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DETERMINATION OF CORROSION RATE IN PLACES OF INSULATION DAMAGE OF UNDERGROUND PIPELINES

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The electromagnetic method of non-contact current measurements makes it possible to quickly monitor the state of passive (insulating coatings) and active (cathodic polarization) corrosion protection of underground pipelines (UP); detect places of unsatisfactory insulation, determine the transient resistance and its components (resistances of soil, insulating layer, polarization) in different sections, the area of insulation damage, the current distribution of cathodic protection of UP. In combination with contact measurements of direct and alternating voltages, ohmic and polarization potentials, it is possible to determine the polarization resistance and estimate the corrosion rate.

Keywords: *electric currents, potentials, underground pipelines, damage insulation, transition resistance, cathodic protection, corrosion, measuring, diagnostics.*

ВИЗНАЧЕННЯ ШВИДКОСТІ КОРОЗІЇ В МІСЦЯХ ПОШКОДЖЕНЬ ІЗОЛЯЦІЇ ПІДЗЕМНИХ ТРУБОПРОВОДІВ

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Корозія призводить до пошкоджень споруд і є причиною скорочення термінів їх придатності до експлуатації. Електромагнітний метод обстежень підземних трубопроводів (ПТ), що базується на триєдиній математичній моделі електромагнетного поля ПТ та вимірюваннях характеристик просторового розподілу зовнішнього електромагнетного поля, дає нові можливості оперативного визначення кількісних показників стану пасивного (ізоляційних покриттів) і активного (електрохімічного катодною поляризацією) захисту від корозії. Розвиток методів і створення нових засобів безконтактних вимірювань струмів (БВС) дають можливості визначати розподіли перехідного опору "труба–земля", виявляти місця незадовільної ізоляції за критерієм критичного заникання сигналу і оцінювати площу наскрізних пошкоджень ізоляції, визначати розподіл струму установки катодного захисту на різних гілках і ділянках ПТ.

Аналітичні дослідження математичних моделей, числове моделювання і експериментальні дослідження на трасах магістральних трубопроводів дають нові співвідношення між параметрами корозійного стану трубопроводу. Зокрема, корозійні процеси на поверхні металу трубопроводу характеризують поляризаційний потенціал, поляризаційний опір, анодний струм витікання та захисний струм катодної поляризації.

Розглянуто можливості визначення цих параметрів на основі БВС та контактних вимірювань постійних і змінних електричних напруг та омічного і поляризаційного потенціалів для оцінки швидкості корозії ПТ. Описано процедури інтегральних, диференційних та локальних обстежень методом БВС з визначенням параметрів ізоляції на різних ділянках ПТ у комплексі з контактними вимірюваннями електричних напруг і потенціалів та визначенням розподілу густини струму катодного захисту ПТ, перехідного опору трубопроводу і його ізоляційного покриву та поляризаційного опору. Показано можливості оцінювання струму корозії та зменшення швидкості корозії від дії захисного струму поляризації, густину якого визначено за безконтактними вимірами змінної компоненти струму установки катодного захисту і коефіцієнта гармоніки, встановленого за відношенням постійної і змінної напруг у ґрунті поперек траси.

Ключові слова: *електричні струми, потенціали, підземні трубопроводи, пошкодження ізоляції, перехідний опір, катодний захист, корозія, вимірювання, діагностування.*

Introduction. Corrosion causes damage of structures and reduces their service life [1]. The electromagnetic method of survey of underground pipelines (UP), based on the traditions of the mathematical model of the electromagnetic field of the UP and measurements of the characteristics of the spatial distribution of the external electromagnetic (EM) field [2–4], provides new opportunities for operational control of corrosion protection (CP) of the UP [2, 5]. The development of methods and the creation of means of non-contact current measurements (NCM) make it possible to determine the distribution of the transient resistance "pipe-ground" and its components, to identify places and estimate the area of through insulation damage, to determine the distribution of cathodic protection current in different sections of the UP [2, 3, 5–8].

Analytical studies of the mathematical models of the UP, numerical modeling, and experimental studies on the routes of main pipelines [2–8] allowed to establish new relationships between the parameters of the corrosion state of the pipeline. In particular, corrosion processes on the metal surface of the pipeline characterize the polarization resistance and the leakage anode current.

This paper considers the possibility of determining these parameters using non-contact current measurements and contact potential measurements to assess the corrosion rate in the UP.

