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OPTIMIZATION OF THE CATHODIC PROTECTION SYSTEM FOR THE MAIN PIPELINES

This study investigated *the multi-criteria task of optimizing the operating modes of cathodic protection stations (CPS), considering monitoring data, geological conditions at the pipeline installation site, climatic or seasonal changes, and other factors.* ***The relevance of this research*** *is associated with a comprehensive solution to the problem of increasing the durability and reliability of trunk pipelines to reduce accidents at their facilities by ensuring the efficiency of electrochemical protection (EChP) systems. The problems of existing EChP systems are analyzed, where the elimination of anode zones ("lack of protection") due to cathodic polarization is carried out without operational consideration of environmental conditions, as a rule, with a margin in terms of protective potential, which often leads to "overprotection", resulting in increased power consumption, gas formation on the metal surface, and detachment and wear insulation of pipelines.* ***The aim of this research*** *is to create a method for optimal regulation of the operation modes of the main pipelines and an adaptive electrochemical protection system that provides control and parameter management of cathodic protection stations, considering changes in external conditions on individual linear sections of main pipelines.* ***Tasks:*** *to develop an adjustment method for finding the effect of the CPS on the value of potentials at control points along the pipeline route; to develop a multicriteria optimization model for regulating the operation modes of the CPS; and to provide an example of testing the method of optimal regulation on the objects of the linear part of the existing main gas pipeline. The following* ***results*** *were obtained. A method is proposed for determining the effect of CPS operating modes on the value of potentials at control points in the mode of interrupting the protection current of other stations. An optimization model was formed according to the criterion of uniformity of the distribution of the protective potential "pipe-ground" along the pipeline route and according to the criterion of the minimum total protective current of all CPSs on a given section of the main pipeline.* ***Conclusions.*** *The scientific novelty of the results obtained is associated with the development of an original optimization method that allows scientifically determining the operation modes of the CPS to ensure the protection of the main pipeline both in time and length with reduced operating costs and adaptability to changes in climatic, seasonal, and geological conditions at the pipeline installation site. The effectiveness of the proposed approach is illustrated by the regulation of the parameters of the CPS based on the monitoring data of the section of the main gas pipeline of the oil and gas complex of the Republic of Kazakhstan.*

Keywords: *electrochemical corrosion protection; main pipelines; cathodic protection stations; protective potential; multi-criteria optimization; remote monitoring.*

Introduction

The effectiveness of corrosion protection of metal underground structures and pipelines is one of the main factors determining the reliability and durability of oil and gas pipeline systems [1]. One of the main means of protection against corrosion of underground pipelines is electrochemical protection (EChP), which is based on the use of cathodic protection stations (CPS) and the displacement of the electrical potential of the protected pipeline to the negative region relative to the potential of the soil [2].

The main criterion for protecting underground pipelines from corrosion is the level of protective potential at the facility, which should be within normalized limits.

When the potential shifts in the positive direction relative to this interval ("lack of protection"), the effectiveness of protection decreases. When it shifts in the negative direction, the effect of "overprotection" occurs, resulting in increased power consumption, gas formation on the metal surface, peeling, and wear of pipeline insulation [3]. This greatly increases the likelihood of accidents and explosions in these areas. Accordingly, one of the tasks of designing and operating electrochemical protection systems of underground pipelines and metal structures is the choice of such parameters of the CPS operation, at which the necessary protective potential will be provided at all structures with minimal energy consumption. Modern automated electrochemical protection systems allow remote monitoring of changes in the

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magnitude of the protective potential and other parameters of the EChP systems, as well as adjustment of the output parameters of cathodic protection stations [4].

However, the presence of many factors affecting corrosion processes and the spatial distribution of the electric field of cathodic protection (operation modes of cathodic protection stations, geometric and electrochemical parameters of protected structures and applied anode grounding, the condition of the insulation coating, the presence of stray currents, resistivity, etc.) significantly complicates the optimization and selection of effective modes of operation of EChP facilities [5].

In addition, the dynamics of these factors should be considered. For example, the specific electrical conductivity of the soil at each specific site depends on its type, humidity, temperature, degree of waterlogging, salinity of the soil, the presence and level of groundwater, and may vary depending on the time of year, rainfall, etc. [6]. Therefore, the existing automated EChP system mainly solves the task of monitoring the protective parameters of the EChP system and their automatic support according to preset settings without adapting in real time to changes in climatic, seasonal, and geological conditions at the pipeline installation site, the condition of the insulation coating, and other factors.

In addition, remote monitoring of the protective potential is usually performed only at the drainage point [7], which does not allow the system to respond to changes in protective parameters along the pipeline route.

Therefore, operating organizations with the power of the EChP system try, as a rule, to move from the anode zone ("lack of protection") to the cathode zone with a margin in terms of the protective potential, which provides protection along the length, which, as noted, is energy-consuming and leads to the development of negative processes. Currently, the choice of operating modes of CPS institutions is carried out according to the recommendations of regulated electrochemical diagnostic studies [8], and the required level of protective flow is determined subjectively.

This makes it relevant and important to develop new and improve existing approaches and methods for modeling and optimizing the protective parameters of CPS.

1. Analysis of the recent research and publications

The review article [9] analyzes the mechanisms of external corrosion and destruction of underground gas and oil pipelines, as well as existing monitoring tools for assessing external corrosion and models for preventing and predicting corrosion. The authors note that to ensure proper corrosion protection of underground metal structures, it is necessary to design and use cathodic protection systems.

A significant number of publications are devoted to the tasks of designing cathodic protection systems, since its effectiveness initially depends on this. This requires conducting electrochemical tests of metal [10], modeling the distribution of the electric field of cathodic protection systems in the ground [11], and designing the location and design of the anode grounding.

Thus, in the study [12], electrochemical tests were carried out to calculate the optimized cathodic protection current, and the authors were able to obtain an empirical equation for the current density in accordance with the service life of the pipeline. The experiments were carried out only to determine the corrosion properties of underground steel pipelines and can be used conditionally in the design of the EChP system for calculations to ensure adequate polarization ability and maintain cathodic protection during the design service life.

This study [13] is devoted to the development of an optimization algorithm for an auxiliary anode system of a grounding grid based on an improved method of simulated annealing. The boundary element method is widely used for modeling cathodic protection systems of underground and offshore structures. In the study [14], using the analysis of boundary elements, the authors investigated the influence of the horizontal distance between parallel pipelines, the rate of damage to the insulation coating, the conductivity of the soil, and the output current of the anode on the interference of parallel pipelines. In conclusion, at the design stage of the EChP system, by changing the layout, it is necessary to ensure the overlap of the protection zones of neighboring cathodic stations and thereby reduce the output currents of cathodic protection stations in the system of intercity parallel pipelines.

A significant amount of work has been devoted to different methods of calculating the main parameters of the EChP for various facilities and conditions for the placement and operation of pipeline systems (PS). The authors in this study [15] performed numerical modeling using the method of boundary elements of anode grounding of casing strings of deep wells. In the study [16], the distribution of the electric field of the cathodic protection system for structures with complex geometry was investigated using numerical modeling by the boundary element method. The optimization scheme of the designed the EChP system was developed by adjusting the amplitude of the supplied current, as well as the location and size of the area of the anode layer.

In the study [17], the problem of optimizing the current regulation of cathodic protection stations for a pipeline in the Jingbian gas field was modeled using COMSOL software. Unfortunately, this study is only a demonstration of the results of solving a specific spatial problem of modeling a cathodic protection system for three gas field stations. This work [18] is devoted to optimize the design of the cathodic protection system for a specific district heating pipeline passing under the Khan River.

The underground trunk pipelines are long, operate under different natural and climatic conditions, and are located in soils with different physicochemical properties and corrosion activity. Therefore, in contrast to the cathodic protection of local facilities, such as wells of oil and gas fields, pumping stations, or underground storage of petroleum products, it is difficult to determine and establish optimized values of the operating modes of the CPS on extended facilities, such as oil and gas pipelines, allowing maintenance of the necessary optimal values of protective potentials along the entire route while considering various requirements for minimum and maximum values of potentials, depending on the operating conditions and hazardous factors affecting corrosion. Therefore, there are very few publications devoted to the analysis and optimization of cathodic protection systems for the main PS.

In the previous study [19], a simulation was carried out to test and optimize the cathodic protection of insulated pipelines, taking into account several environmental factors, such as temperature and the coefficient of coating defects.

The study [20] presents a methodology for optimizing the collection of cathodic protection data in accordance with a proactive approach to management. However, instead of collecting monitoring information from each control and measuring point along the route, the authors solve the problem of selecting and optimizing control points to check the protective parameters.

The previous study [21] considers the problem of modeling and forecasting the operation of a cathode station using historical data and machine learning methods. By modeling linear regression coefficients, the authors propose replacing the predicted values of the operating parameters of cathodic protection stations, where there are limitations in obtaining real-time data. Unfortunately, only a section of the pipeline with one CPS is being considered.

This study [22] proposes a new distributed model for the development of a cathodic protection system for oil and gas pipelines. The main difference between the proposed model and the traditional approach is the use of measured soil resistance throughout the structure instead of a fixed average value. However, the complexity of practical implementation and the cost of such an approach are quite understandable.

