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O. Aziukovskyi[1],
orcid.org/0000-0003-1901-4333,
Yu. Papaika[*1],
orcid.org/0000-0001-6953-1705,
O. Podoltsev[2],
orcid.org/0000-0002-9029-9397,
M. Babenko[1],
orcid.org/0000-0003-2309-0291,
S. Shykhov[1],
orcid.org/0009-0000-9459-9277

1 – Dnipro University of Technology, Dnipro, Ukraine
2 – Institute of Electrodynamics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine
[*] Corresponding author e-mail: papaika.yu.a@nmu.one

SIMULATION OF THE OPERATION MODES OF THE CATODIC PROTECTION COMPLEX OF PIPELINES IN THE APPROACH OF OVERHEAD POWER LINES

Purpose. The purpose of the work is to establish the dependences of the levels of the protective potential of the system of protection of underground steel pipelines when approaching and/or crossing overhead power lines.

Methodology. To achieve the goal, the methods of the theory of equivalent electric circuits and the theory of the electromagnetic field, implemented in the packages of applied computer programs Matlab/Simulink and COMSOL Multiphysics, were used.

Findings. The spatial distribution in the soil of the induced electric field of the overhead power line in the direct location of the pipeline, which varies with a frequency of 50 Hz, was determined. The distribution of both constant and alternating voltage on the pipeline relative to the soil is given. An analysis of corrosion processes in the pipeline was carried out, on the basis of which the relatively safe flow of corrosion processes in the pipeline under the action of simultaneously occurring alternating current with a frequency of 50 Hz and direct current was investigated.

Originality. The scientific novelty of the work consists in determining the regularities of the influence of overhead lines on the nature of the distribution of the protective potential of cathodic protection stations with variable changes in the configuration of pipelines and laying conditions. The existence of significant deviations of the levels of the protective potential in the presence of a variable polyharmonic component of the signal is proven. On the basis of the study, it was established that under the accepted initial conditions, both criteria are unsatisfactory in some sections of the pipeline near the power transmission line.

Practical value. The practical significance of the research results is in determining the set of technical characteristics of the electrotechnical complex of protection against electrochemical corrosion, which allows ensuring the necessary levels of protective potential in the presence of a source of stray currents (overhead power lines).

Keywords: *underground steel pipeline, cathodic protection, electrochemical corrosion, power lines*

Introduction. Underground metal pipelines used to transport gas, oil and water, as well as metal structures connected to the pipelines, undergo destruction over time due to the occurrence and flow of various corrosion mechanisms [1, 2]. To protect pipelines from such destruction, a combined method for creating an insulating coating on their surface and carrying out cathodic polarization is used [3, 4]. The main criterion for cathodic protection is the polarization potential, which for steel should be in the range of –0.85 to –1.15 V relative to the created anode electrode [1]. To maintain the potential of metal structures in a weakly electrically conductive environment, which is the soil, specialized electrical equipment is used. The equipment makes it possible to control and maintain the electrical potential of metal surfaces in such a range of values that provides the necessary protection of metal against corrosion.

If an underground pipeline is laid near an overhead power line (OPL) or an underground cable line, an electromagnetic connection occurs between the metal structure of the pipeline and these lines, as the sources of an electromagnetic field. At the same time, a variable electric field of industrial frequency is induced in the pipeline, which affects the intensity of corrosion processes, both of the pipeline and of the equipment, which provides cathodic protection of the pipeline by creating a constant electric potential on its surface.

It should be noted that many works are devoted to the calculation of magnetic and electric fields near the power lines, in particular [5, 6]. However, in these works, the potential electric field in the air space between the line and the ground is calculated. At the same time, the questions regarding the calculation of the electric field in the soil, as well as the consideration of the alternating electric field and the field of direct currents acting simultaneously in the pipeline, which are formed when cathodic protection is used, are not sufficiently considered in the literature.

The purpose of the work is to develop an electric simulation of a long underground pipeline, as an equivalent electric circuit, using the methods of electromagnetic field theory and the theory of electric circuits. This simulation takes into account the simultaneous action of both the constant power source for cathodic protection and the electromagnetic field of the overhead power line passing nearby this pipeline, the analysis of electrical processes in the metal structures of the pipeline and the assessment of their impact on the corrosion processes.

