с передачей измеренных данных по радиорелейной линии связи в режиме реального времени с локализацией аномальных возмущающих воздействий цифровым инвариантным частотно-регулируемым асинхронным электроприводом компрессорных или насосных станций при любых режимах работы. Система мониторинга также позволяет обнаруживать случаи утечек и повреждения магистрального трубопровода.

Ключевые слова: линейный мониторинг, магистральный трубопровод, нефте и газопровод, давление, температура, вибрация, беспроводной интеллектуальный датчик, насосный агрегат, компрессорная станция, частотно-регулируемый электропривод.

Introduction. The basis for the safe operation of main pipelines (MP), which include main gas pipelines (MG) and main oil pipelines (MO), is the control of pressure and temperature of gas or oil, as well as the reduction of losses due to the timely detection of leaks (no more than 1%). It should also be noted that within the entire infrastructure of oil and gas production between the fields and the end user, the MT network has always been the most vulnerable to terrorism, sabotage and theft, given its vast and long length - up to hundreds and thousands of kilometers. At the same time, there has not yet been an effective solution to protect against damage caused by such factors.

Integration of wireless sensor technology based on miniature computing devices - motors equipped with sensors (for example, temperature, pressure, illumination, vibration level, location, etc.) and transmitters operating in a given frequency range into a digital high-voltage variable-frequency electric drive will automatically control and optimize the technological parameters of the pumped medium along the entire length of the main pipeline.

Therefore, optimization of technological parameters and control of MT integrity by means of wireless sensor monitoring and digital variable-frequency electric drive (VFED) of compressor stations (CS) or pumping stations (PS) is an urgent scientific and technical task.

Object of research: A system of linear monitoring of the main pipeline with a variable-frequency asynchronous electric drive CS or PS based on digital multi-level high-voltage frequency converters with microprocessor control and miniature wireless computing devices – motors.

Aim: To develop an invariant control system for the electric drive of pumping units (PU) with linear monitoring of technological parameters regardless of the type of pumped medium (oil or gas) by MT based on intelligent wireless pressure, temperature and seismic sensors, which will allow monitoring and eliminating anomalies of these parameters, as well as detecting cases of leaks and damage under any conditions works of MT.

Research methods and results: Based on literature and patent research, an optimal configuration of elements of technological and technical monitoring using intelligent wireless sensors and transmission of measured data via a radio relay communication line in real time, regardless of the type of medium being pumped (oil or gas) with localization of anomalous disturbing effects by a digital invariant frequency-controlled electric drive CS or PS is proposed. The optimal configuration of the elements of the automatic control and monitoring system is modeled in the form of an optimization program, which makes it possible to determine the necessary values of the correction signal of the MT monitoring system and the feedback gain on the speed of the PU electric drive, which ensures maximum sensitivity to abnormal changes in the technological parameters of the pumped medium.

The main part. MG compressor stations and MO pumping stations are an integral and integral part of the MP, providing transportation of liquid and/or gaseous media, with the help of PU equipped with power equipment, and serve as a control element in the MP system. It is parameters such as pressure, temperature and vibration that determine the mode of operation of the main pipeline and affect the performance of transportation of liquid and gaseous media (Korshak et al., 2001).

It is known that when the pumping medium moves along the MP, pressure loss occurs due to the friction of the flow against the pipe wall. The pressure drop causes a decrease in the throughput capacity of the MP and simultaneously reduces the temperature of the transported medium. To maintain a given flow rate of the pumping medium and ensure optimal pressure in the pipe, CS or PS are installed at certain distances along the MP route, depending on the type of pumping medium. For example, when pumping gas with a volume of 90 million m^3/day, on a 110 km long section through a pipe with a diameter of 1400 mm, the pressure drops from 7.6 to 5.3 MPa. The increase in gas pressure at compressor stations (CS) is carried out in one, two or three stages with the help of centrifugal superchargers and the most optimal mode of operation of the MG is to maximize the use of its throughput with minimal energy consumption for compression and transportation. It should be noted that when transporting gas or oil through MP, abnormal changes in their pressure and temperature are also possible in the event of a leak (Korshak et al., 2001).

The length of the sections of the gas pipeline between the CS is calculated, on the one hand, based on the magnitude of the gas pressure drop in one section by no more than 1.6-2.5 MPa, and on the other – based on the binding of the station to settlements, sources of water supply, electricity, etc. Therefore, the optimal operation of the CS depends not only on the number of electric drive gas pumping units (EDGPU) installed at the station, but also on their energy performance and technological capabilities, including regulation.

The technological scheme of oil transportation, having a number of its specific features, imposes similar requirements for monitoring the same technological parameters as pressure and temperature with leak detection along the entire MO route (Korshak et al., 2001).

The main parameters of MO and MG, which should be monitored remotely, include:
- pressure inside the pipeline;
- temperature effects;
- seismic effects.

Parameter monitoring should be performed at all points of the technological scheme, where a dangerous operating mode may occur for the MP itself or its equipment. The measurement points of technological and technical parameters for monitoring the progress of the process and automatic protection, as a rule, coincide with each other.

A block diagram on the example of gas transportation by MG, as well as the nature of pressure and temperature changes along the route are shown in Figure 1.

Figure 1 shows: MCS – the main field CS; L – the number of CS along the MG route; BCS – boosting CS for underground gas storage UGS; UCS – urban CS; $P_н$, $t_н$ – nominal values of gas pressure and temperature after CS; $P_к$, $t_к$ – gas pressure and temperature before CS; l – distance between CS.