The number of studies related to the use of machine learning methods to predict the degree of corrosion and the remaining service life of underground pipelines is increasing [9, 23, 24]. As predictive analytics for assessing the corrosion state of PS, this is a promising direction, but these studies cannot be used directly for optimization problems of the EChP system of underground structures because it is a stochastic system.

The analysis has shown that sufficient mathematical models and algorithms have been developed for calculating and optimizing the EChP parameters, which are useful at the design stage of cathodic protection systems and for analyzing "what-if" scenarios. However, they do not solve the problem of complex optimization of the EChP system of extended trunk pipelines.

In any case, to potentially optimize the protective parameters (to have information about the distribution of potential along the entire route of the main pipeline) and to regulate the operating modes of EChP facilities in real time, it is necessary to use automated remote monitoring and control systems.

There are various telemechanical systems for monitoring and controlling the EChP facilities based on remote control controllers with built-in GSM/GPRS modems for mobile communications and other communication channels with an automated control room workplace [25, 26].

Note that the integrated automation of the EChP system fully complies with the concepts of Industry 4.0 and 5.0 [27], based on the availability of complete and reliable digital data from "smart" devices, as well as new possibilities for remote monitoring and processing in real time and advanced analytics [28]. In addition, a distinctive feature of Industry 5.0 is the use of big data analytics using methods and tools such as artificial intelligence, machine learning, data mining, and predictive analytics.

Usually, in automated EChP systems, only CPS are covered by remote monitoring. In the study [29], the construction of an automated the EChP system is considered, where Internet of Things technologies are used, namely, an energy-efficient LPWAN data transmission network, which also covers control and measuring points. This makes it possible to control the protective potential through remote monitoring of control and measuring points inside the pipeline between adjacent CPS, as well as in all corrosion-hazardous areas where control and measuring points are also installed. This gives a more complete picture of the pipeline's safety and allows us to approach the problem of optimizing the operating modes of the EChP facilities for trunk pipelines in conditions of factors varying in time and length of the route.

Thus, there is a contradiction between the requirements for ensuring the effectiveness of electrochemical corrosion protection of main pipelines, extending the life and service life of PS and anticorrosive protection means, and the imperfection of existing methods for optimal control of cathodic protection modes in conditions of time-varying and length-varying factors. This requires the development of methods and applied information technologies aimed at studying the protective parameters of the

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CPS, reducing operating costs, and increasing the reliability of the EChP system.

The aim of this study is to create a method for regulating the optimal parameters of cathodic protection of underground pipelines under conditions of seasonal and climatic changes in the electrical properties of the soil, ensuring that the influence of cathodic protection stations on potentials at control points is found without disconnecting cathodic protection stations and changing their parameters. In accordance with the stated purpose of this study, it is necessary to solve the following tasks:

1. To analyze the problems of existing EChP systems.
2. To develop an adjustment method for finding the influence of cathodic protection stations on the value of potentials at control points along the pipeline route.
3. To create a multicriteria optimization model for regulating the operating modes of cathodic protection stations.
4. To provide an example of the application of optimal regulation methods at the facilities of the linear part of the existing main gas pipeline.

2. The adjustment method for finding the influence of cathodic protection stations on the value of potentials at control points along the pipeline route

To reduce the dimension of the task, as well as considering other factors (soil characteristics, corrosion-hazardous zones, etc.), it is advisable to divide the entire area of responsibility of linear production management of trunk pipelines into sections or automation modules (AM) with the number of CPS, for example, up to 15-20 units. For each AM, except for the CPS, control points with remote control and measuring points (RCMP) with telemechanics are selected, which are located close to the middle between neighboring CPSs, in corrosion-hazardous zones, in zones of stray currents, etc. This preparatory stage for the implementation of the method is used once when forming a new AM and is typical. At this stage of the method, the AM is "adjusted" or tied to the corresponding section of the main pipeline (MP) and the necessary data, in particular: control points where the CPS and CMP are installed; technical characteristics of the CPS; soil characteristics; corrosion-hazardous zones; seasonal operating conditions of the CPS; and limit values of the pipe-to-ground potential at control points, etc.

Let us consider the description of the adjustment technique.

Therefore, control points for measuring potential are assigned on the pipeline section. The control points include the points where the CPS and the CMP are installed, which are located close to the middle between neighboring CPS, in corrosion-hazardous zones, in zones of stray currents, etc. At each point of the pipeline, the value of the pipe-ground potential is determined by a superposition of potentials superimposed by all or at least several neighboring CPS.

In automatic mode, with the use of remote corrosion monitoring and control systems, the pipe-ground potential is measured at U_i i^{th} control points.

The j^{th} base CPS is selected, for which the current values of the output current and output voltage are recorded.

Remotely provide a mode for interrupting the protection currents of other CPSs (to the left and right of the base with the selected step, that is, 1, 2, 3 neighboring stations) and measure the potential "pipe-ground" at the control points, which is a protective offset at the control point caused by the j^{th} CPS.

The scheme of the adjustment technique is shown in Fig. 1.

Determine the coefficient of influence of this CPS on each control point according to the following formula:

$$A_{ij} = \Delta U_{ij} / I_j, \tag{1}$$

where ΔU_{ij} is protective potential shift at the i^{th} control point caused by the j^{th} CPS, B; I_j is the value of the current strength of the base j^{th} CPS, A; $j = 1, 2, ..., n$ is number of CPS; $i = 1, 2, ..., k$ is number of control points; k is the quantity of control points ($k = n + m$); n is the quantity of protection stations that affect the potential at the i^{th} control point; m is the quantity of CMPs.

Repeat the selection of the basic CPS and actions (interrupt mode) for other CPS for this section of MP.

The coefficients of the influence of all CPS on the protective potential of the "pipe-ground" at the control points are determined by the formula (1).

The stationary potential for each control point is determined by the following formula:

$$U_{STi} = U_i - A_{11}I_1 - A_{12}I_2 - ... - A_{ij}I_j, \tag{2}$$

where U_{STi} is stationary potential at the i^{th} control point, V, $i = 1, 2, ..., k$; U_i is measured potential at the i^{th} control point, V; A_{ij} is coefficients of influence of the j^{th} protection station on the potential at the i^{th} control point, Ohm; I_j the value of the current at the output of the j^{th} CPS, A, $j = 1, 2, ..., n$.

According to monitoring data (measurements of potentials), attenuation coefficients are calculated (exponential distribution is used to distribute the potential difference along the pipeline) of the protective potential of the CPS along the pipeline (left shoulder and right shoulder) according to the following formulas:

$$\alpha_{i,j-1} = \left|\ln\left|\Delta U_j\right| - \ln\left|\Delta U_{j-1}\right|\right| / \left|L_j - L_{j-1}\right|;$$
$$\alpha_{i,j+1} = \left|\ln\left|\Delta U_j\right| - \ln\left|\Delta U_{j+1}\right|\right| / \left|L_j - L_{j+1}\right|, \qquad (3)$$

where $\alpha_{i,j-1}$ is the attenuation coefficient of the protective potential of the left shoulder of the j[th] CPS; $\alpha_{i,j-1}$ is the attenuation coefficient of the protective potential of the right shoulder of the j[th] CPS; ΔU_j is the protective potential shift at the j[th] control point caused by the j[th] CPS; ΔU_{j-1} is protective potential shift at the (j-1) control point caused by the j[th] CPS; ΔU_{j+1} is protective potential shift at the (j+1) control point caused by the j[th] CPS; L_j is coordinate (km) of the placement point of the j[th] CPS; L_{j-1} is coordinate (km) (j1) of the control point to the left of the j[th] CPS; L_{j+1} is the coordinate (km) (j+1) of the control point to the right of the j[th] CPS.