Equivalent electrical circuit of an underground pipeline with a cathodic protection system and without an overhead line. The work deals with an underground pipeline built on the basis of a long steel pipe – 7 km long and located in a weakly electrically conductive medium – soil. The schematic representation of the pipeline is shown in Fig. 1, *a*. In the case under consideration, the pipe is covered with a layer of bitumen insulation to reduce currents in the "pipe-soil" system with cathodic protection.

Due to the defects in the insulation, Fig. 1, *a*, the electric current flowing between the soil and the pipe has a complex structure. Cathodic protection is carried out using a direct current source, the minus of which is connected to the surface of the pipe, and the plus - to a specially created anode. As a result, an electric potential is formed on the pipe. It varies from –0.85 to –1.15 V and significantly inhibits the flow of corrosion processes.

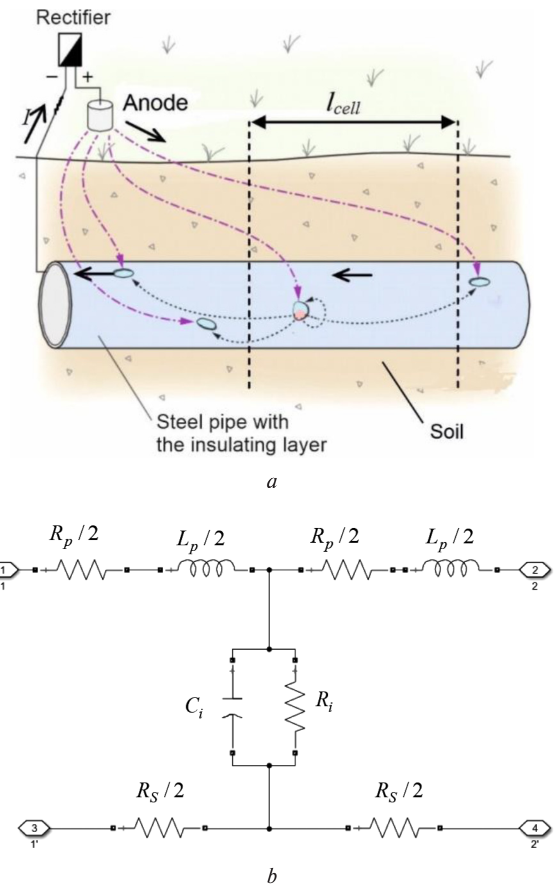


Fig. 1. Structural diagram of the cathodic protection complex (a) and its replacement calculation scheme (b)

To create an equivalent circuit diagram of an extended pipeline, it is advisable to select a unit cell l_{cell} long, for which the equivalent electric circuit will have the form shown in Fig. 1, *b*. The equivalent model of the entire pipeline will consist of such cells connected in series, so that the total length of the pipeline will be equal to $l_p = Nl_{cell}$, where N is the total number of cells. The circuit diagram in Fig. 1, *b* contains the following elements corresponding to the length of the unit cell: active resistance and inductance of the pipe, equivalent active resistance and insulation capacity of the pipe, active soil resistance. Known expressions were used to calculate the values of these parameters – for example [4, 5].

The developed Simulink model of an underground pipeline with a device for cathodic protection is shown in Fig. 2, *a*. The model consists of serially connected unit cells, each of which simulates electrical processes for sections with a length of = 500 m. The number of such cells is 14, which corresponds to the total length of the pipeline – 7 km. The electric circuit of each cell with means of measuring electric currents in longitudinal circuits and voltage on the insulation of the pipeline, the current in this insulation is shown in Fig. 2, *b*. To simulate the cathodic protection process, a direct current source is connected in the centre of the pipeline. In the model, it is assumed that all processes are periodically repeated with a spatial period of 7 km, which is taken into account by the connection in the diagram in Fig. 2, and the output of the last cell with the input of the first cell.

