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IMPROVEMENT OF SAFETY OF AUTONOMOUS ELECTRICAL INSTALLATIONS BY IMPLEMENTING A METHOD FOR CALCULATING THE ELECTROLYTIC GROUNDING ELECTRODES PARAMETERS

P. Budanov
PhD, Associate Professor*
E-mail: pavelfeofanovich@ukr.net
K. Brovko
PhD
Department of integrated electric technologies and processes
Kharkiv Petro Vasylenko
National Technical University of Agriculture
Artyoma str., 44, Kharkiv, Ukraine, 61002
E-mail: brovkokonstantin@gmail.com
A. Cherniuk
PhD, Associate Professor*
E-mail: archer.uipa@gmail.com
I. Pantielieieva
PhD, Associate Professor*
Yu. Oliynyk
PhD*
N. Shmatko
PhD, Associate Professor
Department of Production Organization
and Personnel Management
National Technical University «Kharkiv Polytechnic Institute»
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
P. Vasyuchenko
PhD, Associate Professor
LLC "Energetic"
Kharkivskykh Dyviziy str., 14, Kharkiv, Ukraine, 61091
*Department of Physics, Electrical Engineering
and Power Engineering
Ukrainian Engineering Pedagogics Academy
Universitetskaya str., 16, Kharkiv, Ukraine, 61003

Вирішено проблему підвищення безпеки в процесі заземлення автономних пересувних електроустановок. Розглянуто і досліджено існуючі методики розрахунку нормованого опору заземлювачів електроустановок. Виявлено їх основні недоліки: складність і громіздкість в обчисленнях; імовірнісний і приблизний характер; використання вихідних даних прийнятих для обчислення електрофізичних параметрів стаціонарних заземлювачів; не враховуються в розрахунках структурно-фазові будови грунту і об'єм електроліту. На основі застосування теорії перколяції і апарату фрактально-кластерної геометрії, змодельовано процес електролітичного заземлення в неоднорідних грунтах різної пористої структури, які володіють перколяційними і фрактальними властивостями. Розроблено фізичну модель процесу електролітичного заземлення, яка враховує властивості структури грунту при зміні фрактальної розмірності кластера в певному інтервалі, що утворює електролітичний заземлювач з нормованим опором. Показано, що модель провідності електролітичного заземлювача визначається електропровідністю грунту в перколяційних каналах пористої структури грунту і може розглядатися як функції від об'ємної концентрації електроліту і розміру об'ємної структури електролітичного кластера перколяції. Отримано аналітичні вирази для зв'язку нормованого опору електролітичних заземлювачів і питомого опору грунту з фрактальною розмірністю, об'ємом електроліту, кількістю пір з електролітом, щільністю геометричного об'ємного тіла. Удосконалено метод розрахунку електрофізичних параметрів електролітичних заземлювачів, на основі врахування головного лінійного розміру кластера електролітичного об'ємного тіла, який збігається з глибиною проникнення електроліту для різних структур грунту. Визначено умови провідності електролітичного заземлювача для забезпечення безпеки при експлуатації автономної пересувної електроустановки.

Ключові слова: процес заземлення, електролітичні заземлювачі, перколяційні і фрактальні властивості, нормоване опір

1. Introduction

In accordance with the rules of operation of electrical installations, one of the main requirements in terms of safety is the grounding of conductive part that is in electrical contact with the ground, either directly or through an intermediate conductive medium of the structure of different soils.

To prevent electric shock, conductive parts of electrical installations and equipment must be earthed in order to avoid a possibility of the occurrence of voltage on them, which represents a danger to humans, under all operational modes of the electrical installation.

These requirements are especially relevant for mobile autonomous electrical installations (MAEI) due to the absence of a stationary protective grounding and their work on soils (clay, rocky, sandy) with a different soil structure (DSS).

Calculation of grounding systems is a complex engineering and scientific task, since it is based on source data that are probabilistic in nature, and implies taking into consideration a large number of factors affecting the result. In this case, an error in calculations reaches 20...50 %, and in some cases the estimated values are different from actual data by orders of magnitude.

One of the basic parameters that determines the normalized resistance of a grounding device (NRGD) is the integral indicator of soil properties – the specific resistance of soil (SRS) [1]. This indicator can be determined with a reasonable accuracy only for a specific grounding site, based on the results of multiple measurements, covering all characteristic climatic and weather seasons over time. For MAEI, the application of such a method for determining SRS is impractical.