In the absence of remote monitoring data at the control points of individual instrumentation, the coefficients of the influence of the j[th] CPS on this i[th] control point are calculated by considering the calculated attenuation coefficients according to the following formula:

$$A_{ij} = A_{jj} e^{-\alpha_{ij}\left|L_i - L_j\right|}. \qquad (4)$$

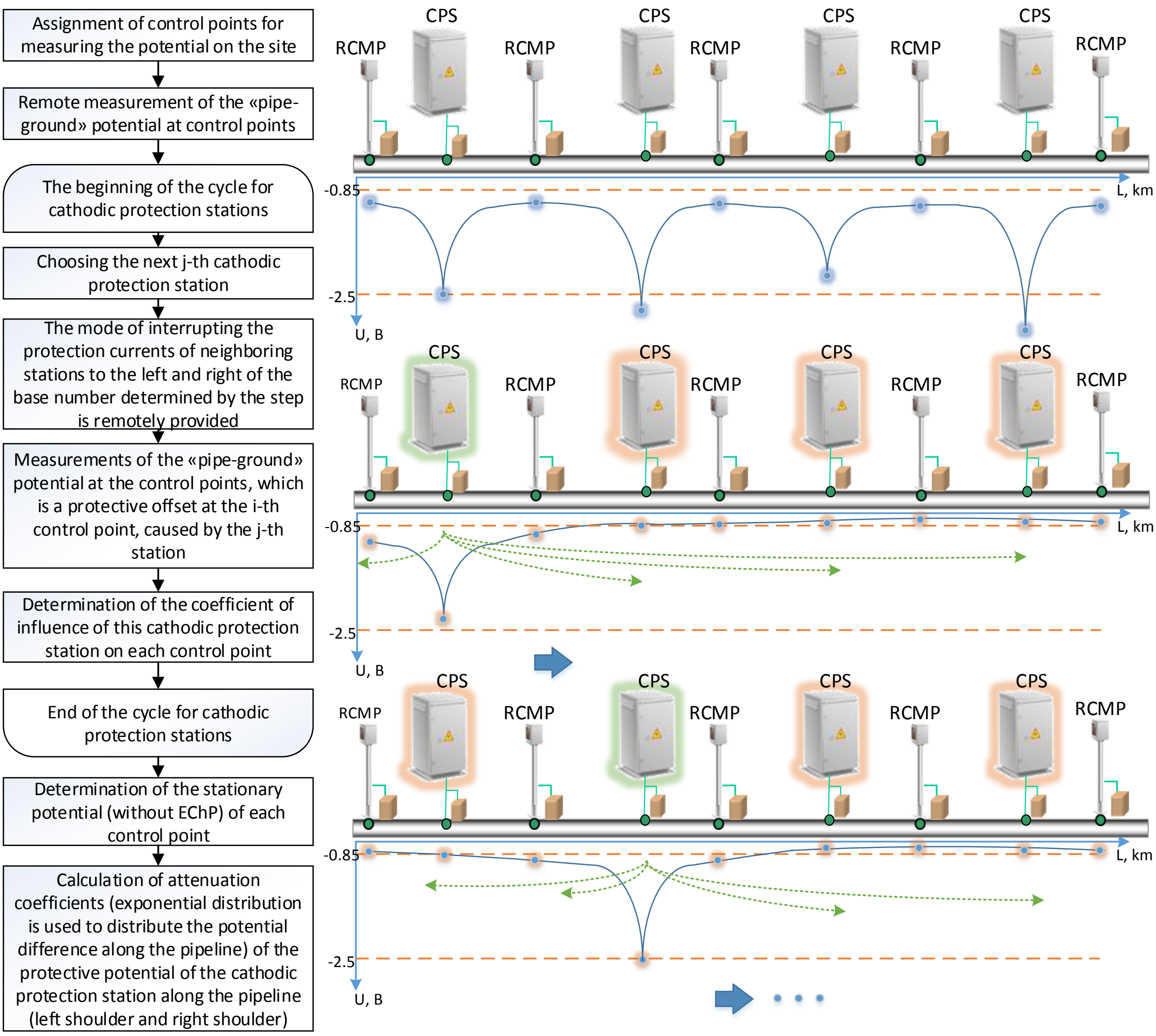

Fig. 1. The scheme of the adjustment technique for finding the effect of CPS

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3. Optimization model for determining the protective parameters of the CPS

The linear equations in the form of the following constraints are compiled for the CPS

$$\begin{aligned} & A_{11}I_1 + A_{12}I_2 + ... + A_{1n}I_n \geq U_{ST1} - U_{PG1min}, \\ & ... \\ & A_{n1}I_1 + A_{n2}I_2 + ... + A_{nn}I_n \geq U_{STn} - U_{PGn\,min}, \end{aligned} \quad (5)$$

$$\begin{aligned} & A_{11}I_1 + A_{12}I_2 + ... + A_{1n}I_n \leq U_{ST1} - U_{PG1max}, \\ & ... \\ & A_{n1}I_1 + A_{n2}I_2 + ... + A_{nn}I_n \leq U_{STn} - U_{PGn\,max}, \end{aligned} \quad (6)$$

where I_j absolute value of the protection current of the j^{th} cathode station, $j = 1, 2, ..., n$; U_{STj} is the difference of potentials "pipe-ground" without EChP (stationary potential), is determined by formula (2); U_{PGjmin} is the minimum protective potential of the "pipe-ground" at the control point of the j^{th} CPS; U_{PGjmax} is the maximum protective potential of the "pipe-ground" at the control point of the j^{th} CPS; A_{ij} is influence coefficient (input resistance over "close ground") for the i^{th} control point, provided that the current load is located only at the j^{th} control point of the CPS, at $i = 1, 2, ..., n$, $j = 1, 2, ..., n$.

Note that U_{STj} is a potential difference "pipe-ground" without EChP (stationary potential) and is determined (measured) when designing an EChP system. In some cases, can be selected as a control point from the tables of the project documentation.

The scheme of the methodology for optimizing the protective parameters of the CPS is shown in Fig. 2.

It should be noted that, unlike most studies, when determining optimal modes, the proposed approach considers various corrosion factors and their totality in the area under consideration.

For this purpose, an adaptive intelligent system is used [30], for which appropriate knowledge models have been developed, reflecting the laws, regulatory framework, and experience in solving the corrosion protection problems of metal underground pipelines and structures. For example, there is a knowledge-oriented model for finding the necessary protective total potential, which takes into account the presence of water-soluble salts and bacteria in the pipeline laying area, the presence of stray currents, etc. The state of safety is determined on the basis of data on the maximum and minimum protective potential obtained because of logical inference by the intelligent system, as well as the current value of the potential obtained because of remote monitoring.

Example of a knowledge base rule:

IF product T>40°C AND product T<=60°C AND (Possibility of microbiological corrosion OR Possibility of stray currents OR Soil resistivity>=10 Ohm*m OR Water-soluble salts > 1g/1kg of soil) THEN Min_protective potential = - 1.0

The linear equations are written in the following form for the selected CMP:

$$\begin{aligned} & A_{11}I_1 + A_{12}I_2 + ... + A_{1n}I_n \geq U_{ST1} - U_{PG1min}; \\ & ... \\ & A_{m1}I_1 + A_{m2}I_2 + ... + A_{mn}I_n \geq U_{STm} - U_{PGm\,min}, \end{aligned} \quad (7)$$

where A_{ij} is coefficients that reflect the fusion of the j^{th} cathode station of the pipeline section to the protective parameters at the installation point of the i^{th} CMP, which are calculated according to the formula (1) or, if there is no monitoring data from the i^{th} CMP, then according to formula (4).

In addition to these linear equations, the following current limits are introduced for each CPS

$$I_j > 0;\ I_j \leq 0.8 \cdot I_N \text{, at } j = 1, 2, ..., n\,, \quad (8)$$

where I_N is nominal (maximum) current of the j^{th} cathode station.

In addition, there may be restrictions on the minimum allowable value of the CPS current, since when operating in minimum modes, a decrease in efficiency coefficient is possible.

The linear constraint equations (5) – (8) are added to the objective function that needs to be minimized

$$F = I_1 + I_2 + ... + I_n \rightarrow \min. \quad (9)$$

In other words, optimal regulation is based on minimizing the output power of the CPS on the section of the main pipeline, while simultaneously observing restrictions on the value of the protective potential at control points and additional restrictions on the CPS current.

Using the obtained system of equations of constraints (5) – (8) and the objective function (9) using the simplex method (the method of sequential improvement of the plan), the optimal values of the current strength at the output of each CPS are determined, at which a protective potential is provided "pipe-ground" corresponding to the regulated values within U_{PGjmin} and U_{PGjmax}.

On the basis of the results of the solution, we build a new schedule for the distribution of potential along the pipeline. The plan should improve the current state of the EChP.