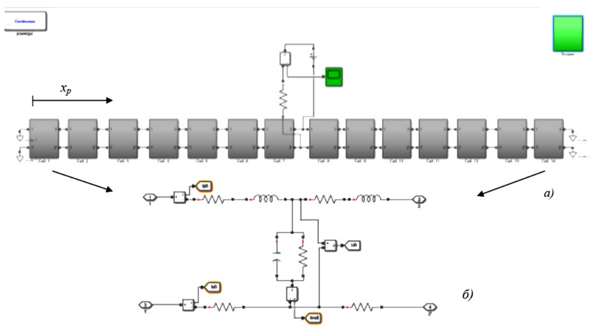


Fig. 2. Simulink research model of protection modes underground pipelines

Further, calculations were carried out with the following parameters of the pipeline and soil:

- the steel pipe of the pipeline with an outer diameter of 45 mm and a wall thickness of 4 mm, is laid in the soil at the depth of 1.2 m and has a total length of 7 km;
- the insulating coating on the pipe is made on the basis of bitumen with the thickness of 20 mm and has $\varepsilon_r = 2.5$ and a surface resistance of 3,000 $\Omega \cdot m^2$;
- soil resistivity was assumed to be 100 $\Omega \cdot$ m.

The results of the calculation of the electric potential distribution along the pipeline (voltage drop across the insulation), to which the coordinate axis x_p is connected, are shown in Fig. 3, *a*. At the same time, the value of the DC source in the circuit diagram in Fig. 2, *a*, which simulates the operation of the device for cathodic protection, has been chosen with the condition that the maximum value of the potential in terms of the modulus is equal to 1.15 V. As can be seen from this figure, the spread of the electric current along the pipe results in the decrease of the electric potential with the distance from the connection point of the power supply and at the beginning and end of the pipeline equals to 0.65 V. Although the required value should be 0.85 V.

Fig. 3, *b* shows the nature of the change in time of the electric potential at different sections of the pipe in the transient process when a direct current source is connected to the pipe.

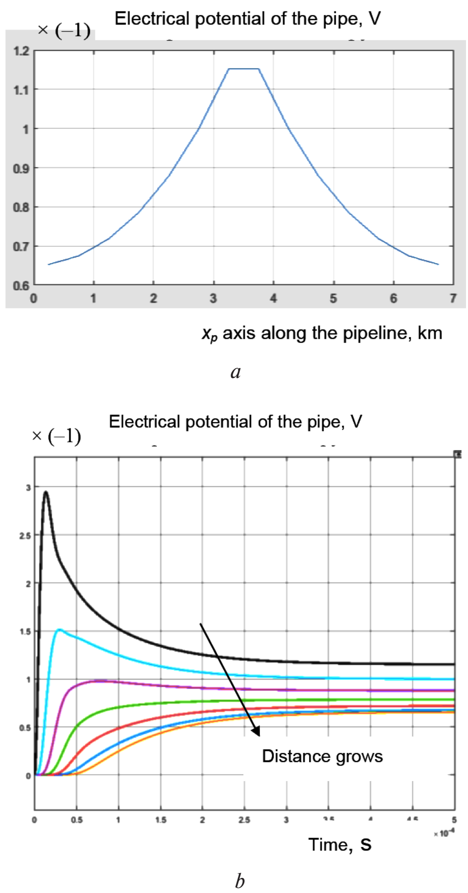


Fig. 3. Distribution of protective potential values along the pipeline route (a) and time (b)

It can be seen that the maximum potential jump occurs at the point of the connection of such a source to the pipe and that the transient process decays in about 0.4 ms. This time must be taken into account when building a cathodic protection device control system [6, 7].

Further, the paper deals with the case when the pipeline is laid near an overhead power line. At the same time, two currents will flow simultaneously in its steel pipe – the direct current from the cathodic protection device and the alternating current with a frequency of 50 Hz due to the influence of the overhead line. Corrosion processes in the steel pipe will depend on the ratio of these currents, which will be different in different sections of the pipeline, and the presence of such currents should be taken into account at the pipeline design stage [8, 9].

Calculation of the induced electric field in the soil around an overhead power line (OPL). Further, the work considers a three-phase overhead line of 330 kV with a nominal current of 2 kA. The geometric dimensions regarding the location of the conductors in such a line are shown in Fig. 4, *a*.

