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Research of the location of grounding conductors of electrical protection systems

Abstract.*In the article, based on the derived equations for the smooth distribution of the flowing current along the ground electrodes of electrical protection systems, a method is proposed for calculating the service life and the permissible current load on it, which, unlike conventional calculations, does not lead to an overestimation or underestimation of the service life and the permissible load current and takes into account the method of connection cable to the ground electrode.*

Streszczenie. *W artykule, w oparciu o wyprowadzone równania na płynny rozkład przepływającego prądu wzdłuż elektrod uziemiających systemów zabezpieczeń elektrycznych, zaproponowano metodę obliczania trwałości użytkowej i dopuszczalnego na niej obciążenia prądowego, która w odróżnieniu od konwencjonalnych obliczeń , nie prowadzi do zawyżenia lub zaniżenia trwałości użytkowej i dopuszczalnego prądu obciążenia oraz uwzględnia sposób podłączenia przewodu do elektrody uziemiającej. (****Badania lokalizacji przewodów uziemiających w układach zabezpieczeń elektrycznych****)*

Key words: electrical protection, grounding conductors, flowing current density, soil resistance.
Słowa kluczowe: ochrona elektryczna, przewody uziemiające, gęstość prądu płynącego, rezystancja gruntu.

Introduction

The continuing rapid growth in the length of main and distribution oil and gas pipelines operating in zones influenced by stray currents puts one of the first places on the further development of electrical protection issues as one of the economical and promising methods.

Electrical protection measures include preserving underground metal pipelines using electrical drains, cathode installations, protectors, etc.

One of the main and important components of electrical protection against stray currents are grounding electrodes, which create a closed circuit through which current flows from the positive pole of the current source to the grounding electrode. Therefore, the choice of its design and type is largely determined by the technical and economic performance indicators of electrical protection installations. Power losses in grounding account for about 70% of the total losses [1-10].

Principles for calculating the draining current of grounding conductors.

When calculating the service life T and permissible current load Id of anode grounding systems of electrical protection systems of underground metal structures, certain simplifying assumptions are used. Thus, for ground electrodes located in homogeneous soil or in one of the horizontal layers of layered soil [1], it is assumed that the density of the flowing current j (″leakage current), including the dissolution current of the ground electrode, is the same along its entire length. This assumption is true in many cases [2].

For vertical grounding conductors crossing the interface between layers of layered soil [8], it is assumed that the current density j_i in each i-th layer along the length of the corresponding part i of the grounding conductor is constant and inversely proportional to the resistivity ρ_i of the soil in this layer, $j_i \sim \rho_i^{-1}$ [3]. This assumption was also used when calculating the current spreading resistance R of such grounding electrodes in two-layer soil using the method of induced potentials, as well as when estimating the service life and permissible current load, taking into account the primary and temporary redistribution of current between the upper and lower parts of the grounding electrode due to the effect of mutual influence (shielding). However, the validity of the above relationship is questioned by the well-known grounding equation for the distribution of the flowing current along the length in homogeneous soil, which shows that the dependence of the density of the flowing current on the resistivity of the soil is much weaker than the inverse proportionality, or is completely absent.

In addition, it is usually implicitly assumed that the method of connecting the cable to the ground electrode does not affect the service life and permissible current load values. However, preliminary estimates have already shown that they may depend on how the current is supplied - to one end of the ground electrode, to both, or between them. Such connections are further designated for brevity as one - , two - and end-to-end [7].

Ground electrode located in homogeneous soil.

With a single-end supply of current I_0 at point x=0 of a grounding electrode of length l, the current distribution along it is described by the equation

(1) $$I(x) = I_0 \frac{sh[\alpha(l-x)]}{sh(\alpha l)},$$

where: α- is the current propagation coefficient, determined in the general case by the expression [5].

(2) $$\alpha = \sqrt{r/lR} = \sqrt{\rho_a/SlR},$$

where: r - is the longitudinal resistance of the ground electrode per unit length, ρ_a is the resistivity of the anode material, S- is its cross-sectional area.

The density of the flowing current is equal to the derivative of the function I(x).

Further, to simplify the notation and presentation, by the value j we will understand the modulus of the relative linear density of the flowing current [6,7,8]:

(3) $$j(x) = \frac{1}{I_0}\left|\frac{dI(x)}{dx}\right| = \alpha\frac{ch[\alpha(l-x)]}{sh(\alpha l)}.$$

At I_0=1 the value of j is equal to the linear density of the flowing current. For αl <<1, expansion of (1) and (3) into Maclaurin series gives, respectively,

(4) $I(x)=1-x/l$,
(5) $j = l^{-1}$.