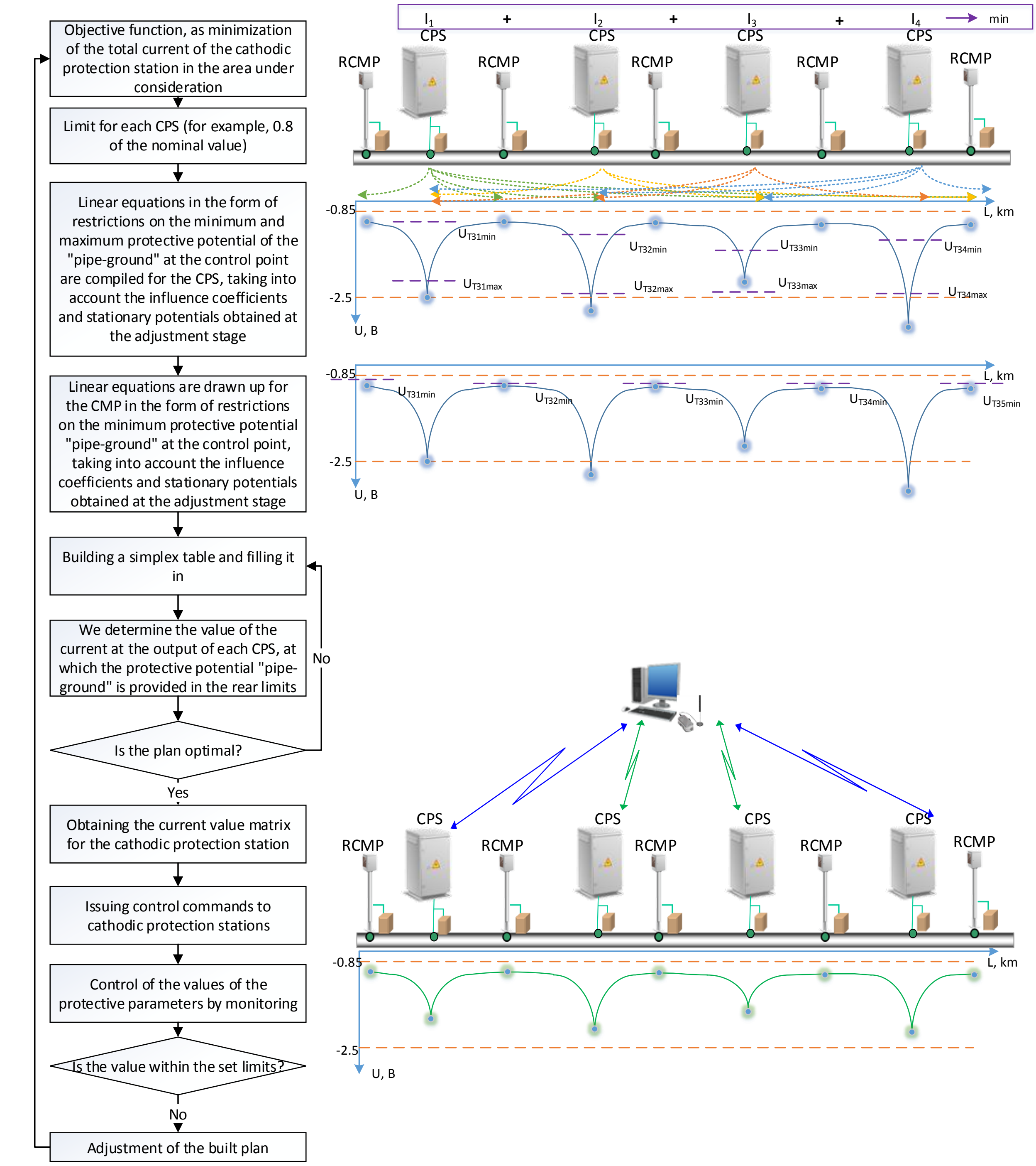

Fig. 2. Scheme of the methodology for optimizing the protective parameters of the CPS

When using a remote monitoring and control system, the calculated values of the current strength at the output of the corresponding CPS are set.

At the control points, remotely (or in some cases manually), the correspondence of the measured values of the "pipe-ground" potential to the regulated value is checked. If necessary, the received plan is adjusted.

4. Example of optimizing the protective parameters of the CPS and adaptive control of the EChP system

The considered methods formed the basis for the development of an adaptive system for monitoring and controlling the protective parameters of the CPS, which

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can be used in automatic or automated mode by specialists of the EChP service [29].

The adaptive system for optimizing the modes of operation of the CPS is multicriteria because the optimization is performed both by the criterion of optimality of the distribution of the protective potential (the uniformity of the distribution of the protective potential "pipe-ground" along the pipeline) and by the criterion of the minimum total protective current of all CPS at a given site.

As an example, let us consider the solution of the optimization problem in the adaptive control system and the control of the parameters of the CPS for one of the main gas pipelines of the Republic of Kazakhstan on a section from 103 to 220 km.

Table 1 shows the initial data on CPS at the site, EChP at the site is carried out by 10 CPS.

For each CPS we have the following data: location meter; status (on/off); rated current; rated voltage; actual current; actual voltage; minimum value of the potential "pipe-ground"; maximum value of the potential "pipe-ground"; current value of the potential "pipe-ground"; attenuation coefficients of the left and right shoulder of the CPS.

Table 1

Initial data on the CPS on the 103-220 km section

Name	Kilometer	Status	I_N, A	U_N, V	I, A	U, V	R, Ohm	U_{PGjmin}, V	U_{PGjmax}, V	U_{PGj}, V	$\alpha_{i,j-1}$	$\alpha_{i,j+1}$
CPS-3.0	108	On	60	50	36.4	40	1.09	-1.0	-2.5	-2.0	0.00009	0.00013
CPS -1.2	130	On	25	48	12	15	1.25	-1.0	-3.5	-1.8	0.00010	0.00014
CPS -3.0	137	On	60	50	20	25	1.25	-1.0	-3.5	-2.0	0.00013	0.00013
CPS -1.2	148	On	25	48	15	25	1.66	-1.0	-3.5	-1.7	0.00012	0.00013
CPS -3.0	157	On	60	50	21	25	1.19	-1.0	-3.5	-1.5	0.00012	0.00013
CPS -3.0	165	On	60	50	19	24	1.26	-1.0	-3.5	-1.6	0.00012	0.00014
CPS -1.2	181	On	25	48	14	17	1.21	-1.0	-3.5	-1.9	0.00013	0.00019
CPS -3.0	193	On	60	50	20	25	1.25	-1.0	-3.5	-2.0	0.00013	0.00014
CPS -3.0	205	On	60	50	24	30	1.25	-1.0	-2.5	-1.8	0.00013	0.00015
CPS -3.0	214	On	60	50	20	25	1.25	-1.0	-2.5	-1.5	0.00013	0.00013
Sum:					165							

Table 2 presents the initial data on the remote control and measuring stations (RCMP) at the site.

Table 2

Initial data on the RCMP on the 103-220 km section

Name	Kilometer	U_{PGj}, V	U_{PGjmin}, V	U_{PGjmax}, V
5-RCMP	103	-1.0	-1.0	-2.5
7-RCMP	113	-1.0	-1.0	-2.5
9-RCMP	124	-1.0	-1.0	-3.5
11-RCMP	134	-1.0	-1.0	-3.5
13-RCMP	141	-1.0	-1.0	-3.5
16-RCMP	153	-1.0	-1.0	-3.5
18-RCMP	161	-1.0	-1.0	-3.5
20-RCMP	172	-1.0	-1.0	-3.5
22-RCMP	187	-1.0	-1.0	-3.5
27-RCMP	200	-1.0	-1.0	-2.5
29-RCMP	210	-1.0	-1.0	-2.5
31-RCMP	220	-1.0	-1.0	-2.5

For each RCMP we have the following data: the kilometer of the location; the current value of the "pipe-ground" potential; the minimum value of the "pipe-ground" potential; the maximum value of the "pipe-ground" potential. Therefore, first, a sequential selection of base stations is carried out without changing their cathodic protection parameters, relative to which the values of the "pipe-ground" potential are measured at control points, including the base station and dedicated control and measuring points, in the mode of interrupting the protection currents of other stations, determining the coefficients of influence of each station on the potential "pipe-ground". Fig. 3 shows a matrix of attenuation coefficients in the adjustment mode, calculated in the adaptive control and control system of the protective parameters of the CPS. After forming the coefficients of the equations, the optimization problem is solved. Figure 4 shows a plan for the intermediate distribution of the total potential over the considered section at the first iteration with the minimization of the total current of all CPS. Table 3 shows the value of the CPS current after minimizing the total current. The total value of the CPS current decreased from the initial value by 17.23 A.

Table 3

Protective current of CPS after the first iteration

Name	Kilometer	I, A
CPS-3.0	108	37.83
CPS-1.2	130	15.41
CPS-3.0	137	4.89
CPS-1.2	148	9.23
CPS-3.0	157	5.02
CPS-3.0	165	11.99
CPS-1.2	181	14.35
CPS-3.0	193	5.09
CPS-3.0	205	9.98
CPS-3.0	214	33.98
Sum:		147.77

Fig. 5 shows the results of modeling and optimization of the protective parameters of the CPS. The second iteration of optimization is an attempt to remove reserves in terms of the maximum (modulo) protective potential at the lower limit at the control points of the CPS installation, which will lead to a certain decrease (modulo) of the protective potential and, consequently, a reduction in the risks of the development of processes leading to hydrogen embrittlement of pipeline metal.

We see a new plan for the distribution of the total potential across the site with a correction above and below for U_{T3jmin} and U_{T3jmax}.

Indeed, the value of the protective potential has decreased modulo compliance with the corresponding restrictions at the control points.