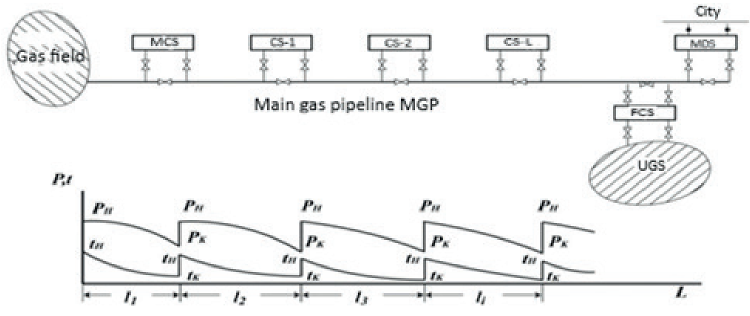


Figure 1 - Diagram of MG and changes in gas pressure and temperature along the route

Figure 2 shows a diagram of linear monitoring of the infrastructure of the main pipeline with radio relay data distribution based on wireless sensors.

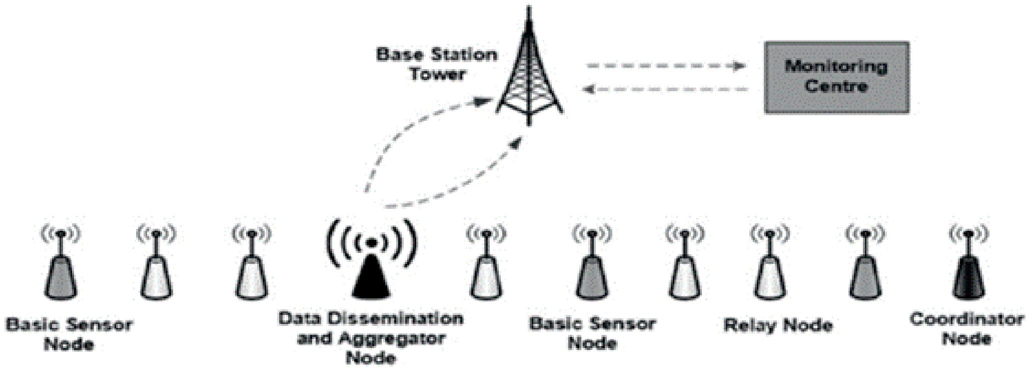


Figure 2 - linear monitoring of the infrastructure of MO and MG

In Figure 2, the following designations are adopted: Basic Sensor Node; Data Dissemination and Aggregator Node; Really Node; Coordinator Node; Base Station Tower; Monitoring Center. At the same time, the monitoring center coordinates communication in the wireless sensor data transmission network (Salman et al., 2016).

WSN coverage requirements may provide a uniform layout of nodes or require tighter deployment for wider surveillance.

WirelessHART™ technology is based on a wireless network communication protocol used in process automation applications (Figure 3). It adds wireless capabilities to the HART protocol, maintaining compatibility with existing HART devices, commands, and already known and used tools (WirelessHART™ technology).

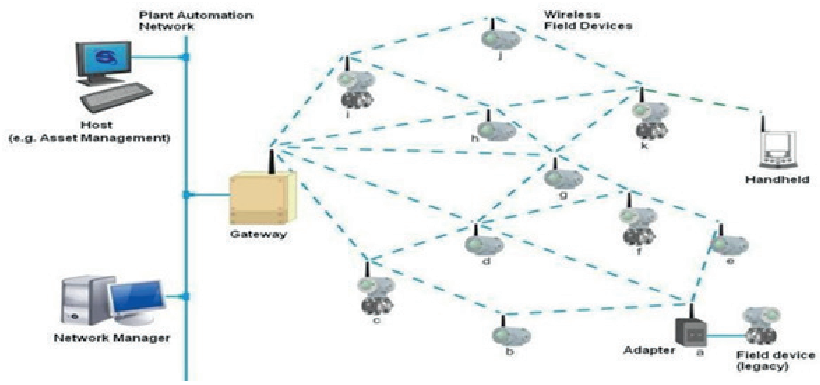


Figure 3 - WirelessHART™ technology for pressure and temperature measurement

The company SimpliMote produces a full line of intelligent wireless pressure sensors LD400WH and temperature TT400WH, which are able to operate autonomously without connecting to the power supply system, transmitting a signal using a radio channel (Figure 4 and Figure 5).

Figure 4 - Pressure sensor
WirelessHART LD400WH

Figure 5 - Temperature sensor
WirelessHART TT400WH

Such sensors can work in difficult conditions where there is no possibility of constant monitoring of the received data by personnel, and high data accuracy is ensured by a short update time (LD400WH pressure and TT400WH temperature sensors). At the same time, the WirelessHART™ pressure and temperature converters have the same design and differ only in the measuring element, so, for example, either a thermocouple or a resistance thermometer is used as a converter in a temperature sensor.

Similar temperature and pressure sensors are manufactured by ABB, Emerson and Semistar. Emerson and Semistar are additionally manufacturers of wireless seismic sensors (SU) to solve problems of preventing damage to pipelines and are designed to send alarms by the operator - only when a real and specific threat is detected (ABB sensors).

Figure 6 shows the block diagram of the 2.4 GHz SimpliMote module, where: pin expansion connector – pin connector; logger flash – flash memory for data logging; antenna; processor, analog and digital input/output; high-frequency radio transmitter.