There are a number of methods and procedures of calculation (PC) and grounding techniques for MAEI [2], which imply intentional local modification of SRS parameter. However, PC to determine NRGD for electrolytic grounding (ELG) are based on the classical calculation methods for stationary grounding electrodes and do not take into consideration the features that are characteristic of EG.

Existing PC of NRGD [3] consider soil structure as a pseudo-homogeneous structure with layered variations of large scale, or as a medium with parameters that change gradually in the specified direction. All the properties of the soil structure, predetermined by its heterogeneity, are expressed in calculation formulae by characteristic empirical coefficients whose magnitudes of values could be within a few orders of magnitude.

During operation of EG systems there is the deliberate formation of a certain structure and properties of soil at the site of grounding. There is a need to solve the inverse problem, that is, not determining the actual SRS but rather determining the conditions necessary for the formation of the structure and properties of soil which would provide for acceptable SRS. However, existing calculation procedures [4] do not take into consideration changes in the geometrical size of the soil's structure at the electrolyte flow.

Therefore, geometrical data on the size of ELG, immersed in soil, and SRS at the site of grounding cannot be applied to calculate NRGD because they are formed during operation of ELG systems [5]. Consequently, determining the electrophysical parameters of ELG for MAEI requires the improved PC, built on the model that would take into consideration the geometrical and structural-phase characteristics of the system soil–electrolyte, which is a relevant scientific-practical task.

2. Literature review and problem statement

Modern methods of ELG calculation are based on the use of the geometrical size of grounding electrodes and averaged tabular values for SRS known in advance [6]. To calculate the normalized resistance of electrolytic grounding electrodes (NREG), the use of such PC predetermines considerable errors. The formation of an electrolytic body in the structure of soil is random in nature and its form is uncertain, while SRS, specified in tables for various soils, depending on a moisture content, differs by several orders of magnitude [7].

Depending on the design characteristics of grounding devices (GD), there are several PC of their parameters as well as diagnosing techniques [8]. A characteristic feature of ELG is the progress of electro-physical phenomena in multiphase porous media. The structural elements of soil are characterized by the volume of natural electrolyte, which it contains, and the electrolyte, introduced purposefully, and the proportion of the unfilled pore volume of space [9].

Electrophysical processes in porous media have their own characteristics, and require a separate approach to their theoretical description. The closest to the physical essence of the process of ELG are the porous media spreading electric current in the electrolyte due to the ionic conductivity of the latter [10].

Simulation of electrophysical processes in porous media should consider both the structural-phase characteristics of a medium and the current spreading processes, accompanied by the transfer of matter [11].

Thus, the existing and applied modeling methods [12] of the process of conductivity of medium of porous structures for different soils do not take into consideration the structural-phase changes during operation. They aim to define the relation between input and output parameters of the structure in general. Such an approach does not elucidate the mechanism of forming conductivity by changes in the structural-phase parameters of ELG for MAEI [13].

There are several techniques for grounding the electrical installations [14], which imply a local change in the parameter (treating soil with salts, electrolytic grounding, etc.). However, PC for determining NREG are based on classic PC for stationary grounding electrodes and ignore the features that are characteristic of ELG.

Applying known PC to the estimation of NREG [15], developed for stationary grounding electrodes, is not possible. Specific resistance of soil is not a reference magnitude; it is built deliberately in the form of a volumetric body, formed by the electrolyte impregnating the soil. In this case, the estimation problem should address the issue on the electrolyte volume required to achieve NREG in soil with known characteristics [16].

Consequently, the calculation and determining of the electrophysical parameters (SRS) by employing existing PC [17] for ELG, is probabilistic in nature, or very close to it, which significantly affects the operational reliability of autonomous mobile electrical installations. In this regard, the problem has been set to construct new physical models of ELG process, which would consider both the geometrical and structural-phase characteristics of the system "soil – electrolyte" and the electrophysical parameters of a porous medium in various soils.

Thus, our analysis of the scientific, technical, and special literature [18] aimed to study processes in the porous structures of a heterogeneous soil medium allows us to apply the apparatus of percolation theory and fractal geometry. These theories have defined the research methods to explore the properties of an electrolytic volumetric body.

3. The aim and objectives of the study

The aim of this study is to improve the method for calculating the magnitude of the normalized resistance of electrolytic grounding electrodes for electrolytic grounding employing the apparatus of fractal-cluster geometry in order to ensure meeting safety requirements during operation of mobile electrical installations.