Non-contact operational observation of the UP. The non-contact method using equipment such as non-contact current meter BIT or NCM [2, 3] determines the location and direction of the UP. As a source of probing current, we use a cathodic protection installation (CPI), which supplies a time-stable rectified pulsating current to the pipeline [1–5]. In the absence of such CPI, it is possible to use the alternator.

For integrated surveys of the zone of CPI action, we measure the currents in all lines and arms of the UP connection to the CPI and in the anode (drainage) wire. According to the largest values of current, we find those UP arms in which the lowest resistance is the "pipe-ground", which is the worst insulation [1–5].

For differential surveys along the route, we measure the depth h_n of the UP occurrence and the amplitude of the alternating current component J_n at the points of the route $n = 0, 1, 2, \ldots$. We record the time of measurements and geographical GPS coordinates of points n. We also determine the distances between them – the intervals of the pipeline length Δl_n.

We determine the current consumption at each interval Δl_n of the length of the pipeline, located in one arm of the zone of the source of probing current action

$$\Delta J_n = J_n - J_{n-1} \text{ , A.} \tag{1}$$

The relative current consumption per unit length of the pipeline (relative linear current leakage density) is determined by the formula:

$$\delta J_n = \frac{\Delta J_n}{J_{nc} \cdot \Delta l_n} \cdot 100 \cdot \text{, \%/m,} \tag{2}$$

where $J_{nc} = (J_n + J_{n-1})/2$ is the average current in the pipeline on the n interval.

The relative linear current flow density δJ_n with sufficient accuracy for practice is equal to the signal attenuation $\alpha_n = (\Delta l_n)^{-1}\ln(J_n/J_{n-1})$ along the UP. It is proportional to the electrical conductivity of insulating coatings and is an indicator of the UP insulation damage: the largest values δJ_n indicate the places of the highest conductivity of the "pipe-ground" resistance, which is the lowest of the protective coatings.

To detect unsatisfactory insulation of the UP we use critical attenuation [2, 3], which is determined by the electromagnetic wave attenuation in the soil and calculated by the formula

$$\delta J_{kr} = 0,2\sqrt{f/\rho_g} \text{ , \%/m,} \tag{3}$$

where f is current frequency, Hz; ρ_g is specific electrical resistance of the soil, (Ω·m).

If the relative flow rate (attenuation) of the current in the pipeline on some interval exceeds the critical value $\delta J_n > \delta J_{kr}$ it can be argued, that the insulation on this n interval of this UP section is unsatisfactory.

The area of the through insulation damage in the UP can be determined by comparing the current loss coefficients α_1 in this area and outside it, α_2 is in the area without damage [2, 7, 8]. The total area of damage on the UP site is estimated by the equivalent area of a circle with a radius a_d :

$$a_d = \frac{m^2(p^2-1)\,l}{Z}\left\{1+\sqrt{1+\frac{4Zt_i}{m^2(p^2-1)\,l}}\right\}, \tag{4}$$

where $m=\frac{\alpha_2}{\alpha_g}$; $p=\frac{\alpha_1}{\alpha_2}$; $\alpha_g=\sqrt{\pi f \mu_0 \sigma_g}$; $Z = 2N(1-m^2)(1-p^2m^2)$; $N = 6 -$ $-\ln(r_p\sqrt{f\sigma_g})$; $r_p = D/2$ is pipe radius; t_i – insulation thickness; $\sigma_g = 1/\rho_g$ – specific electrical conductivity of the soil. Thus, we have $\alpha_1 > \alpha_2$ and $\alpha_2 < \alpha_g$.

Use of NCM for quantitative estimation of parameters of the converter of cathodic protection of the UP is reasonable if the array of data of current measurements is correct. It is obvious that the current in the UP $J(l)$ with a distance from CPI in the zone of its action decreases and increases with the approach to CPI. These changes in $J(l)$ are in fact monotonic. However, in homogeneities of the route or errors of the operator cause NCM errors. These errors lead to a violation of monotony and must be corrected. To correct the data set, we detect and remove gross errors of NCM, apply them to smooth and averaging methods [2, 3].

Contact measurements of direct and alternating voltages and polarization potential. We use the PPM equipment. Then we connect PPM to the UP metal and the copper sulfate reference electrode (RE) installed on the soil surface above the UP, as well as to the auxiliary electrode (AE) installed at a distance $x = (5\ldots8)\,h$ from the UP. Such connections of voltmeters are traditional for contact electrometric UP inspections [1, 2. 5].