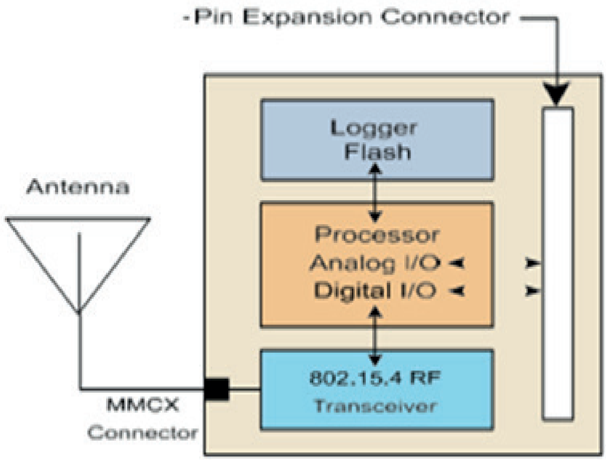


Figure 6 - Block diagram of SimpliMote module

The Simple Mode module (node) is based on microelectronic device boards and is designed specifically for deeply embedded sensor networks with high data transfer rates, providing wireless communication with each node as a router capability. The pin connector is necessary for connecting light, temperature, RH, barometric, accelerating/seismic, acoustic, magnetic and other sensors.

The base station allows collecting sensor network data on a PC or other computer platform. Therefore, a powerful ARM-based microcontroller (MCU) is built into Simple Mode to provide support for scalar and multimedia data, to which integrated circuits and interfaces are connected via various protocols. The DF 100 controller is the main element of the WirelessHART™ architecture, which allows selecting several independent information transmission paths for each device and automatic route selection. It combines powerful communication features with access to equipment via the WirelessHART™ protocol.

As noted above, the reduction of gas losses due to the timely detection of leaks in the pipeline is the basis of its operational safety. For example, in the Siberia – Ural –Volga pipeline, through which a wide fraction of light hydrocarbons was transported, a narrow gap with a length of 1.7 m was formed. Due to a pipeline leak and special weather conditions, gas accumulated in lowland along which the Trans-Siberian line passed 900 m from the pipeline. As a result, at the moment of the meeting of two passenger trains, a powerful volumetric explosion of a cloud of light hydrocarbons formed as a result of an accident on a nearby pipeline and a giant fire broke out. The shock wave dropped 11 wagons from the tracks, seven of them completely burned down. The remaining 27 cars were burned on the outside and burned out inside. According to official data, 575 people died; 623 became disabled, having received severe burns and bodily injuries (Russian Federation, 1989).

The ignition of the gas mixture could have occurred from an accidental spark or a cigarette thrown out of the train window. At the same time, about three hours before the disaster, the instruments showed a pressure drop in the pipeline. However, instead of looking for a leak, the staff on duty only increased the gas supply to restore pressure.

As a result of these actions, a significant amount of propane, butane and other flammable hydrocarbons leaked out through an almost two-meter crack in the pipe under pressure, which accumulated in the lowland in the form of a "gas lake". The drivers of passing trains warned the train dispatcher of the section that there was strong gas pollution on the stretch, but they did not attach importance to this.

No country in the world is guaranteed against the occurrence of such emergencies that occur during the transportation of gas through the pipeline. Therefore, monitoring the integrity of the pipeline with flammable fractions of light hydrocarbons is vital.

Gas leakage in MG, as a rule, is associated either with artificial damage to the pipeline, or with natural shifts and subsidence of the soil, it is also possible that there is a defect in the manufacture of the pipeline and a violation of technology during its laying. Any of the above cases causes vibrations that can be detected by seismic sensors.

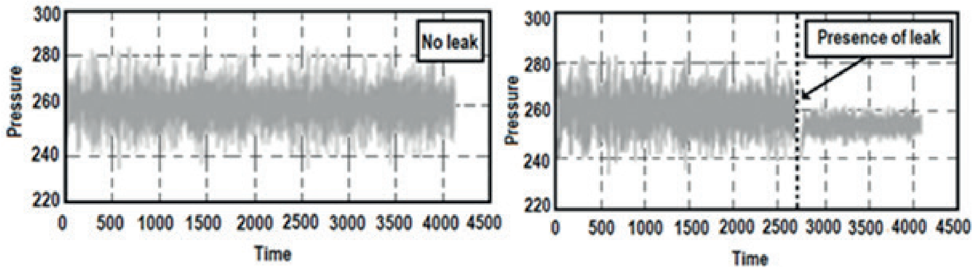
A seismic sensor (SU) based on modern wireless technologies solves the problem of timely detection of pipeline damage and prevention of leakage. SU sensors are installed approximately at a distance of 200-300 m from each other and are placed either along the pipeline or within 10 m from the pipeline on both sides at a depth between the pipe and the ground surface, thereby forming a block of several sensors. Each sensor unit is an autonomous object with a separate identifier depending on the characteristics of the zone.

Obtaining accurate seismic signaling is achieved through the use of several geophones (filters), which are very sensitive to the frequency domain of damage to the gas pipeline and are characteristic of the act of digging. This identification method also allows filtering out signals that are beyond a certain distance from either side of the pipeline, thereby reducing the minimum false alarm rate. The location of the identified threat depends on the exact measurement of the signal on each sensor.

The identification mechanism installed in each autonomous sensor unit and microprocessor monitoring system guarantees a confidence level of up to 99% after an integration time of less than 1 minute. In case of damage to the gas pipeline, SU sensors provide wireless transmission of an alarm message to the operator of the control center indicating the exact location of the damage on the monitor, as well as intervention commands located along the MG line. Receiving an alarm signal on a portable computer, the intervention team, this is located closest to the damage site, leaves on patrol vehicles to eliminate the accident. At the same time, the gas supply at this section of the MG stops.