To accomplish the aim, the following tasks have been set:

– to perform an analysis of the physical processes at ELG and to build a physical model of ELG conductivity in porous soils with a different structure;

– to improve PC of electrophysical parameters for ELG, based on the accounting for the structural-phase characteristics of different soil structures and their percolation and fractal properties;

– to carry out experimental study into determining a dependence of the ELG electrophysical parameters on structural-phase characteristics of the porous structure of soils with a different structure and volume of electrolyte.

4. Improvement of safety of autonomous sources of electricity employing a method for the calculation of parameters of electrolytic grounding electrodes

4. 1. Modeling the process of electrolytic grounding based on the theory of percolation and the apparatus of fractal geometry

In order to consider and model the processes of electrolytic grounding under conditions of the electrolyte flow through the porous structure of a heterogeneous medium, we have applied the theory of percolation and the apparatus of fractal-cluster geometry. As is known, the main current conductor in the soil structure is the electrolyte, which possesses ionic conductivity. The larger its volume in the soil the less its specific resistivity ρ. Hence, for a heterogeneous soil medium there are certain optimal values for the volumetric electrolyte concentration V_c, that is $V_{c\ \min}>V_c>V_{c\ \max}$, at which specific soil resistance ρ reaches a minimum, and the soil electrical conductivity σ – a maximum. The heterogeneous soil medium is a porous volumetric structure that contains a sufficient number of voids whose characteristic size l_{por} is small in comparison with the typical size of a volumetric body $L_{V\text{т}}$.

In addition, pores in the heterogeneous soil medium can be communicating or not communicating (dead-point). Part of the pores' space, which are connected via porous channels, is the effective pore space of the structure of a heterogeneous soil medium (Fig. 1).

For the electrolyte molecules in the porous structure of a heterogeneous soil medium, the process of the formation of ion channels of conductance from the dielectric to the conducting phase of soil is based on the phase transitions of percolation. The process of the formation of current conductive paths implies the formation of a percolation cluster (Fig. 2).

The electrolyte, in line with the percolation theory, when flowing through the structure of soil, fills the pores thereby forming at least a single current conducting percolation path that connects a layer of soil-dielectric and soil-conductor (Fig. 2).

Knowing the critical concentration x_{ot}, below which there is no flow, has important practical significance in the percolation theory when modeling physical processes of the electrolyte transfer.

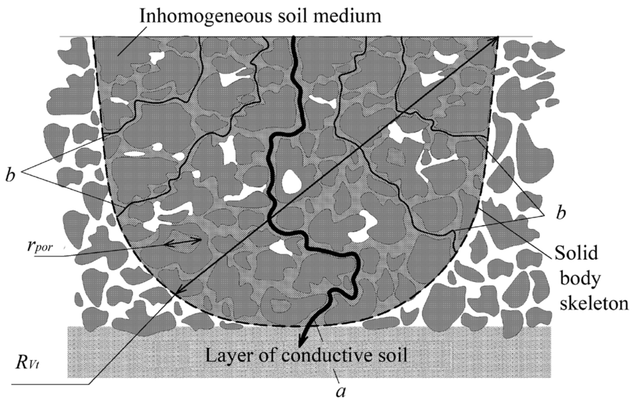


Fig. 1. Porous structure of inhomogeneous soil: *a* – interconnecting pores; *b* – dead-end pores

For a volumetric electrolytic body, in which the number of pores is very large, there is a critical reliability x_{ot}, which equals the threshold of the flow x_c and is derived from expression (1):

$$x_{ot}=x_c=\frac{N_{por.el}}{N_0}=\lim_{N_0\to\infty}x_c\left(N_0\right), \quad (1)$$

where $N_{por.rl.}=\left(\frac{L_{kl}}{r_{0por}}\right)^{d_f}$ is the number of conductive pores in the volume of an electrolytic soil body; L_{kl} is the cluster size; r_{0por} is the radius of the middle pore; d_f is the fractal dimensionality; N_0 is the total number of pores in the volume of an electrolytic body in soil.

Based on the above reasoning, it follows that when $x_{ot}=0$ the structure of a volumetric electrolytic body is not conductive, and at $x_{ob.el.t}=1$ is unambiguously conductive. Hence it follows that there is a critical reliability or a percolation threshold $x_{ot}=x_c$ in the interval over which there is a transition of the porous structure of a heterogeneous soil medium from the dielectric to conductive phase (Fig. 2).