Next we measure constant U_{pg} and variable V_{pg} pipe-ground voltages between the metal of the pipe and RE and constant U_{gg} and variable V_{gg} voltages at the same resistance between RE and the AE. The polarization potential (PP) is determined [2, 5] by the formula

$$U_{pol} = U_{pg} - V_{pg}\,U_{gg} / V_{gg} \tag{5}$$

where the second term is the ohmic component of the potential and relation

$$k = V_{gg} / U_{gg} \tag{6}$$

is the measured harmonic coefficient, which is the ratio of the variable to the constant component of the rectified pulsating current that flows at the UP is the measurement site.

Polarization potential U_{pol} (with the removal of the ohmic component) is considered to be the main indicator (criterion) of UP electrochemical corrosion protection [1, 2].

Resistance of the insulating coating (insulation layer with possible pores, defects) in the UP area in low-frequency alternating current can be considered active (its reactive component can be neglected) [2, 5]. Then in operating conditions:

$$R_{in} = V_{in} / j_n \text{ , } \Omega\cdot\text{m}^2. \tag{7}$$

The alternating voltage on the insulating layer V_{in} is found by measuring the alternating voltage V_{pg} between the pipe metal and RE, placed on the soil surface above the UP, and the voltage drop in the soil above V_g

$$V_{in} = V_{pg} - V_g . \quad (8)$$

V_g can be determined by measuring the voltage $V_{gg} = V_x$ on the ground between the RE and AE electrodes, spaced apart x. To do this, use the previously obtained [2, 4] dependence:

$$V_g = V_x \cdot \ln\left(\frac{4h}{D} - 1\right) / \ln\left(\frac{x^2}{h^2} + 1\right). \quad (9)$$

Hence, it is useful to note that the voltage V_g in the soil above the UP will be equal to the voltage $V_{gg} \equiv V_x$ between the RE and AE electrodes on the soil surface $V_g = V_x$ if the distance x between these electrodes is chosen according to

$$x = h\sqrt{2\left(\frac{2h}{D} - 1\right)}. \quad \text{Then} \quad V_g = V_x \equiv V_{gg}. \quad (10)$$

Then instead of (8) we have

$$V_{in} = V_{pg} - V_{gg} . \quad (11)$$

Determination of the current distribution of the UP cathodic protection. According to the measurements of the variable current component of CPI and the harmonic coefficient k, we determine the costs of the direct component ΔI_n of the cathodic protection current in the n-area of the UP [2, 5]:

$$\Delta I_n = \Delta J_n / k_n . \quad (12)$$

Having the diameter D, determine the flow density of the variable j and direct i components of the cathodic protection current in the UP area:

$$j_n = \Delta J_n / s_n \quad \text{and} \quad i_n = \Delta I_n / s_n , \quad (13)$$

where $s_n = \pi D \cdot \Delta l_n$ is the surface area of the controlled UP section; $i_n = j_n / k_n$.

For the current density of cathodic polarization in places of insulation damage in the n-area UP we have:

$$i_{pn} = \Delta J_n / \pi\, a_d^2\, k_n . \quad (14)$$

The transient resistance of the “pipe-ground” in direct current in the UP site is determined by measuring the displacement of the potential difference “pipe-ground” ΔU_{pg} with respect to the current density of the cathodic protection at the site i_n, which caused this displacement:

$$R_{mgn} = \frac{\Delta U_{pg}}{i_n}, \ \Omega \cdot \text{m}^2. \quad (15)$$

Displacements ΔU_{pg} are found by the difference of measurements U_{pg} without polarizing current (natural potential) and in the presence of polarizing current [1].

The transient resistance of the interfacial and insulating layers in direct current in the UP area, similarly to (7)–(11), is determined by the ratio

$$R_{pgin} = U_{in} / i_n , \ \Omega \cdot \text{m}^2, \quad (16)$$

where, in contrast to (8), we must take into account one more component – the polarization potential U_{pol} :

$$U_{in} = U_{pg} - U_{gg} - U_{pol} , \quad (17)$$

while the density of direct current i_n is determined using the results of the NCM device and the harmonic coefficient according to formulas (6), (13).

The obtained value (16) of the transient resistance of the protective coating “metal–soil” in direct current includes both the resistance of the insulating coating R_{in} and the polarization resistance R_{pol} in the studied area. It can be used when calculating the cathodic polarization of the underground pipelines.