	6 - (CPS-3.0)	10 - (CPS-1.2)	12 - (CPS-3.0)	14 - (CPS-1.2)	17 - (CPS-3.0)
5 - (RCMP)	0.397888436168169	0.0244774344368669	0.0122579125982113	0.00259703404200228	0.00072856007267912
6 - (CPS-3.0)	0.725	0.0446007934727413	0.0223353729987445	0.00473210455318652	0.0013275230056425
7 - (RCMP)	0.397888436168169	0.0812679442990162	0.0406977030547469	0.00862245667177468	0.00241890462653212
9 - (RCMP)	0.106290047544504	0.304220159974982	0.152348651620554	0.0322774886296269	0.00905497928851553
10 - (CPS-1.2)	0.0517369204283799	0.625	0.312990129486083	0.0663119445968859	0.0186028501720189
11 - (RCMP)	0.0320139471042773	0.386739619878838	0.505815336401497	0.107165036222661	0.0300635899708293
12 - (CPS-3.0)	0.0223353729987445	0.269819077143175	0.725	0.153602798630364	0.0430910278124709
13 - (RCMP)	0.0138207578614184	0.166959563728656	0.448617959059452	0.248233550971721	0.0696383070119163
14 - (CPS-1.2)	0.00596656661053952	0.0720782006487891	0.193673093925242	0.575	0.161307874681346
16 - (RCMP)	0.00327452118339418	0.0395573552247754	0.106290047544504	0.315566690754065	0.293922111107917
17 - (CPS-3.0)	0.00202621932440171	0.0244774344368669	0.0657705161348241	0.19526742724584	0.475
18 - (RCMP)	0.00125379086609644	0.0151462299035569	0.0406977030547469	0.12082824094044	0.293922111107917
19 - (CPS-3.0)	0.0007758249647387...	0.00937223551279857	0.0251830627349355	0.0747665087550949	0.181874120838178
20 - (RCMP)	0.0003349318016166...	0.00404609269893088	0.0108717931948463	0.0322774886296269	0.0785169719052536
21 - (CPS-1.2)	0.0001137413412252...	0.00137403497690158	0.00369201232470691	0.0109612907176767	0.0266640123462135
22 - (RCMP)	5.5363854437293E-5	0.0006688146247747...	0.00179709532808311	0.00533543298506222	0.012978768162464
23 - (CPS-3.0)	2.69484810459919E-5	0.0003255470274281...	0.0008747402051195...	0.00259703404200228	0.00631744468266079
27 - (RCMP)	1.16339428579838E-5	0.00014054207761178	0.0003776345518166...	0.00112116692563594	0.00272730735068575
28 - (CPS-3.0)	6.38484321411449E-6	7.71311275541747E-5	0.0002072502362281...	0.0006153094547927...	0.00149677800926111
29 - (RCMP)	3.50407625054202E-6	4.23304603067837E-5	0.0001137413412252...	0.0003376889885889...	0.0008214491881321...
30 - (CPS-3.0)	2.16826418745773E-6	2.61933858053468E-5	7.03812529119267E-5	0.0002089563377346...	0.0005082991148288...
31 - (RCMP)	1.05540748476227E-6	1.27496896319825E-5	3.42582336321696E-5	0.0001017099687894...	0.0002474157408453...

	19 - (CPS-3.0)	21 - (CPS-1.2)	23 - (CPS-3.0)	28 - (CPS-3.0)	30 - (CPS-3.0)
5 - (RCMP)	0.0003083247287116...	5.81175666335297E-5	1.47896399730996E-5	3.02075538839829E-6	7.79634610615603E-7
6 - (CPS-3.0)	0.0005618042848107...	0.0001058971107959...	2.69484810459919E-5	5.50417518458146E-6	1.42058688143782E-6
7 - (RCMP)	0.00102367414949369	0.0001929571164882...	4.9103333955869E-5	1.00292610844688E-5	2.58847806425598E-6
9 - (RCMP)	0.00383204369456401	0.0007223197947567...	0.0001838144700251...	3.75437503417309E-5	9.68976412030667E-6
10 - (CPS-1.2)	0.0078726778307508	0.00148395777505371	0.0003776345518166...	7.71311275541747E-5	9.68976412030667E-6
11 - (RCMP)	0.0127228331189878	0.00239818617419942	0.0006102855325744...	0.0001246496408525...	3.21711498331556E-5
12 - (CPS-3.0)	0.0182360109459877	0.00343739078507195	0.0008747402051195...	0.00017866399674838	4.61118553560899E-5
13 - (RCMP)	0.0294707504879202	0.00555507925808852	0.00141364525406271	0.0002887343117385...	7.45201890785981E-5
14 - (CPS-1.2)	0.0682650732111736	0.0128676021468379	0.00327452118339418	0.0006688146247747...	0.0001726161050851...
16 - (RCMP)	0.124387073308114	0.0234462997876985	0.00596656661053952	0.0012186597017782	0.0003145270503258...
17 - (CPS-3.0)	0.201018765136934	0.0378909649130403	0.00964241556827173	0.00196944474902778	0.0005082991148288...
18 - (RCMP)	0.324861280698224	0.0612346184703534	0.0155828609751902	0.00318276924543699	0.0008214491881321...
19 - (CPS-3.0)	0.525	0.0989596994379863	0.0251830627349355	0.00514359190563752	0.0013275230056425
20 - (RCMP)	0.226648024800267	0.229226979810334	0.0583333214893411	0.0119144464322573	0.00307503045118747
21 - (CPS-1.2)	0.0769686551184338	0.675	0.171772625044538	0.0350842267713336	0.00905497928851553
22 - (RCMP)	0.0374646665171027	0.328557772772981	0.352895385570979	0.0720782006487891	0.0186028501720189
23 - (CPS-3.0)	0.0182360109459877	0.159926237110432	0.725	0.148079849176326	0.0382183132060279
27 - (RCMP)	0.0078726778307508	0.0690418395329878	0.312990129486083	0.343007272558767	0.0885276386187197
28 - (CPS-3.0)	0.00432061720073551	0.0378909649130403	0.171772625044538	0.625	0.161307874681346
29 - (RCMP)	0.00237120499487165	0.020795002447107	0.0942708153868588	0.343007272558767	0.293922111107917
30 - (CPS-3.0)	0.00146726226939434	0.0128676021468379	0.0583333214893411	0.212247203528087	0.475
31 - (RCMP)	0.0007141932197126...	0.0062633343737687	0.0283938239467656	0.103311805138492	0.231207321580987

Fig. 3. Matrix of the attenuation coefficients in the adjustment mode

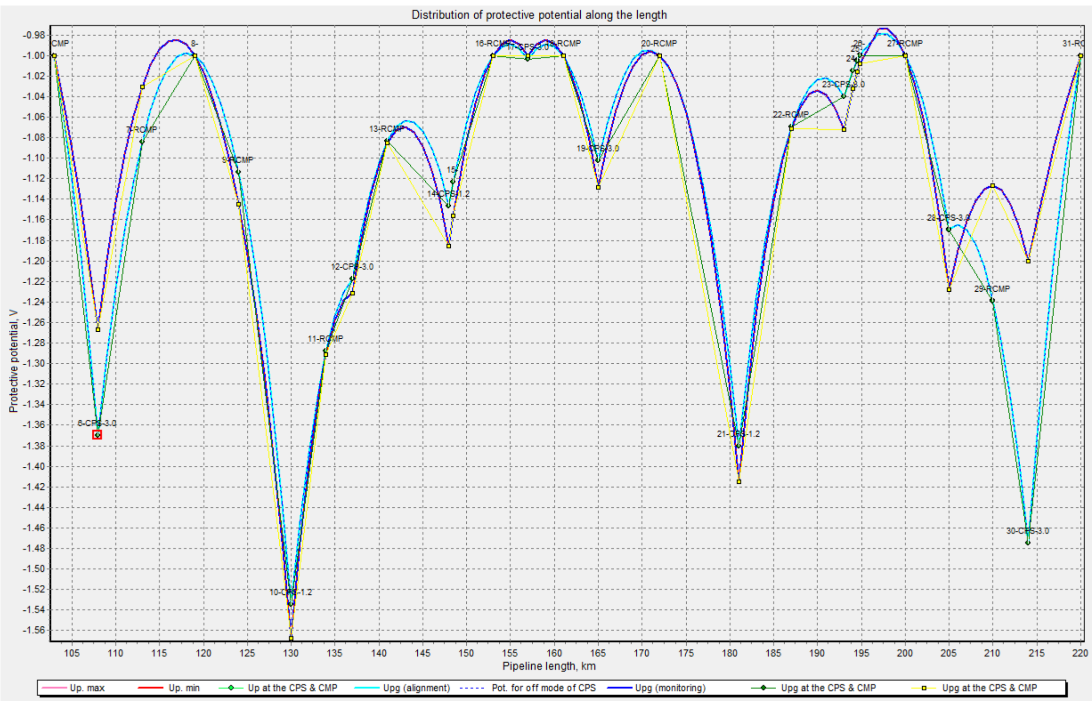

Fig. 4. The initial plan after minimizing the total current of all CPS on the site