The electromagnetic field in a two-dimensional setting in the transverse plane *x0y* satisfies the following equation for the vector magnetic potential (complex quantity) $\underline{\mathbf{A}} = (0, 0, \underline{A}_z)$

$$j\omega\sigma\underline{A} + \mu_0^{-1}\nabla\times(\nabla\times\underline{A}) = \delta_A\underline{I}_A + \delta_B\underline{I}_B + \delta_C\underline{I}_C, \qquad (1)$$

where σ is specific electrical conductivity of soil and air (a relatively small value was set), and δ_A, δ_B, δ_C are Dirac delta functions that specify the spatial position of linear conductors with current $\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$, respectively.

The intensity of the induced electric field at an arbitrary point in space is calculated as [10]

$$\underline{E}_z = -j\omega\underline{A}_z,$$

where $\underline{E}_z = E_z\angle\varphi_E$.

The finite element method implemented in the COMSOL Multiphysics package was used for the numerical calculation of the differential equation (1) with the boundary condition – magnetic isolation on all outer boundaries of the calculation domain. The value of electrical conductivity of the soil was taken as in the previous section – 0.01 $(\text{Ohm}\cdot\text{m})^{-1}$.

The distribution of the $E_z(x, y)$ electric field strength modulus in the calculation area with dimensions of 120 × 300 m is shown in Fig. 5, *a*. It can be seen that on the surface of the soil in the zone of the line, the voltage value is 0.3–0.4 V/m.

The distribution of the $E_z(x)$ electric field strength and its phase angle $\varphi_E(x)$ in the soil exactly at the depth of the pipeline laying – 1.2 m and along the transverse coordinate *x* is shown in Figs. 5, *b* and *c*, respectively. It can be seen from these figures that the characteristic distance for such a line, when the value of the magnetic field decreases by *e*-times, is about 40 m, and the phase angle of the $\varphi_E(x)$ electric field changes by about 30° when crossing the area under the line.

The obtained data make it possible to determine the induced electric field in the pipeline. So, for example, when the pipeline crosses the air line at a certain angle β (Fig. 5, *b*), then based on the data in Figs. 5, *b, c*, the magnitude of the electromotive force acting in each cell depending on its distance from the air line and the relative direction characterized by angle β, will be determined as

$$\underline{U}_{1,2} = \int_{x1,z1}^{x2,z2} \underline{E}_z \cos\beta\, dl. \qquad (2)$$

Note that this value is complex, and therefore it is important to know its amplitude as well as the phase angle in order to set the appropriate sinusoidal function for each cell in the Simulink model of the pipeline (Fig. 2, *a*). At the same time, the distance of this cell to the air line is also taken into account.

Simulink-model based calculation of the electrical processes in an underground pipeline with an overhead line. Characteristic features of AC corrosion processes in an underground pipeline are considered, for example, in works [11, 12]. For the quantitative analysis of these processes, it is necessary to calculate both the direct current in the pipeline (DC current) and the alternating current (AC current) and then carry out their comparative analysis. Thus, in work [12], certain limits to a safe level are given for the density of the AC electric current flowing from the pipeline into the soil. Also, according to ISO 18086 [13, 14], a certain threshold value of AC voltage on the pipeline relative to the reference electrode (comparison electrode) is acceptable, which for a steel pipe is $U_{AC} < 15$ V.

According to the results of these works, two main criteria for the safe flow of AC corrosion processes can be identified in a pipeline under the influence of an external electromagnetic field [15, 16]:

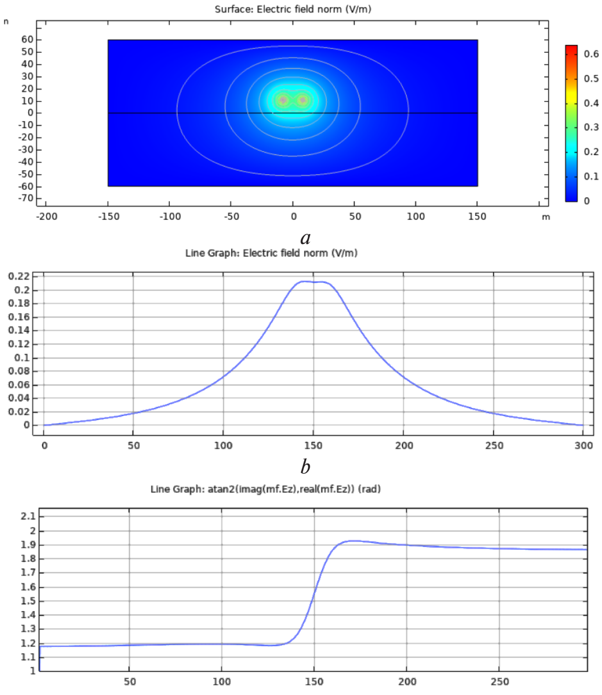


Fig. 5. Distribution of protective potential x-coordinate, m

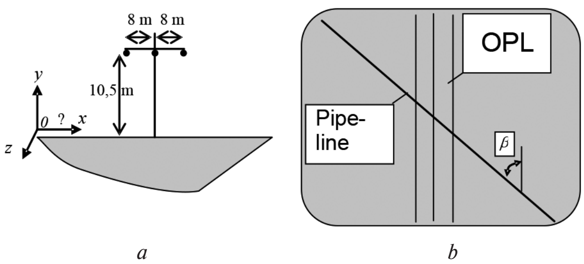


Fig. 4. The location of OPL elements in space (a) and the intersection of the pipeline and overhead line (b)

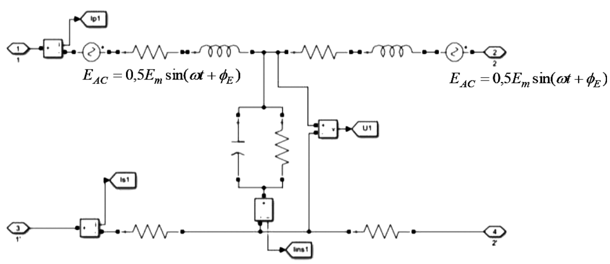


Fig. 6. Consideration of additional voltage sources

criterion 1

$$U_{AC} < 15 \text{ V}; \quad (3)$$

criterion 2

$$\text{when } 0.1 \text{ A/m}^2 < J_{DC} < 1 \text{ A/m}^2, \quad J_{AC}/J_{DC} < 25, \quad (4)$$

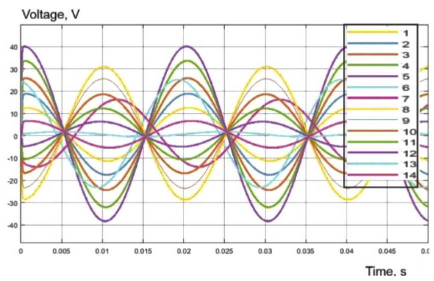
$$\text{when } 1 \text{ A/m}^2 < J_{DC} < 20 \text{ A/m}^2, \quad J_{AC} < 70 \text{ A/m}^2. \quad (5)$$

Further, based on the results of the calculations, it will be determine to what extent the investigated pipeline meets these criteria.

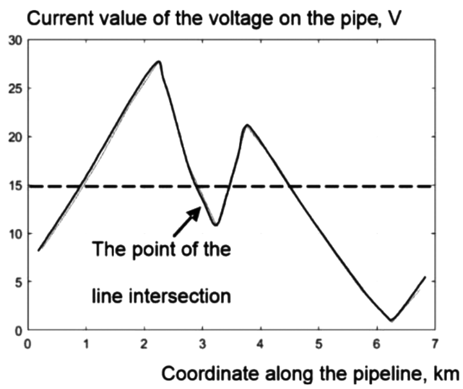
For the calculation of electrical processes in the pipeline, we further considered the option when the pipeline crosses the space under the overhead line at an angle of $\beta = 45°$. The Simulink model containing 14 serially connected elementary cells (Fig. 2) was used for the calculation. The electric circuit of each cell differs from the circuit of the cell in Fig. 2, *b* by the presence of additional voltage sources E_{AC} (Fig. 7), the value of which was calculated according to expression (2) and according to the results of the calculation of the electric field in Fig. 6 depending on the distance of each cell from the air line [17, 18].