The polarization resistance of a unit of the surface for the given UP area on the obtained components of the transition resistance “metal–soil” and the resistance of the insulating layer [2, 5] can be defined as:

$$R_{pol} = R_{pgin} - R_{in} . \quad (18)$$

Taking into account equality (9) and the area of insulation damage (4), we obtain the polarization resistance at the points of contact of the UP metal with the ground.

The obtained values of polarization resistance of the UP can be used to estimate the rate of residual corrosion [1, 2, 9–19] in places of insulation damage in real conditions of the pipelines and associated underground metal structures.

Note that the method described here for determining the polarization resistance (18) can be used in the practice for the UP diagnostics. This method differs from the method of R_{pol} definition proposed in previous works [6, 8] by measuring the attenuations of DC and AC currents in different UP sections. Method (18) has a significant advantage over other methods because it is based on measurements of currents and potentials from the soil surface [5, 18] without UP excavation or probes penetration into its surface.

Corrosion current. The corrosion rate, as is known [8–16], can be estimated by the density of the flowing anode current i_a in places of damaged pipeline insulation. In corrosimetry, the method of polarization resistance is used to determine the corrosion rate, and the correlative Stern–Giri ratio is used

$$i_a = \frac{b_a \cdot b_c}{2.3 R_{pol}(b_a + b_c)} , \quad (19)$$

where b_a, b_c are Tafel constants for anodic and cathodic reactions; R_{pol} are polarization resistance of charge transfer through the double electric layer at the site of the insulation defect.

The polarization resistance can be used to determine the corrosion current density [9–13]

$$i_{cor} = K / R_{pol} , \quad (20)$$

where the coefficient of proportionality K is called the constant of the method of polarization resistance. It is determined by the Tafel constants β_a, β_k; for activation and diffusion control, respectively, we have [10]

$$K_A = \frac{\beta_a \beta_k}{2,3\left(\beta_a + \beta_k\right)} \text{ та } K_Д = \frac{\beta_a}{2,3} . \quad (21)$$

This correlation is the basis of the electrochemical method for determining the corrosion rate – the method of polarization resistance [9].

To determine the coefficient K, the Tafel constants can be calculated theoretically depending on the parameters of the pipeline material and soil electrolyte, potential, operating time, selected from the literature or determined in laboratory experiments [9–12]. In the works by S. Polyakov [13–14] it is proposed to determine a stable method of polarization resistance based on computer analysis of the equations of polarization curves, which are obtained experimentally. A significant advantage of this method is to determine the polarization resistance directly for the conditions of the pipeline.

Corrosion current is a constant value for a certain "metal–environment" system. Under conditions of hydrogen depolarization, we can take $\beta_k = 2\beta_a$ [11, 15], from formulas (20) and (21) we have

$$i_{cor} = \beta_a / 4.6 \cdot R_{pol} \, . \qquad (22)$$

A review of the results of studies by different authors [6, 8, 11, 15] shows that the corrosion rates of different cast irons and steels in the same soil differ little. However, the corrosion rates of steel in different soils differ significantly (may differ 10 fold or more) and according to published data they take the values in the range from i_{cor} = 0.01 A/m^2 to i_{cor}= 0.5 A/m^2.

In the laboratory, the value i_{cor} is determined by weight [4, 10, 11]. The advantage of the method of polarization resistance is that it makes it possible to determine i_{cor} in real operating conditions of the UP [2, 6, 8].

Determination of residual corrosion current. With electrochemical cathodic protection of the underground pipeline, the corrosion current in the sections with damaged insulation is reduced and can be evaluated [12] by the formula

$$i_{cor}^{p} = \frac{K}{R_{pol}} e^{\frac{2{,}3\cdot\Delta E_k}{\beta_a}} \, , \qquad (23)$$