There are various methods of leak detection and localization based on pressure in the main oil and gas pipelines during their monitoring (Mohamed et al., 2013). In our proposed methodology, we use a distributed implementation of the NPW negative pressure wave in combination with machine learning (ML) for leak detection.

Leaks and bursts in the pipeline lead to a transition in the pressure wave passing along the liquid inside the pipeline. The leakage point generates two waves of transients of the same magnitude in opposite directions. Due to the high fluid pressure, leakage causes attenuation in the transient signal, thereby causing NPW. Figure 7 shows pressure waveforms in the main pipeline in the absence of leakage and in the presence of 60% leakage.



a) Pressure in the absence of leakage b) Pressure profile in the presence of 60% leakage

Figure 7 - Leakage pressure along the pipeline depending on time

Slow and smaller leaks are more difficult due to the very small pressure difference between the normal and abnormal case. The position of the disturbance indicates the arrival time of the signals reflected from the leak, which can be used to measure the transit time of the transient signal from its source by dividing the pipeline into zones. Adjacent sensor nodes are grouped to form communities of nodes that acquire NPW functions and transmit information through a gateway to a managed network.

The basic formula of engineering hydraulics relating pressure p, density p and velocity is the Darcy-Weisbach formula:

$$\Delta p = \lambda \frac{l}{d} \cdot \rho \cdot \frac{\omega^2}{2}, \quad (1)$$

where D p – is the pressure loss to overcome the hydraulic resistance on the section of the gas pipeline l; l – is the coefficient of hydraulic resistance; l and d - are the length and inner diameter of the pipe, m; w – is the gas velocity, m/s; r – is the gas density, kg/m^3.

Hydraulic calculation of low, medium and high pressure networks is distinguished (Komina et al., 2010). In the hydraulic calculation of medium and high pressure pipelines, in which pressure differences are significant, it is necessary to take into account the change in density, gas velocity and the difference in gas temperature from 0 degrees Celsius. Therefore, the formulas for determining pressure losses to overcome friction forces in such gas pipelines have the following form:

– for medium and high pressure gas pipelines

$$p_b^2 - p_e^2 = \frac{16}{\pi^2} \cdot \lambda \cdot \frac{G_0^2}{d^5} \cdot \rho_0 \cdot P_0 \cdot l \cdot \frac{T}{T_0}, \quad (2)$$

where $p_н$ – is the absolute gas pressure at the beginning of the gas pipeline, MPa; $p_к$ – is the absolute gas pressure at the end of the gas pipeline, MPa; P_0 – is 0.101325 MPa; l – is the coefficient of hydraulic friction; G_0 - is the gas flow rate, m^3/s, in normal conditions; d - is the inner diameter of the gas pipeline, m; r_0-is the gas density under normal conditions, kg /m^3; l - the estimated length of the gas pipeline of constant diameter, m; T - gas temperature, °C; T_0- gas temperature in normal conditions, 0°C.

– for low pressure gas pipelines

$$p_b^2 - p_e^2 = \frac{8}{\pi^2} \cdot \lambda \cdot \frac{G_0^2}{d^5} \cdot \rho_0 \cdot l \cdot \frac{T}{T_0}, \quad (3)$$

where p_b - is the gas pressure at the beginning of the gas pipeline, Pa; p_e - is the gas pressure at the end of the gas pipeline, Pa.

The average gas velocity in the pipeline is determined from the expression:

$$\omega = V/F, \quad (4)$$

where V - is the volume flow rate of gas, m^3/s; F - is the cross-sectional area of the gas pipeline pipe, m^3.

Depending on the flow velocity, pipe diameter and viscosity of the gas, its flow can be laminar, i.e. ordered in the form of layers moving relative to each other and turbulent when vortices occur in the gas flow and the layers mix with each other.

The Reynolds number, which determines the mode of gas flow through the pipeline, taking into account the gas temperature is calculated by the formula:

$$\mathrm{Re} = \frac{\omega \cdot d}{\nu} = \frac{4}{\pi} \cdot \frac{G}{\nu \cdot d}, \quad (5)$$

where w is the gas flow velocity, m/s; d - is the inner diameter of the pipeline, m; n is the coefficient of kinematic viscosity of the gas at temperature T, m^2/s; G - is the volume flow rate of the gas at temperature, m^3/s.

The interval of transition of laminar motion to turbulent is called critical and is characterized by Re = 2000– 4000. At Re< 2000 the flow is laminar, and at Re > 4000 the flow is turbulent.

From the above analysis, it can be seen that the formulas of engineering hydraulics (1,2,3,4,5) are valid both for calculating the modes of oil movement in MO and for the modes of gas movement in MG. Therefore, by analogy with oil leakage in MO, the gas leakage point in MG also generates negative pressure waves NPW, which can be detected by LD400WH sensors with subsequent identification.

Gas leaks in MG, as a rule, are associated with artificial damage to the pipeline or natural shifts of the layers of the earth's surface, resulting in mechanical vibrations that can be detected by seismic sensors SU.

Monitoring of main oil and gas pipelines, similar to bridges and tunnels, is not only difficult because of the large linear span, but also because of the critical requirements for determining the conditions of liquid or gas (Mohamed et al., 2013). Inaccuracies in sensor measurements from one device can spread over the network, which causes distortion in measurements from other sensors during aggregation. Therefore, linear WSNs (LWSNs) are a special case when multi-way communication over long distances leads to an increase in data delivery time (Figure 1).