The results of calculating the instantaneous values of the AC voltage on the pipeline insulation for various cells in the steady state are shown in Fig. 7, *a*. It can be seen from this figure that these voltages have different amplitude and phase in different sections of the pipeline. The distribution of the effective value of this voltage along the pipeline is shown in Fig. 8, *b*. The greatest value of this voltage is reached in the area near the point of the pipeline intersection of the space under the overhead line. At the same time, the voltage threshold value of 15 V according to criterion 1, expression (3) is exceeded on these sections [19]. This value is marked with a dashed line in the figure.

To use criterion 2, we calculated the distribution of the electric current density – constant J_{DC} and variable J_{AC} (current value) flowing from the pipe into the insulation and into the ground. The distribution of these currents along the pipeline is shown in Fig. 8, *a*, and the ratio of these currents is shown in Fig. 8, *b*.

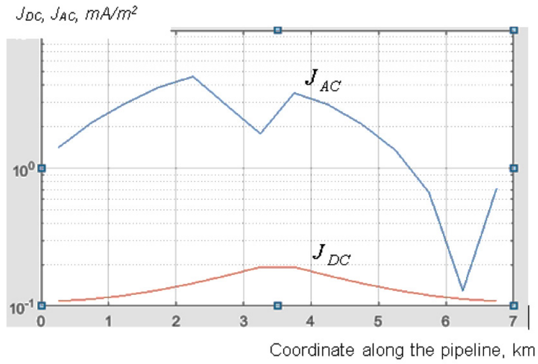


a

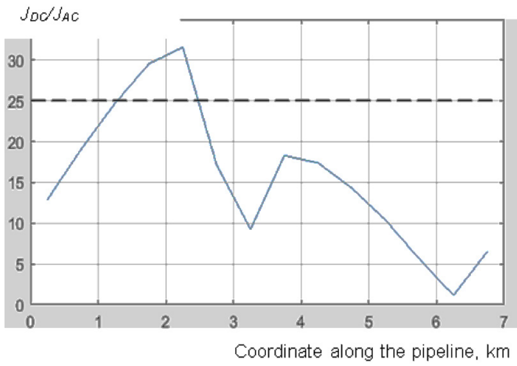


b

Fig. 7. Distribution of protective potential by time (a) and coordinate (b)



a



b

Fig. 8. Distribution of density of direct and alternating electric current (a) and relative value (b) according to criterion 2

It can be seen that in some areas value J_{AC}/J_{DC} exceeds the permissible threshold value according to criterion 2, expression (4) – which is shown in the figure with a dashed line.

The influence of the electromagnetic field of the overhead line on the underground pipeline, which is laid near this line, leads to the emergence of the alternating electric current in the circuit of the cathodic protection power source. In the work, this current was calculated using an ammeter Fig. 2, *a*, connected in series with a direct current source. The immediate value of this current is shown in Fig. 9. Measuring this current in practice and comparing it with the calculation enables assessing the intensity of the air line influence on the pipeline.

Next, let us innumerate several ways to reduce the level of the electromagnetic field of the power transmission line and, accordingly, its influence on the corrosion processes of the underground pipeline:

- for a double circuit overhead line, there is an optimal alternation of phase conductors in the line, where the electric field in the area of the pipeline location is minimal [20, 21];
- choosing a safe distance from the line, using the results of the field calculation in Fig. 6, *b* and (3–5) criteria [22];

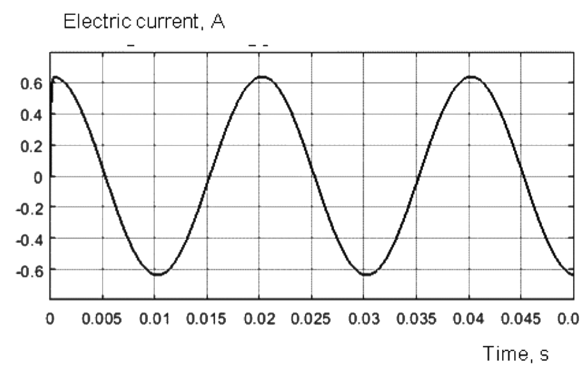


Fig. 9. Instantaneous value of alternating current (source – OPL)

- for the pipeline which crosses the space under the overhead line, it is preferably to carry out this crossing at a right angle, then in expression (2) there will be angle $\beta \approx 90^\circ$, which will lead to a significant reduction of the induced voltage and the AC current, respectively [23, 24].