Expression (5) is the justification for the mentioned assumption about the constancy of the rate of dissolution of the ground electrode along its length. However, in the aspect considered here, it is also remarkable in that it shows the independence of j at small αl from the characteristics of the ground electrode (ρ_a, S), soil (ρ) and the location of the ground electrode in the ground (vertical or horizontal; from certain depths - distances t from the surface land).

Counting the second coordinate y from the end x=l, it is easy to verify that when a current of $0,5I_0$ is supplied to each end of the ground electrode, the current distribution along its length has the form$I(x,y) = \frac{0.5I_0}{sh(\alpha l)1}\{sh[\alpha(l-x)] + sh[\alpha(l-y)]\}$

Differentiating (6) with respect to x, y and then replacing the variables (y = -x), for the distribution of current j we obtain the expression

(6) $$j(x) = \frac{0.5\alpha}{sh(\alpha l)}\{ch[\alpha(l-x)] + ch(\alpha x)\}.$$

It is useful to introduce a correction (for calculations of T and I_d) coefficient of uneven dissolution of the ground electrode k_n, defining k_n as the ratio of the highest current j to the value accepted under the assumption of uniform current distribution (equation (5)). In many special situations k_n=1, but in the general case, when the inequality αl <<1 is not necessarily satisfied, the introduction of k_n allows you to calculate T and Id based on the dissolution rate that occurs in the most dangerous zones of the ground electrode - at the cable connection points [1].

Using equations (3) and (7), we can verify that with a single-end supply of current I_0 (at point x=0) and two-end supply of currents $0.5I_0$ (at points x=0 and y=), the value of k_n is determined accordingly by the equations

(8) $$k_{n1}=\alpha l/cth(\alpha l),$$

(9) $$k_{n12}=\frac{\alpha l}{2sh(\alpha l)}[ch(\alpha l) + 1],$$

that is, with a known α, the value of k_n is easily calculated. This allows you to calculate the permissible amount of electricity Q_d using a simple formula

(10) $$Q_d = I_d T = \frac{\varepsilon M}{E_c k_n},$$

where: ε-is the safety factor, M is the mass of the ground electrode, E_c is the empirical average (in the operating range of current densities) current consumption of the ground electrode material. Equation (9) differs from the usually used one in the presence of the coefficient kn in the denominator and becomes normal when k_n =1.

The dependences of the coefficients k_n on αl (Fig.1) show that in all cases $k_{n12}<k_{n1}$, i.e. a two-ended cable connection provides a more uniform distribution of the flowing current than a single-ended one.

With increasing αl, both coefficients increase. However, taking into account the low accuracy of the experimental determination of E_C and the values of ρ and ρ_a that affect α, it is unlikely that serious importance should be given to an increase in k_n by less than 10-12%. It can be accepted that k_{n1} should be taken into account at αl ≥ 0.55, and k_{n12} – at αl ≥ 1.25 (Fig. 1) [1,5].

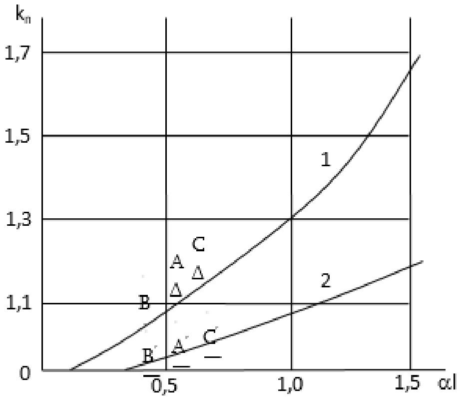

Fig.1. The influence of αl on the correction factors k_{n1} (1) and k_{n12} (2) in homogeneous soil.

In connection with this, it is advisable to assess how realistic such values of αl are. Table 1 shows the values of α and αl for some real (or similar) anode grounding conductors in soils with different resistivities [13].

For the purpose of simplification, we considered vertical non-buried (t=0) cylindrical solid or tubular ground electrodes, for which from equation (2) and the known equations for R it follows, respectively

(11) $$\alpha = \frac{2.83}{d_o}\sqrt{\frac{\rho_a}{\rho} ln^{-1}(\frac{4l}{d_o})};$$

(12) $$\alpha = 2.83\sqrt{\frac{1}{(d_o^2-d_i^2)}\frac{\rho_a}{\rho} ln^{-1}(\frac{4l}{d_o})}.$$

where: d_0 - is the outer diameter of the ground electrode, d_i - is the internal diameter of the tubular ground electrode. As can be seen from Table 1, in high-resistivity soil (ρ=200 Ω·m) the values of αl are in the range ≈3x10-3...4x10-1, i.e. and with a single-end current supply, the distribution of its flow is almost uniform (k_{n1}≈1) [10].