LWSN networks may be simplified in topology, but the solution of routing and node deployment to save resources is not simple. Similar problems with the network have been the subject of research recently. At the same time, the quality of service in a linear WSN requires an intelligent method of data exchange in combination with sleep cycles and node activity.

The complete architectural diagram of the leak detection system for LWSN, including the main modules, is shown in Figure 8. This system can also monitor temperature anomalies from -40 to +80°C by TT400WH sensors and damage to the main gas pipeline by SU seismic sensors.

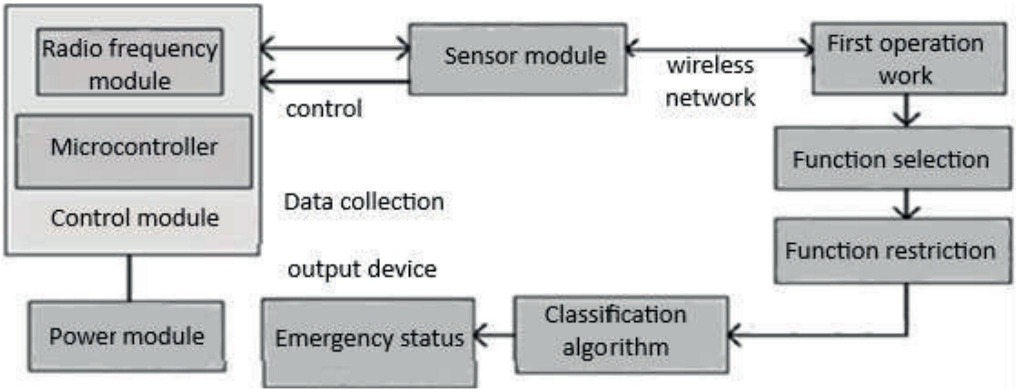


Figure 8 - Leak detection system for LWSN

Solving the problem of monitoring the technological parameters of the MC based on SimpliMote wireless sensors using WirelessHART technology brings the process of controlling the EDGPU electric drive to a new higher quality level. Therefore, the development of a modern EDGPU fleet should be associated with the improvement of pipeline equipment, compression technologies, the use of new units and management principles.

The technical solutions laid down in the EDGPU during their manufacture and commissioning, today no longer meet modern requirements for energy efficiency, management and reliability of gas transport. The inability to smoothly regulate the speed of rotation of the drive causes large power losses during operation of the unit, since it is not able to provide the necessary revolutions with maximum polytropic efficiency for any gas parameters at the inlet and outlet of the supercharger. In addition, power losses in the gearbox, sliding bearings, oil/gas sealing system and drive power losses from eddy currents of the rotor windings indicate moral and physical wear of the EDGPU fleet.

Analysis of the state of stationary EDGPU types STD-4000-2, EDGPU - 6.3, EDGPU - C - 6.3, which are installed on the CS in the Republic of Kazakhstan (RK), allows us to state that most of them are morally and physically outdated and require modernization or replacement.

The STD-4000-2 and EDGPU - C-6.3 units have the highest operating time over 180 thousand hours, and the distribution of EDGPU over the operating time ranges indicates that about 30% of the fleet have developed the assigned resource (100 thousand hours). Since these units operate at a constant rotational speed of 8000 - 8314 rpm with a synchronous rotation frequency the electric motor (SD) 3000 rpm, the power consumption, the polytropic efficiency of the supercharger will definitely depend on its performance. In turn, the performance of the supercharger is also determined by the characteristics of the main gas pipeline.

The positive qualities of the STD series synchronous electric motors currently in operation include: high efficiency (more than 97%), a service life of more than 20 years and relatively low maintenance costs. However, the limited life of the rotor (only 150 starts before repair) leads to insufficient efficiency and reliability of the EDGPU and to an increase in the number of its failures.

The need to introduce variable-frequency EDGPU is due to the unevenness of seasonal, monthly and daily gas consumption with variations in technological and natural factors of a stochastic nature. Only in this case, accurate testing of all optimal technological modes is ensured without deterioration of efficiency and other energy characteristics.

Rapid development of microelectronics and microprocessor technology expands the possibilities of automatic control of the EDGPU. Therefore, at present, the main industrialized countries of the world are gradually switching to microprocessor-controlled EDGPU systems that can be integrated with wireless MG monitoring technologies.

To date, the first units of a new generation of variable-frequency electric gas pumping equipment of the EDGPU-4.0/8200 and EDGPU-6.3/8200 types with FCHVM have been installed and put into operation in a number of CS in the Republic of Kazakhstan. The main advantages of these variable-frequency EDGPUs with asynchronous high-speed gearless drive are:

1. Accurate real-time testing of all technological modes of gas pipelines with high energy characteristics (efficiency, power factor) in static, quasi-static and dynamic modes of CS operation.

2. Diagnostics, signaling with functional separation of operating and emergency modes with indication and output to the interface with "memory" are provided, and in case of an emergency, intensive braking of the electric motor is provided in the electric drive.

3. Availability of communication tools and interfaces for the exchange of information about the state of the EDGPU and integration into the automated control system CS.

4. Extremely high efficiency of AC electric machines (up to 95-98%) and frequency converters, which is practically unchanged over the entire speed control range.

5. High reliability of up to 40,000 hours (4.5 years) and virtually maintenance-free up to 35,000 hours (4 years), service life without replacement of basic components and parts (30 years).