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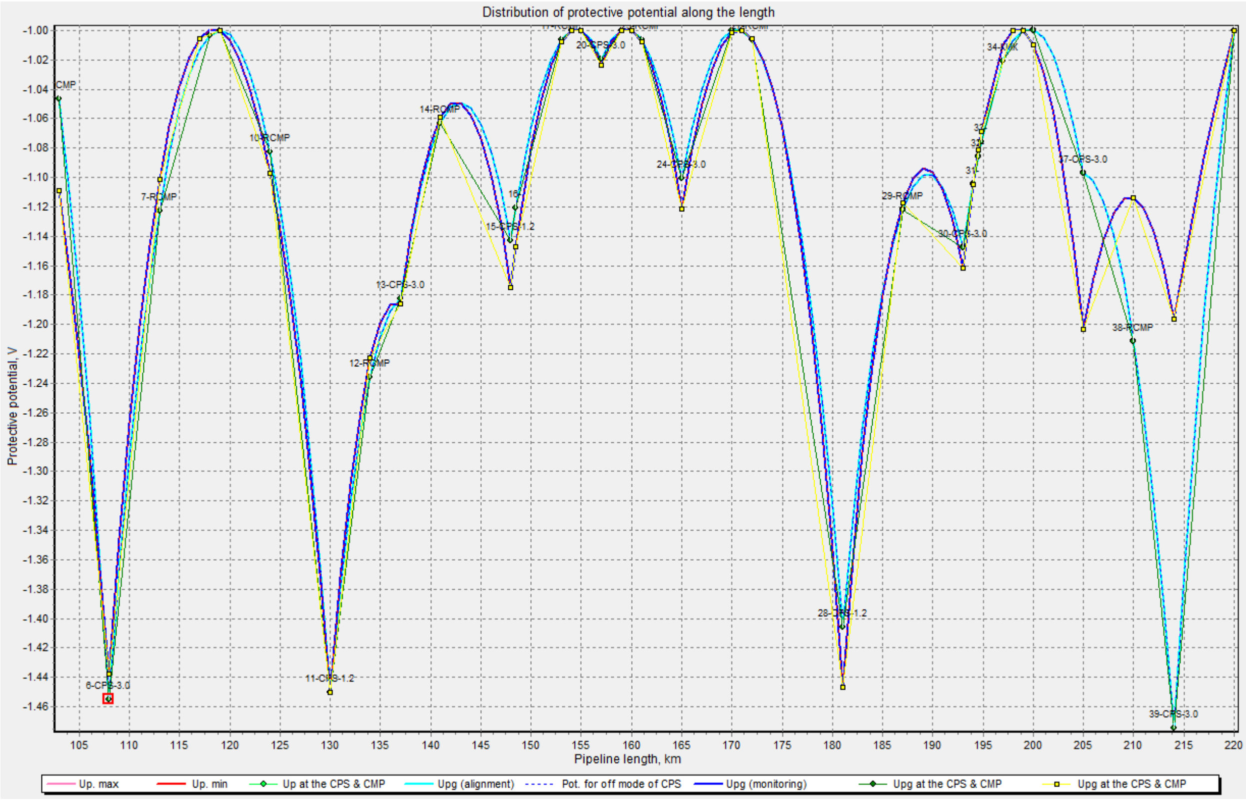

Fig. 5. A new plan for the distribution of the total potential, adjusted from top to U_{PGjmin} and from bottom to U_{PGjmax}

Considering the minimum value of the protective potential "pipe-ground" is necessary to prevent "failures" during optimization at points that are not necessarily located strictly in the middle between neighboring CPS because there are different attenuation coefficients on the left and right and other conditions.

If there are many dips, the introduction of optimization constraints for each of them significantly complicates the calculations. It is advisable to limit ourselves to one equation for the CMP located in the middle of the section between neighboring CPS.

Table 4 shows the values of the CPS current after optimization according to the distribution of the protective potential. The total value of the CPS current has slightly increased from the one obtained at the previous optimization stage and is 151.64, which is less than the initial 13.36 A.

The results of the approbation of the proposed approach to determine the optimal modes of operation of the CPS on the real object of the main gas pipeline were to ensure: protection over the entire length of the studied section; reduction of the total power of the CPS; reduction of the effect on the properties of metal and insulation coatings of increased current density; reduction of current strength will also lead to a decrease in the rate of dissolution of the anode grounding, which will increase its resource.

Table 4

Protective current of the CPS after optimization according to the criterion of distribution of the protective potential

Name	Kilometer	I, A
CPS-3.0	108	42.42
CPS-1.2	130	13.64
CPS-3.0	137	4.90
CPS-1.2	148	9.23
CPS-3.0	157	6.05
CPS-3.0	165	11.53
CPS-1.2	181	14.37
CPS-3.0	193	8.73
CPS-3.0	205	5.62
CPS-3.0	214	35.15
Sum:		151.64

5. Discussion of the results

The proposed method can be implemented in automatic and automated modes more efficiently using systems of remote corrosion monitoring and control of protection parameters and CPS. This method of regulating the optimal parameters of cathodic protection of underground pipelines can be implemented without means of remote control on individual instrumentation, considering them fictitious (without telemechanics or absent). At the same time, it is important that a linear equation for limiting the minimum value of the protective potential has already been compiled for this "fictitious" control point, which will be considered when solving the problem of optimizing the protection currents of all CPSs and the distribution of potential along the pipeline. To do this, the coefficients of influence on these control points of installation of CMP are calculated automatically according to formulas (3) and (4).

We will analyze the possible results of the optimization problem. These typical cases are possible.

1. When optimizing the objective function, $I_j = 0$ was obtained for individual CPS. This indicates that the CPS data are redundant at the given potential limits. This allows you to increase the resource of the reserved CPS.

In practice, with other constraints $I_j \neq 0$ the mathematical model provides restrictions on $I_j > 0$ and $I_j \leq I_N$, reducing the objective function to a minimum. If you unload the neighboring CPS slightly, that is, use the data disabled or redundant CPS, you need to set other restrictions, namely, for example, $I_j \geq 1,...,I_N$. Then the value of the objective function will increase somewhat (it may be within Ampere units). At the same time, there will no longer be a situation in the plan where $I_j = 0$, that is, all CPS will be included.

It is also possible to remove situations $I_j = 0$ by increasing the minimum constraints for the CPS equations sequentially, for example, by $\Delta U_{ij} = 0.05B$, but not more than $U_{T3j\min} = 1.2B$.

On the other hand, in the optimal plan, there should be no CPS with $I_j = 0$, otherwise, with further calculations, a case of "division by 0" may occur, which is unacceptable.

If it is necessary to determine the CPS that can be disabled, then we put restrictions $I_j \geq 0$. Then, having received a plan for the CPS with $I_j = 0$, you can simply turn them off. CPS data will no longer participate in optimization. If all CPS should participate in optimization, it is necessary to introduce restrictions $I_j \geq 1$.

2. The case when there is no solution under the given constraints (not received). It is necessary to choose the CPS that has the maximum (greatest) potential. Next, the maximum limit is adjusted for this CPS and for the control and measuring points on the left RCMPi-1 and on the right RCMPi+1, if necessary) until a solution is obtained (for example, on $\Delta U_{ij} = 0.05B$). If there is no solution, you need to choose another CPS that has the maximum potential. Next, it is necessary to similarly repeat the adjustment of the maximum limit for the CPS and for neighboring RCMP. Therefore, we consistently "release" the restrictions from below for all CPS and RCMP.

3. If one or more CPSs are excluded from the EChP system for various reasons, such as power outage (about which a message was received), converter failure or load circuit break (a message was received), stolen, etc., it is necessary to consider a new model of the EChP system in this section. Then, the initial matrices of the influence coefficients are adjusted without additional work and calculations. In this case, it is necessary to exclude the data from the optimization CPS and include a new ("fictitious") CMP instead. Its potential can be calculated using the known extinction coefficients of the remaining CPS. Thus, it is possible to introduce a completely new control point (fictitious CMP) without performing the calculations given in the method. It is only necessary to add a linear equation corresponding to this control point to the system of equations, considering the limitation of the minimum value of the protective potential. Then, using the simplex method, a new optimal plan of protective currents of the remaining neighboring CPS will be obtained, which will compensate for the "dips" of potentials through the CPS that have a failure (or are absent), without going beyond the permissible minimum potential value. The developed system allows to simulate this situation. Fig. 6 shows the graph of the potential distribution while maintaining the protective parameters on the site, but when the station is switched off at 165 km. We see that this will lead to a "failure" of the protective potential, which at some point becomes less than the lower limit according to regulatory documentation in -0.85 B. After the first optimization step according to the criterion of minimizing the total current, the CPS received a new plan, as shown in Fig. 7. The current values at the neighboring stations increased by 157 and 181 km to ensure the necessary level and distribution of the pipe-ground potential (Table 5). At the same time, it should be noted that the potential at the drainage point of the station at 181 km is almost on the verge of reaching a maximum value of -2.5 B. Therefore, in the next step, we perform optimization according to the criterion of the distribution of the protective potential (Fig. 8). On the site, the maximum value of the "pipe-ground" potential is now no lower than -1.6B, which means that we no longer have problems with the reserve in terms of the protective potential and the negative consequences of "overprotection".