Conclusions. The paper proposes and implements a new approach to the calculation of electrical processes in an underground pipeline, which is located near an overhead power line and which is under the influence of its electromagnetic field for the purpose of the analysis of the corrosion processes in this pipeline.

The presence of a device providing the cathodic protection in the pipeline is taken into account. The basis of this approach is the use of the methods of the theory of equivalent electric circuits and the theory of the electromagnetic field and their computer implementation in the Matlab/Simulink and COMSOL Multiphysics packages, respectively. According to this approach, at the first stage, the spatial distribution of the induced electric field of the overhead power line, which varies with a frequency of 50 Hz, is calculated in the soil directly at the location of the pipeline. At the second stage, electrical processes in the pipeline are calculated on the basis of these data, additionally including a constant voltage source simulating cathodic protection processes, and on the basis of the Simulink model built.

The calculation of the processes in the steel insulated pipeline laid in the soil at a depth of 1.2 m, 7 km long and crossing the space under the 330 kV overhead line at an angle of 45° was carried out. It was shown that in this case it is important to take into account both the amplitude and the phase of the induced electric field in the pipeline. The distribution along the pipeline of both constant and alternating voltage relative to the soil is given. To analyse the corrosion processes in the pipeline based on these data, the paper considers two criteria for the relatively safe flow of corrosion processes in the pipeline with the simultaneous flow of both alternating and direct currents. Based on the results of the calculations, it was established that both criteria are not met in some sections of the pipeline under investigation. Several methods are proposed to reduce the induced electric field in the pipeline to a safe level.

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Моделювання режимів роботи комплексу катодного захисту трубопроводів при переході повітряних ліній електропередач

О. О. Азюковський[1], *Ю. А. Папаїка*[*1], *О. Д. Подольцев*[2], *М. В. Бабенко*[1], *С. К. Шихов*[1]

1 – Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна

2 – Інститут Електродинаміки Національної академії наук України, м. Київ, Україна

[*] Автор-кореспондент e-mail: papaika.yu.a@nmu.one

Мета. Встановити залежності рівнів вихідного потенціалу системи захисту підземних сталевих трубопроводів при наближенні та/або переході траси повітряних ліній електропередачі (ЛЕП).

Методика. Для досягнення мети використані методи теорії еквівалентних електричних кіл і теорії електромагнітного поля, реалізовані в пакетах прикладних комп'ютерних програм Matlab/Simulink і COMSOL Multiphysics.

Результати. Визначено просторовий розподіл у ґрунті наведеного електричного поля повітряної лінії електропередачі в місці безпосереднього розташування трубопроводу, що змінюється із частотою 50 Гц. Наведено розподіл як постійної, так і змінної напруги на трубопроводі відносно ґрунту. Проведено аналіз корозійних процесів у трубопроводі, на підставі якого досліджено відносно безпечний перебіг корозійних процесів у трубопроводі під дією одночасно виникаючих змінного струму частотою 50 Гц і постійного струму.

Наукова новизна. Полягає у визначенні закономірностей впливу повітряних ліній на характер розподілу захисного потенціалу станцій катодного захисту при змінах конфігурації трубопроводів та умов прокладання. Доведене існування значних відхилень рівнів захисного потенціалу за наявності змінної полігармонічної складової сигналу. На підставі дослідження встановлено, що за прийнятих вихідних умов обидва запропоновані критерії є незадовільними на окремих ділянках газопроводу поблизу ЛЕП.

Практична значимість. Полягає у визначенні комплексу технічних характеристик електротехнічного комплексу захисту від електрохімічної корозії, що дозволяє забезпечити необхідні рівні захисного потенціалу за наявності джерела блукаючих струмів (повітряних ліній електропередач).

Ключові слова: *підземний сталевий трубопровід, катодний захист, електрохімічна корозія, лінії електропередач*

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