6. The initial capital costs of electric drive are 3-9 times lower than gas turbine installations and convertible aircraft engines, and the simplicity of block installation has additional advantages.

7. The cost of M&R is up to 4% of operating costs (in the absence of oil-free and gearless systems), while for gas turbines they amount to 15-30% of the cost of the engine.

8. Complexity of repairs is also significantly lower – by 1.5-2 times.

9. Presence of a multifunctional controller that performs the functions of intelligent control and monitoring of the technical condition of the electric drive in real time makes it possible to implement sparsely populated technologies on the CS.

10. Environmental friendliness – no emissions of CO_x and NO_x into the atmosphere and low noise and vibration, etc (Krasnov et al., 2014, Onishchenko et al., 2014, Puzhailo et al., 2010).

It should be noted that, unlike the EDGPU drive on synchronous motors, the absence of an electromagnetic excitation system with contact rings with a spark on them ensures the explosion safety of asynchronous motors with a short-circuited rotor (AM with short circuit), which also does not limit the frequency of EDGPU starts and provides high reliability with a service life of up to 50 years (resource 200,000 hours). Explosion safety, simplicity of design with minimal weight and size indicators, allows you to assemble the AM with a short circuit in a single housing with superchargers and blowing of the stator windings with pumped natural gas, while reducing the total area of the compressor shop. In addition, a synchronous gearless drive with an electromagnetic suspension system of the rotor and the absence of an oil supply system reduces operating costs and maintenance costs. As a result, an asynchronous electric drive at a low cost of the AM itself has undeniable advantages over a synchronous one.

Therefore, in recent years, leading manufacturers have been switching to replacing the EDGPU fleet with synchronous drive, which has exhausted its life, with new units with asynchronous drive, more adapted to operation in conjunction with high-voltage frequency converters (HVFC).

An analysis of HVFC`s currently manufactured by foreign firms has shown that the topology of a multilevel high-voltage frequency converter (HVFC) with a cascade connection of single-phase low-voltage (LVFC) meets modern technical requirements to the greatest extent. Of the foreign manufacturers of HVFC, it is necessary to mention the HYUNDAI Company. According to this topology, high-voltage converters of the HVFC series of CJSC “Electrotex” and converters “Eratron-V” of CJSC “ERASIB” for EDGPU based on intelligent control systems are being developed and produced today (Krasnov et al., 2014, Onishchenko et al., 2014, Puzhailo et al., 2010).

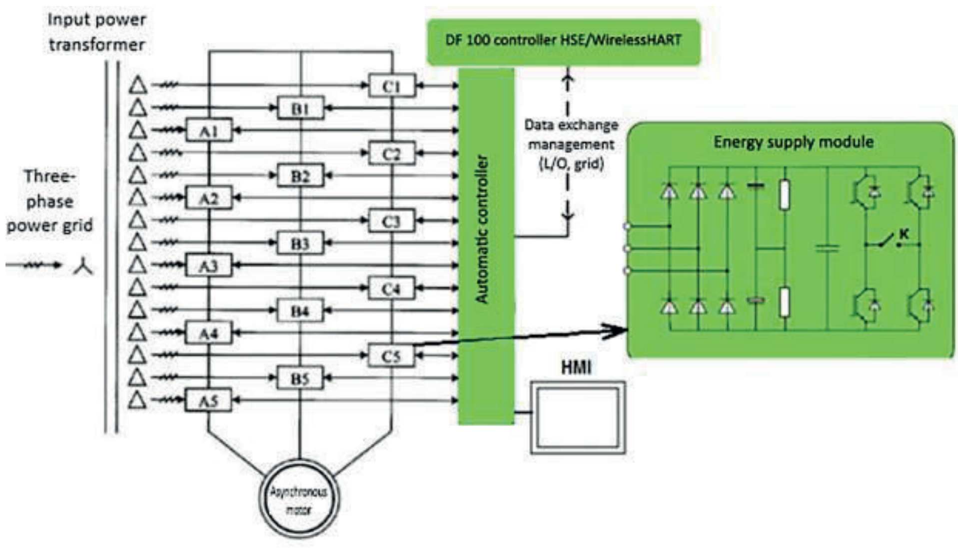


Figure 9 - Block diagram of asynchronous high-voltage variable frequency electric drive EDGPU

HVFC for EDGPU is represented by intelligent power modules of voltage inverters, which are powered from an input transformer with 15 groups of three-phase secondary windings. The number of groups of three-phase secondary windings of the input transformer is determined by the supply voltage of single-phase low-voltage power modules and their number does not have to be equal to 15, but depends on the HVFC series. In order to reduce the influence of the converter on the supply network, the secondary windings are connected in a triangle and shifted in phase by 60 electrical degrees relative to each other, since the current in the network has minimal distortion.

The power intelligent module contains a three-phase rectifier, a capacitor filter, a single-phase inverter on IGBT modules. The minimum voltage of a single-phase inverter is 690 V. The serial connection of 5 blocks allows to obtain the maximum effective value of the phase voltage at the output of the converter 3450 V (line voltage 6000 V). Mutual compensation of higher harmonics is provided by means of a phase control system of the output voltage of individual cells, the phases of which are shifted by 12 electrical degrees. At the same time, the output voltage of the HPV is regulated by synchronized pulse-width modulation of the voltage in each cell with its proportional change depending on the frequency, thereby ensuring a sinusoidal shape of current and voltage, as well as good electromagnetic compatibility of the converter.