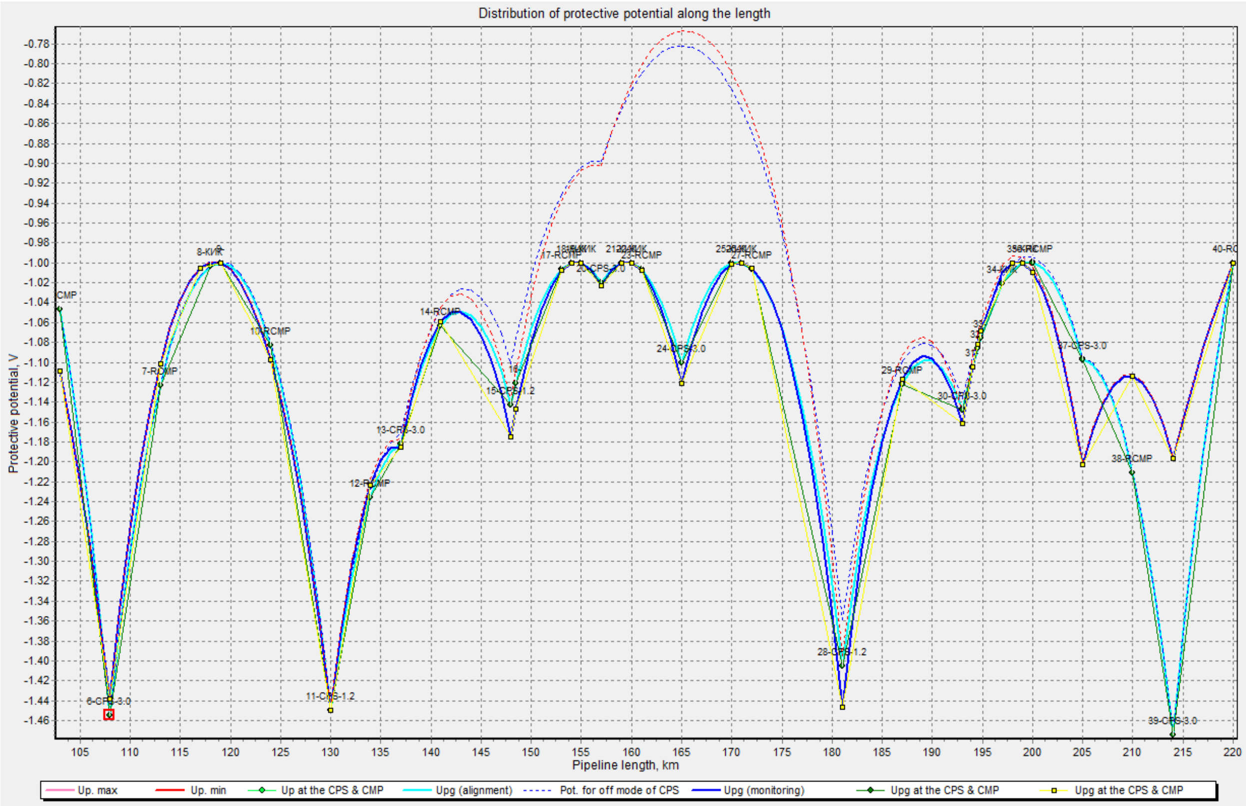

Fig. 6. Deviation ("failure") from the optimal plan for a disconnected CPS for 165 km of pipeline

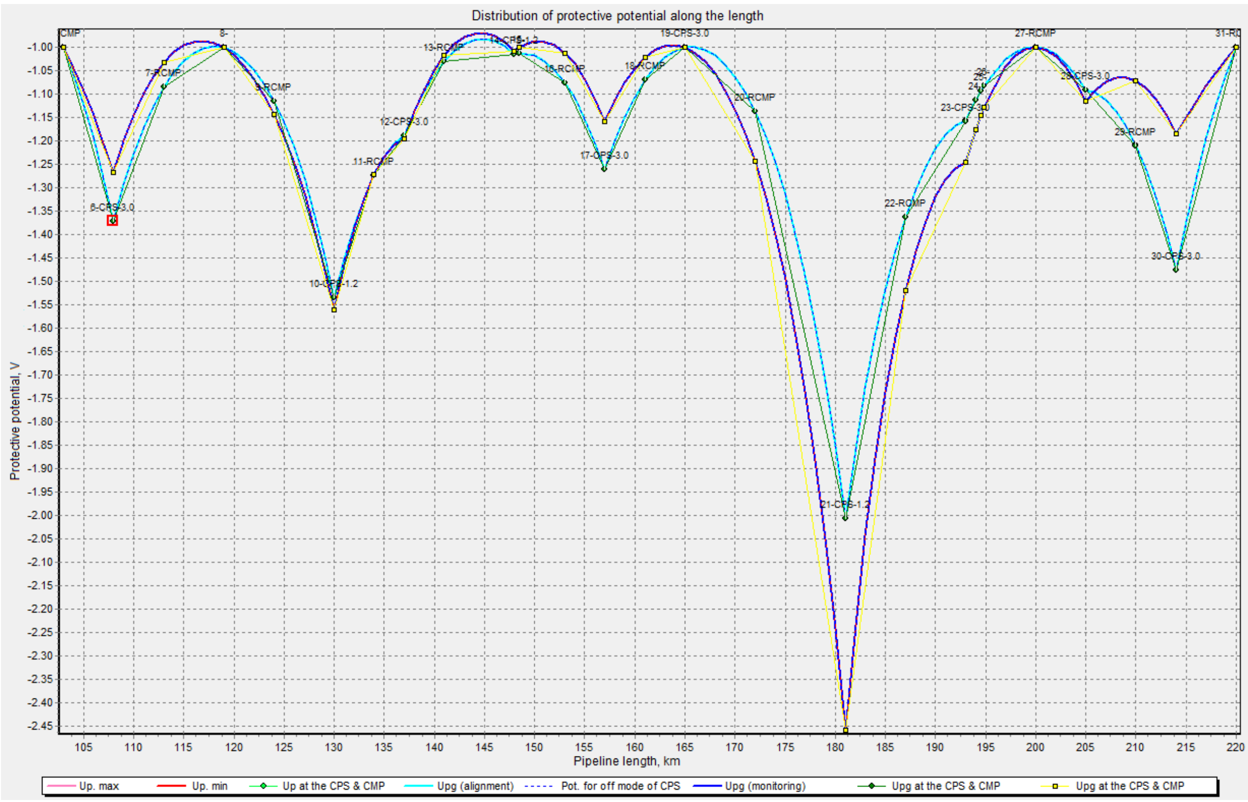

Fig. 7. The new plan for the disconnected CPS for 165 km of pipeline

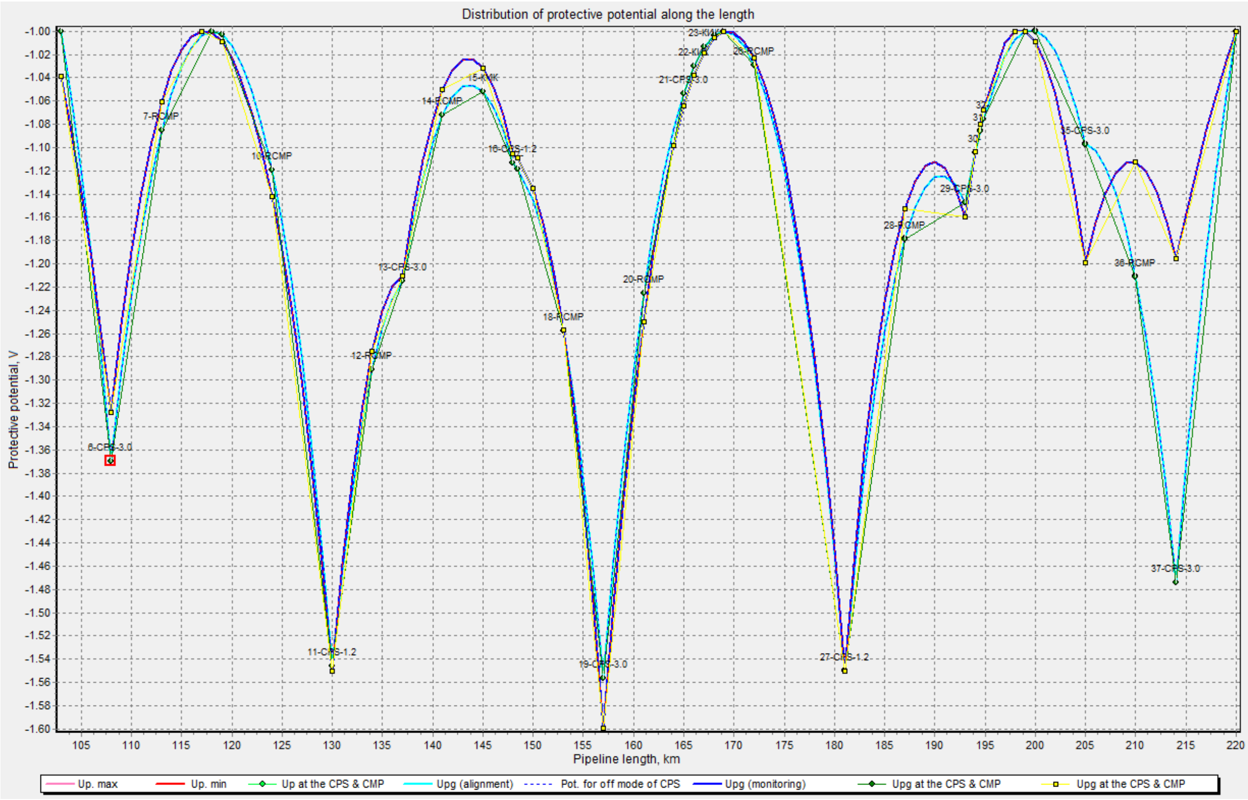

Fig. 8. A new plan for the distribution of the total potential, with the CPS disconnected for 165 km of pipeline, adjusted from above to U_{PGjmin} and from below to U_{PGjmax}

Table 5

The protective current of the stations after the exclusion of CPS and optimization by the criterion of minimizing the total current

Name	Kilometer	I, A
CPS-3.0	108	37.83
CPS-1.2	130	15.71
CPS-3.0	137	4.90
CPS-1.2	148	2.68
CPS-3.0	157	24.13
CPS-1.2	181	28.12
CPS-3.0	193	4.90
CPS-3.0	205	5.25
CPS-3.0	214	35.25
Sum:		158.77

Of course, this required changing the modes of operation of the CPS. We see that the current value of the station at 157 km increased to 38.37 A, but it has a power of 3 kW, and the current of the station at 181 km decreased from the preset value of 28.12 A (which exceeded the nominal value for a station with a power of 1.2 kW) to 17.75 A, which corresponds to 70% of the nominal current at this CPS. At the same time, the total value of the current of all CPS on the site increased slightly from that obtained at the previous optimization stage and was 165.64 (Table 6).