In soil of average resistance (ρ=20 Ω·m), the same applies to all anode grounding electrodes made of steel pipes, carbon-graphite anodes with l ≤12 m and ferrosilide №9-11. If the current supply is two-terminal, then the group in which the uneven distribution of j should be taken into account includes only grounding conductors № 8 and 13 with ρ = 20 Ω·m, and with ρ = 2 Ω·m - also №10-12. For example, for anode №11 in low-resistivity soil, the values of k_{n1} and k_{n12} are 1.8 and 1.23, i.e. the usual calculation method, allowing k_n=1, gives a value of T (or I_d) that is overestimated by 45 and 19%, respectively [11].

Thus, the two-terminal connection expands the standard-size range of anode grounding conductors and soil resistances, where the uneven distribution of the flowing current can be neglected. It is also clear that this unevenness should most adversely affect the values of T or I_d of long anodes with relatively high ρ_a (EGT, ferrosilide), installed in low-resistivity soils and connected to the cable at only one end.

Table 1. Values of α and αl of some grounding conductors in homogeneous soils with different resistivities.

Number ground electrode	Anode material and shape	d_o	d_i	l	ρ_a, Ω·m	ρ_a, Ω·m					
		m				2		20		200	
						α, m^{-1}	αl	α, m^{-1}	αl	α, m^{-1}	αl
1	Steel, pipe	0,15	0,138	6	$1x10^{-7}$	$4.8x10^{-3}$	$2.9x10^{-2}$	$1.52x10^{-3}$	$9.2x10^{-3}$	$4.8x10^{-4}$	$2.9x10^{-3}$
2				12		$4.5x10^{-3}$	$5.8x10^{-2}$	$1.42x10^{-3}$	$1.7x10^{-2}$	$4.5x10^{-4}$	$5.8x10^{-3}$
3				60		$4x10^{-3}$	0.24	$1.26x10^{-3}$	$7.6x10^{-2}$	$4x10^{-4}$	$2.4x10^{-2}$
4				100		$3.83x10^{-3}$	0.383	$1.21x10^{-3}$	0.121	$3.83x10^{-4}$	$3.83x10^{-2}$
5	Carbon graphite (EGT), Kernel	0,11	-	3	$2.22x10^{-5}$	$8.7x10^{-2}$	0.26	$2.75x10^{-2}$	$8.2x10^{-2}$	$8.7x10^{-3}$	$2.6x10^{-2}$
6				6		$8.13x10^{-2}$	0.49	$2.6x10^{-2}$	0.155	$8.2x10^{-3}$	$5.1x10^{-2}$
7				12		$7.65x10^{-2}$	0.92	$2.4x10^{-2}$	0.29	$7.6x10^{-3}$	$9.2x10^{-2}$
8				60		$6.8x10^{-3}$	4.08	$2.15x10^{-2}$	1.29	$6.8x10^{-3}$	0.408
9	Ferrosilide, kernel	0,05	-	7	$6.3x10^{-5}$	0.126	0.88	$4x10^{-2}$	0.278	$1.26x10^{-2}$	$8.8x10^{-2}$
10		0,10		14		0.12	1.656	$3.18x10^{-2}$	0.524	$1.2x10^{-2}$	0.166
11				28		$6x10^{-2}$	1.68	$1.9x10^{-2}$	0.53	$6x10^{-3}$	0.168
12				60		$5.7x10^{-2}$	3.42	$1.8x10^{-2}$	1.08	$5.7x10^{-3}$	0.34
13		0,05		50		-	-	$3.48x10^{-2}$	1.744	-	-

Grounding conductor located in one of the layers of two-layer soil.

If the grounding conductors are located entirely in one of the layers of a two-layer soil, to calculate α using equation (2), the values of R found from the corresponding Burgsdorff equations should be used. Under this condition, the ground electrode can be considered as located in homogeneous soil and used to calculate j(x) of equation (1).

Due to the relative complexity of the design equations for the end-to-end cable connection, let us compare this method with those discussed above using the specific example of Fig.2, which shows the distribution of the flow of the same total current (I_0) along the length of the ground electrode [5] in all three cases of supply. As you can see, the maximum values of j (and, naturally, k_n) for inter-, one- and two-end cable connections are respectively 1.462: 1.141:1.000. Qualitatively the same picture was obtained in other cases. Thus, the most uneven distribution of the flowing current is created with an end-to-end connection.

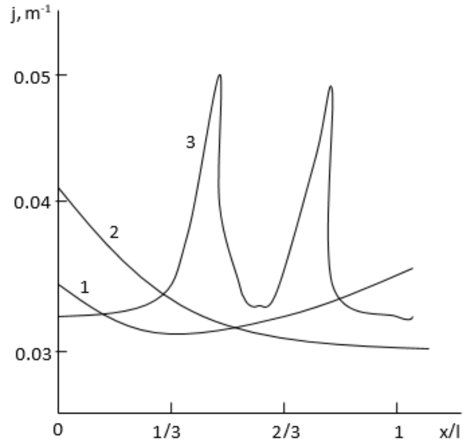

Fig.2. Dependence of the relative linear density of the flowing current j on x/l for two-end (1), single-end (2) and (3) inter-end connection of the cable to the ground electrode in homogeneous soil.