The operational advantage of this diagram is its high survivability. In case of failure of the power unit, its shutdown does not occur, since the key K is closed, which shunts the module inverter, disabling it. One power module is switched off simultaneously in other phases. The ACS of the FC increases the voltage on the remaining units in operation, and the HVFC continues to function.

The multifunctional controller as part of the EDGPU drive performs the functions of local intelligent control and monitoring of the technical condition of the electric drive in real time. However, L/O communication – as a means (interface) of interprocessor information exchange of local processes with processes from the outside, allows you to integrate a wireless technology controller WirelessHART into the EDGPU control system.

Literary and patent studies have shown that despite the large number of currently existing methods and means of monitoring MP, they do not provide sufficiently effective control not only over the technological parameters of the pumped medium, but also over its technical condition (Shaklein et al.,2015, Puzhailo et al., 2012, Karandin et al., 2007, Puzhailo et al., 2013).

The development of digital radio relay lines (RRL), which has achieved high qualitative and quantitative development all over the world, has now become an absolutely necessary link in the development of wireless sensor networks, which consist of miniature computing devices - motors equipped with digital sensors and transmitters operating in a given frequency range. Each mod allows you to take measurements, independently carry out initial data processing and maintain communication with an external information system. Sensors integrated into a wireless network form a geographically distributed self-organizing system for collecting, processing and transmitting information.

Flexible architecture, reduced installation costs distinguish wireless networks of intelligent sensors among wired data transfer interfaces, especially when it comes to a large number of interconnected devices. It should be noted that the sensors used can work in difficult conditions, where there is no possibility of constant monitoring of the received data by personnel, and high accuracy and transmission speed are ensured by a short update time. The main field of application of wireless sensor networks (WSN) is the control and observation of the measured parameters of physical media and objects (Salman et al., 2016, Mohamed et al., 2013).

Consequently, the integration of wireless sensor technology into a digital high-voltage frequency-controlled electric drive allows you to automatically monitor and optimize the pressure and temperature values of the pumping medium along the entire length of the MP, as well as monitor its integrity and detect leaks of transported gas or oil in a timely manner.

To implement this technological diagram, the EDGPU electric drive must be frequency-controlled and invariant, i.e. a combined automatic control system (ACS for deviation and perturbation) with negative feedback on the main technological parameters – pressure and temperature not only at the outlet of the compressor station, but also with pressure and temperature monitoring along the entire MG route. At the same time, as the analysis of high-voltage frequency converters currently produced by foreign companies has shown, the topology of a multi-level, cascaded intelligent single-phase LFC by the type of an autonomous voltage inverter with microprocessor control (HVFC) is the most promising.

In accordance with the above, the authors of this article have proposed a method and a system of technological and technical monitoring of MP in real time, which, by increasing the reliability of control, make it possible to increase the efficiency of management under any operating modes of MP, preventing emergencies and thereby ensuring the safety of operation of oil or gas pipelines. The monitoring system of technological and technical parameters of main pipelines is shown in Figure 10.

The monitoring system of technological and technical parameters of main pipelines in accordance with Figure 1 contains a pumping station - 2, depending on the type of pumping medium: CS - for gas pipelines and PS - for oil pipelines. The pumping station - 2 is installed on each linear section of MP - 1 and is equipped with PA - 4, which has a HVFC - 3 with microprocessor control and a block for calculating control parameters – 6. The system also contains a set of sensors, including contact sensors 11,12 measuring the real values of the pressure and temperature of the pumped medium at the outlet of the stations and wireless digital sensors 13,14,15 - pressure, temperature and vibration at the MP diagnostic points. The system includes radio relay stations 16 installed along the MP highway and a base station 17 with radio relay equipment located near the control room, where a monitoring center 18 is installed, which is connected to the system computer 19 and equipped with a microcontroller with a radio platform. The location of MP damage is determined by portable field computers 20.

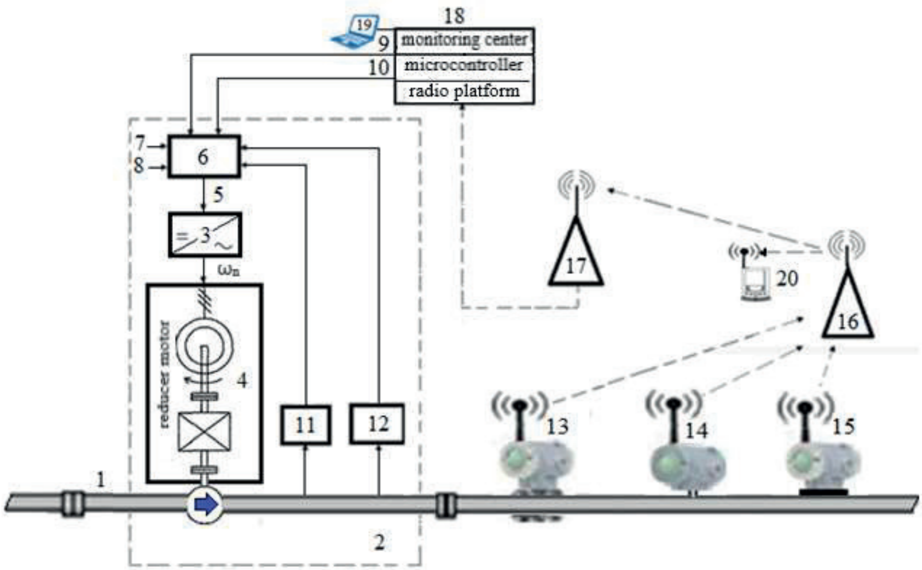


Figure 10 - Block diagram of a wireless network for monitoring technological and technical parameters on one linear section of MP