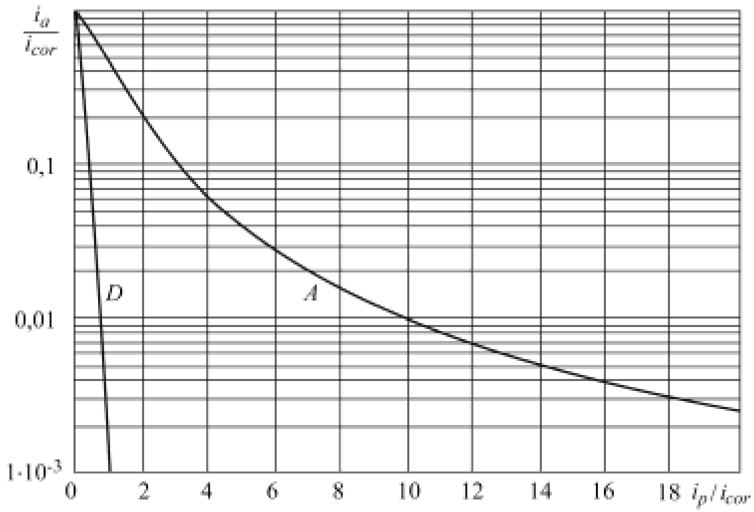
where i_{cor}^{p} is corrosion current density when applying cathodic polarization, it is called residual corrosion [13, 14]; ΔE_k is displacement of the stationary potential of the UP, the values of which are measured by contact methods.

The given value i_{cor}^{p} corresponds to the anode current density i_a when a polarization current i_p is applied to the pipeline, which causes a potential shift; that is $i_{cor}^{p} = i_a$. Anode current density is known to be a major indicator of corrosion [10, 11].

In previous studies [6, 8, 16. 17], using the known equations of electrochemical corrosion, valid under conditions when the metal dissolved from the active state in the absence of concentration polarization, it was shown how the reduction of corrosion current i_{cor} depended on the value of superimposed polarizing current. In this case a relation that shows the dependence of the corrosion inhibition coefficient $\gamma = i_{cor} / i_a$ on the value of the polarization current is obtained. In this case, the anode current density i_a in cathodic polarization decreases $i_a < i_{cor}$. The obtained dependence is expressed by the ratio

$$\gamma = \left(B - \frac{1}{3B} \frac{i_p}{i_{cor}} \right) \text{, where } B = \sqrt{\frac{1}{2} + \frac{1}{27} \frac{i_p^3}{i_{cor}^3} + \sqrt{\frac{1}{4} + \frac{1}{27} \frac{i_p^3}{i_{cor}^3}}} \, . \qquad (24)$$

From this solution, for a given ratio $A = i_p / i_{cor}$ the minimum value of the braking coefficient is calculated [6, 8, 17]. As can be seen from the calculations [6] performed by formulas (24) (Fig. curve A), if values i_p is commensurate with i_{cor}, the decrease in corrosion rate i_a under these conditions is insignificant. But for values i_p with the greater order of magnitude, corrosion can be reduced by two orders of magnitude [6, 16]. The obtained formulas also make it possible to calculate the value of the maximum required density of the protective current of the pipeline polarization depending on the soil, if the value i_{cor} is known (the range of it changes and the possibilities of determining for specific conditions is shown above).



Reduction of corrosion rate i_a from polarizing current i_p of the UP during diffusion (*D*) and activation (*A*) control.

Note, that in cases where the corrosion rate is determined by the limiting current of oxygen reduction (i.e. in diffusion control) between the degree of protection $P = 1 - 1/\gamma$ and current density, there is a direct proportionality [8, 16].

To determine the residual corrosion current i_a it is necessary to know the density of the polarization current i_p at the places of insulation damage of the UP. Non-contact methods for measuring the distribution of the external magnetic field over the route of the pipeline determine the leakage (inflow) of alternating current ΔJ in the section of the pipeline. The consumption of the direct component of the current ΔI (which is the polarizing current) in this area is found using the harmonic coefficients *k*, in this case $\Delta I = \Delta J/k$. The polarization resistance R_{pol} is determined by formula (18).

CONCLUSIONS

The obtained researche results give the chance to formulate the order of estimation of the parameters of the underground pipeline corrosion.

Non-contact measurements of the characteristics of the magnetic field on the UP rout and determination of current distribution give information about the condition of insulating coatings of the UP, places of insulation damage, the current distribution of cathodic protection, and the most probable places of corrosion.

Investigation of the dependences of the spatial and temporal characteristics of the electromagnetic field on the UP parameters makes it possible to determine the parameters of corrosion protection and corrosion condition. By distribution along the UP the time-varying and direct current components of the cathodic protection installation, it is possible to determine the components of the pipe-ground transition resistance, polarization resistance, estimate the area of insulation damage in the pipeline section and reduce corrosion rate between the known corrosion current and defined polarization potential, polarization resistance, and polarizing current density.

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