Table 6

Protective current of stations after the exclusion of CPS and optimization according to the criteria of the potential distribution

Name	Kilometer	I, A
CPS-3.0	108	37.79
CPS-1.2	130	15.71
CPS-3.0	137	4.90
CPS-1.2	148	2.68
CPS-3.0	157	38.37
CPS-1.2	181	17.75
CPS-3.0	193	7.73
CPS-3.0	205	5.62
CPS-3.0	214	35.15
Sum:		165.70

4. During operation, when external conditions (precipitation, temperature, etc.) and if the signal "lack of protection" or "overprotection" from the CPS or RCMP is received, the monitoring results are analyzed and the corresponding correction and calculation or selection of appropriate cases of the necessary ready-made data for standard conditions are performed. At the same time, a

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new optimization problem is solved in the proposed way. The current propagation coefficients of the left and right protection arms were calculated. Furthermore, based on the results of the solution, a new schedule for the distribution of the pipe-to-ground potential along the pipeline is constructed. The plan should improve the current state of the EChP. For example, in the "rain" state, "overprotection" takes place, and in the "parched" state, "under protection" is possible in the middle sections of the pipeline between the CPS.

Note that the same EChP states can occur in the zones of stray currents. For example, they are fixed during measurements on any RCMP. When such zones are detected, for example, when a message is received from the RCMP for a potential deviation, it is necessary to introduce an amendment to the limitations in the controls for this RCMP.

Conclusions

A study has been conducted related to the creation of a method for regulating the optimal parameters of cathodic protection of underground pipelines in seasonal, seasonal and climatic changes in the electrical properties of the soil.

1. The analysis of the problems of existing EChP systems of main pipelines has shown that the existing systems do not solve the main task – optimization and maintenance of protective parameters depending on the dynamics of external conditions, the condition of structures, etc.

2. An adjustment method was developed to determine the influence of cathodic protection stations on the value of potentials at control points along the pipeline route. This makes it possible to remotely build a model of potential distribution along the main pipeline route, without significant time and resources, and without disconnecting the CPS for a long time. This method also considers the action of other extraneous current sources affecting the pipeline.

3. A multicriteria optimization model for regulating the modes of CPS operation has been developed. Optimization is performed both by the criterion of optimality of the distribution of the protective potential (uniformity of the distribution of the protective potential "pipe-ground" along the length of the pipeline) and by the criterion of the minimum total protective current of all CPSs on a given section of the main pipeline. At the same time, when determining the optimal modes, the proposed approach considers various corrosion factors and their aggregates at the site under consideration. For this purpose, an adaptive intelligent system is used, for which appropriate knowledge models have been developed, reflecting the laws, regulatory framework, and experience in solving the corrosion protection problems of metal underground pipelines and structures.

4. An example of the application of optimal regulation methods at the facilities of the linear part of the existing main gas pipeline of the Republic of Kazakhstan is given. The results of the implementation were as follows: reduction of the time of regulation of the optimal parameters of the operating modes of cathodic protection stations; improvement of the efficiency of cathodic protection of pipelines in conditions of changing electrical properties of the soil; reduction of operating costs by optimizing (minimizing) the total protection current of all cathodic protection stations on a given section of the pipeline; constant support of potentials in regulated ranges, through the use of remote control systems corrosion monitoring and remote control of CPS parameters and modes; reduction of measurement time to determine the coefficients of influence of cathodic protection stations on the potential at control points and determination of optimal values of CPS currents using the claimed method; reduction of operating costs; reduction of influence on the properties of metal and insulation coatings of increased current density; reduction of the speed of anode grounding by reducing the current strength of CPS.

Mathematical methods and models used: system analysis; simplex optimization method (method of sequential improvement of the plan).

Due to the proposed approach, it becomes possible to maintain the EChP process at an optimal level between the zones of "lack of protection" and "overprotection" and thereby reduce the harmful consequences caused by modern EChP systems. Consequently, as estimates show, the technical resources of the pipeline can be extended to a minimum of 5-10 years and reduce their accident rate due to corrosion.

The system monitors and continuously ensures the EChP process both in time and duration, controlling the protective potential through remote monitoring of the instrumentation and control systems in the middle of the pipeline between neighboring CPS, as well as in all corrosion-hazardous areas, where control and measuring points are also installed. This gives a more complete picture of the pipeline's safety, which means that it increases the real protection of the pipeline from corrosion by about 20...30 %

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Contribution of the authors: adaptive system for monitoring and controlling the protective parameters of cathodic protection stations, an example of optimizing the protective parameters on an existing main gas pipeline – **Oleksandr Prokhorov**; assessment of the influence of the operating modes of cathodic protection stations on the value of potentials at control points, optimization of the regulation of the operating modes of cathodic protection stations – **Valeriy Prokhorov**; analysis of the influence of factors affecting corrosion processes and spatial distribution of the electric field of cathodic protection – **Alisher Khussanov**; analysis of the problems of existing systems of electrochemical protection of pipeline systems – **Zhakhongir Khussanov**; analysis of the results and drafting of the manuscript – **Botagoz Kaldybyeva**, **Dilfuza Turdybekova**.

All authors have read and agreed with the published version of this manuscript.

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ОПТИМІЗАЦІЯ СИСТЕМИ КАТОДНОГО ЗАХИСТУ МАГІСТРАЛЬНИХ ТРУБОПРОВОДІВ

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Досліджується *багатокритеріальне завдання оптимізації режимів роботи станцій катодного* захисту (СКЗ) з урахуванням даних моніторингу, геологічних умов у місці прокладання трубопроводу, кліматичних чи сезонних змін та інших факторів. **Актуальність** дослідження пов'язана з комплексним рішенням проблеми підвищення довговічності та експлуатаційної надійності магістральних трубопроводів з метою зниження аварійності на їх об'єктах за рахунок забезпечення ефективності роботи систем електрохімічного захисту (ЕХЗ). Проаналізовані проблеми існуючих систем ЕХЗ, де усунення анодних зон («недозахист») за рахунок катодної поляризації здійснюється без оперативного обліку умов зовнішнього середовища, як правило, із запасом за величиною захисного потенціалу, що часто призводить до «перезахисту», наслідком чого є підвищена витрата електроенергії, газоутворення на поверхні металу, відшарування та знос ізоляції трубопроводів. **Метою** дослідження є створення методу оптимального регулювання режимів роботи СКЗ магістральних трубопроводів та адаптивної системи ЕХЗ, що забезпечує контроль та керування параметрами станцій катодного захисту з урахуванням зміни зовнішніх умов на окремих лінійних ділянках магістральних трубопроводів. **Завдання:** розробити метод юстування для знаходження впливу СКЗ на значення потенціалів у контрольних точках впродовж траси трубопроводу; розробити багатокритеріальну оптимізаційну модель регулювання режимів роботи СКЗ; навести приклад апробації методу оптимального регулювання на об'єктах лінійної частини діючого магістрального газопроводу. Отримані такі **результати.** Запропоновано метод знаходження впливу режимів роботи СКЗ на значення потенціалів у контрольних точках в режимі переривання струму захисту інших станцій. Сформовано оптимізаційну модель за критерієм рівномірності розподілу захисного сумарного потенціалу впродовж траси трубопроводу і за критерієм мінімального сумарного захисного струму всіх СКЗ на заданій ділянці магістрального трубопроводу. **Висновки.** Наукова новизна отриманих результатів пов’язана з розробкою оригінального оптимізаційного методу, який дозволяє науково-обґрунтовано визначити режими роботи СКЗ для забезпечення захищеності магістрального трубопроводу як у часі, так і за протяжністю із скороченням експлуатаційних витрат та адаптивністю до зміни кліматичних, сезонних та геологічних умов у місці прокладання трубопроводу. Ефективність запропонованого підходу проілюстровано на прикладі регулювання параметрами СКЗ на основі даних моніторингу ділянки магістрального газопроводу нафтогазового комплексу Республіки Казахстан.

Ключові слова: електрохімічний захист від корозії; магістральні трубопроводи; станції катодного захисту; захисний потенціал; багатокритеріальна оптимізація; дистанційний моніторинг.

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