The method of monitoring technological parameters along the entire length of the MP is that the data obtained from digital sensors 13,14 of the pressure and temperature of the pumped medium using a radio signal is transmitted via relay radio relay stations 16 to the base station 17 to the monitoring center 18, where in the microprocessor of the microcontroller, they are compared with the proper nominal values of pressure and temperature stored in the processor memory at the corresponding points along the MP. As a result, corrective signals are calculated for pressure 9 and temperature 10 in case of abnormal deviations of these parameters. Further, the correction signals 9 and 10 are fed to the control parameters calculation unit 6, which, comparing the set values of pressure 7 and temperature 8, with the pressure and temperature values from the contact sensors 11,12 installed at the output of the stations, outputs a control signal 5 to a multi-level high-voltage converter HVFC-3. The control signal 5, taking into account the state of the technological parameters of the MT, corrects the rotation frequency of the pumping unit, thereby bringing the pressure and temperature of the pumped medium to the set values. Based on the results of calculating all the above values of technological parameters, it is possible to control the rotation speed of the PA in order to optimize pressure and temperature along the entire MT route. In addition, as a result of the calculation of the data obtained, abnormal deviations of the parameters are detected with the calculation of emergency areas, which are output to the dispatcher's system computer 19. The control signal 5, taking into account the state of the technological parameters of the MP, corrects the rotation frequency of the AM (ω_n) pumping unit, thereby bringing the pressure and temperature of the pumped medium to the set values. Based on the results of calculating all the above values of technological parameters, it is possible to control the rotation speed of the PA in order to optimize pressure and temperature along the entire MT route. In addition, as a result of the calculation of the data obtained, abnormal deviations of the parameters are detected with the calculation of emergency areas, which are output to the dispatcher's system computer 19.

Vibration sensor 15 (seismic sensor SU) is designed to give alarm signals to operators - only when a real and specific threat is detected in accordance with the identified threat method described above in this article. The location of the identified threat, as noted, comes from an accurate measurement of the signal on each sensor 15. In this case, the alarm signal sent via radio frequency communication from the sensor's sensitive unit is received by the operator of the control center and displayed on the local computer 19 and on portable field computers 20 in the form of a map indicating the location of the accident. Upon receiving an alarm, the intervention team (located along the line) and the guards in patrol vehicles proceed to immediately eliminate the accident or detain the saboteurs.

The optimal configuration of the elements of this automatic control and monitoring system CS is modeled in the form of an optimization program P of the following type:

$$P = \begin{cases} \min_{\{x,s,e\}} f(x,s) = G(x) + \alpha\|S\|; \\ G_1(x) + \beta \cdot e \le S_1 \\ G_E(x) = S_E \end{cases} \tag{7}$$

where $x \in R^n, s_1 \in R^p, s_E \in R^q, e \in \{0,1\}$, x – the set of gas flow variables Q and pressure P, G(x) – is an objective function representing an economic optimization criterion, $C_I(x)$ – is a set of p linear and nonlinear inequality constraints for active objects, β – is a vector whose coefficients are zero or maximum values of constraints, e – is a vector of binary variables, $C_E(x)$ – is a set of q linear and nonlinear equality constraints, s – is a deviation variable whose nonzero value denotes a violation of the constraint, α – is the coefficient corresponding to the permissible degree of violation of restrictions (Onishchenko et al., 2014, Puzhailo et al., 2010).

As a result, at a given flow rate of the pumped medium, the pressure and temperature are set and stabilized at a given optimal energy consumption level (7). Consequently, this system limits the excess of pressure and temperature of the transported medium above and below the limit values along the MP route by means of a variable-frequency electric drive PA according to the FC-AM-PA diagram. At the same time, unacceptable deformations and stress states of the MP are almost completely eliminated, which eliminates possible destruction of its integrity and the integrity of the anticorrosive insulation, thereby increasing the safety of its operation under any operating conditions.

Conclusions. A block diagram and an architectural diagram of linear monitoring is proposed using the example of WirelessHART™ wireless technology, which contains intelligent digital computing devices – motes that allow monitoring anomalies of pressure, temperature and damage to the main pipeline. At the same time, negative pressure waves NPW arising inside the pipeline are used to determine gas leaks, which are recorded by wireless pressure sensors at the leakage point.

The HVFC topology based on intelligent LFC modules with microprocessor control for a digital PA variable-frequency electric drive, which integrates well with wireless sensor technology (WSN), meets modern technical requirements to the greatest extent.

Asynchronous gearless electric drive EDGPU, having a number of technological advantages, is more adapted to operation in conjunction with HVFC than EDGPU with synchronous drive.

The optimal configuration of the elements of technological and technical monitoring of the main pipeline (MP) is proposed, regardless of the type of medium being pumped (oil or gas), based on intelligent wireless sensors, with the transmission of measured data via a radio relay communication line in real time with the localization of abnormal disturbing effects by a digital invariant variable-frequency electric drive of compressor or pumping stations. The monitoring system also allows you to detect cases of leaks and damage to the main pipeline under any operating conditions.

Linear monitoring of the parameters of the main gas pipelines with intelligent wireless sensors reduces the likelihood of emergency modes of operation, improves the environment and increases the safety of MP operation, since abnormal changes in pressure and temperature occurring inside the pipeline are constantly monitored.

The data obtained during the present research can be recommended for the design of monitoring systems of main pipelines of the Republic of Kazakhstan.

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