In view of the fairly widespread use of coke coating of anode grounding electrodes, it seemed useful to evaluate its effect on current distribution. A corresponding correct estimate is possible with a known specific resistance of the sprinkling ρ_0. In this case, for a ground electrode with a sprinkling of diameter d_0, under the usual assumption $\rho_0 << \rho$, the longitudinal resistance per unit length r, included in equation (2), for example, for a tubular anode, is equal to [11,12,13]

$$r = \frac{1.274\rho_a\rho_0}{\rho_a(d_0{}^2 - d_{ou}^2) + \rho_0(d_{ou}^2 - d_i^2)}. \tag{13}$$

In the design equation for R included in equation (2), d_0 should be substituted instead of d_{outer}, and in equation (8) for Q_d – the value of E_c for the ground electrode with sprinkling. We have not encountered the value ρ_0 in the literature.

Therefore, a quantitative assessment was carried out for anodes №1-6 of Table 1 with d_0=0.35m, ρ=20 Ω·m and the assumption that ρ_0 is 10 times greater than for solid carbon graphite, i.e. equals 2.2x10-4 Ω·m. As could be expected, for a steel grounding conductor (№ 2), for which this value is two orders of magnitude greater than ρ_a, sprinkling increases αl, but only slightly – from 0.017 to 0.018, negligibly increasing the values of k_{n1} and k_{n12}, in both cases differing from one only [5,8.9] in the third and fourth decimal places. Consequently, in this case, sprinkling is useful only from the point of view of reducing the current consumption of grounding material. In all other cases, sprinkling reduced αl. Although this decrease was significant (by 47-89%); k_{n1} without sprinkling exceeded 1.1 only for anodes №12 and 13 – 1.36 and 1.85, respectively. Sprinkling reduced these values to 1.105 and 1.011, i.e. ensured an almost uniform distribution of j(x). For ground electrode №12 without sprinkling, the k_{n12} value was 1.026, i.e. we can say that in this case, uniform dissolution can be ensured either by sprinkling or by connecting the cable at two ends. For ground electrode №13, the values of k_{n12} without sprinkling were 1.24, with sprinkling -1.003, i.e. even with a double-ended cable connection, its equalizing effect was useful. Thus, with the accepted value of ρ_0, sprinkling in some cases can improve the uniformity of dissolution of ferrosilide anode grounding conductors. A decrease or increase in real ρ_0 against this value, respectively, improves or worsens the leveling effect of the sprinkling.If ρ_0 is unknown, then in two situations an approximate estimate is sufficient, taking into account the influence of the sprinkling only on the value of E_c. So, if (as in some of the examples given) for carbon-graphite and ferrosilide anodes αl in the absence of sprinkling does not exceed 0.55 for a single-end connection and 1.25 for a double-end connection, then the improvement in the distribution of the flowing current by sprinkling practically does not matter. In the case of steel or cast iron grounding conductors ($\rho_a \leq 10\text{-}5\ \Omega \cdot m$), the relation $\rho_a \ll \rho_0$ is satisfied [7,9,10]. And if d_0 and d_i are quantities of approximately the same order, then the first product in the denominator of the right-hand side of equation (8) can be neglected, and it takes the same form as in the absence of sprinkling:

$$r = \frac{1.274\rho_a}{d_o^2 - d_i^2}. \qquad (14)$$

In homogeneous soil, the usual calculation can overestimate, and for vertical grounding conductors crossing the interface between layers of two-layer soil, it can significantly underestimate or overestimate T or I_d. It is shown that it is advisable to calculate these quantities using the same simple formula (9) for all cases, which includes the coefficient k_n, determined by the value of j in the most dangerous zone of the ground electrode - at the cable connection point [13].

Conclusions

The applied methods for calculating the service life T and permissible current load I_d of grounding conductors of electrical protection systems of underground metal structures are critically analyzed. It is shown that the distribution of the flowing current j(x) along the length (x) of the ground electrode is influenced by the method of connecting the cable. The distributions j(x) are derived for a two-terminal cable connection to a ground electrode located in homogeneous soil or in a homogeneous layer of soil.

The main parameter that determines j(x) is the uneven resistance of the soil, the product αl of the coefficient of propagation (spreading) of the current α in the soil along the length of the grounding rod l (or its section in the soil space). The specified limit values αl, above which legality is taken into account, are usually allowed for uniform distribution of the flowing current along the length of the ground electrode or its section away from the ground. It is shown that for small αl (at least ≤0.55), a vertical ground electrode crossing the interface between layers of a two-layer soil can be considered as advancing in soil obstacles.

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