Thus, expression (1) is the primary assertion of the percolation theory and the percolation threshold is a constant magnitude x_c=const for the structure of a volumetric electrolytic body and the dimensionality of its space.

In order to construct a percolation model of conductivity of the electrolytic volumetric structure, we employed the apparatus of percolation theory, where the conductivity of a stochastic two-phase system is defined by probability $P(x_{ob.el.t})$. A pore, randomly filled with the electrolyte, belongs to the infinite connecting percolation cluster R_k, as shown in expression (2):

$$P\left(x_{ob.el.t}\right)=\lim_{N_0\to\infty}\frac{N_{por}\cdot x_{por}}{N_0}, \quad (2)$$

where $\frac{N_{por.BK}}{N_0}=R_k$ N_{por} is the number of pores that form a percolation cluster; N_0 is the total number of pores in the volume of an electrolytic body.

Based on the above, and taking into consideration expression (2), soil electrical conductivity in the porous structure of a heterogeneous soil medium can be represented in the general form by expression (3):

$$\sigma=f\left(x_c,R_k\right)\cong f\left(x_c,L_{kl}\right). \quad (3)$$

Based on ratio (3), a model of conductivity of the electrolytic grounding electrode represnets, in the general form, the electrical conductivity conductivity of the percolation channel of soil σ. Electrical conductivity can be considered to be a function of the volumetric concentration of electrolyte x_c and the size of the volumetric structure of electrolytic percolation cluster R_k, which is identical to the size of cluster L_{kl} for spaces of the Euclidian dimensionality $3>d_f>2$.

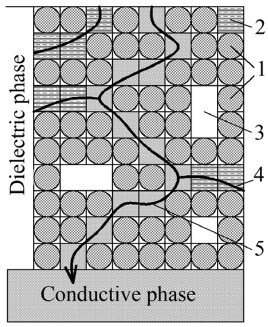


Fig. 2. Schematic of forming a conductive percolation channel when the electrolyte flows through the porous structure of a volumetric body of the heterogeneous soil medium: 1 – solid particles (0.05–1.0 μm); 2 – separate isolated pore filled with electrolyte molecules; 3 – free porous space; 4 – dead channels; 5 – conductive percolation channel

It should be noted that the percolation cluster, formed by the merger of pores filled with the electrolyte molecules, interconnected by the conductive percolation channels (Fig. 3), is, in fact, an example of a random statistical fractal. Therefore, the percolation cluster has fractal properties, that is, it is characterized and defined by the fractal dimensionality d_f (4):

$$d_f = \frac{\ln N_{por}}{\ln n}, \qquad (4)$$

where N_{por} is the number of pores that form a percolation cluster but which have n times smaller spatial scale than the cluster itself, if it is possible to make the original percolation cluster out of them.

Our study has found that fractal dimensionality d_f of the cluster of a volumetric electrolytic body increases by $+\Delta d_f$ in the case of an increase in the probability P_1 of a merger of the pore and cluster (Fig. 3, *a*).

Thus, having determined the value for fractal dimensionality d_f of a percolation cluster, it is possible to determine the probability value P_1 for the merger between pores with the electrolyte molecules and the cluster. Therefore, based on this, it is possible to determine the probability of the formation of percolation channels of conductivity for electrolytic grounding electrodes for various soil structures.

At large size scale $l>R_{kl}$ the system acts as a homogeneous macrosystem, composed of elements the size of R. The properties of these elements are defined by the behavior of the system on the scale of an intermediate asymptotic $l<R_{kl}$, where the geometry of objects is fractal.

Knowing the magnitude of d_f, we propose to express mass M_{kl} and density ρ_{kl} of the fractal structure of the percolation cluster of a volumetric electrolytic body in the form of ratios (5):

$$M_{kl} = m_0 \left(\frac{L_{kl}}{l_0} \right)^{d_3 - d_f}; \quad \rho_{kl} = \rho_0 \left(\frac{L_{kl}}{l_0} \right)^{d_3 - d_f}, \qquad (5)$$

where m_0 is the mass of an average pore; R_{kl} is size of the fractal percolation cluster; l_0 is the pore size; d_f is the fractal dimensionality of the fractal cluster; ρ_0 is the density of the electrolyte; d_3=3 is the Euclidean dimensionality of a volumetric body, which houses the percolation fractal cluster.

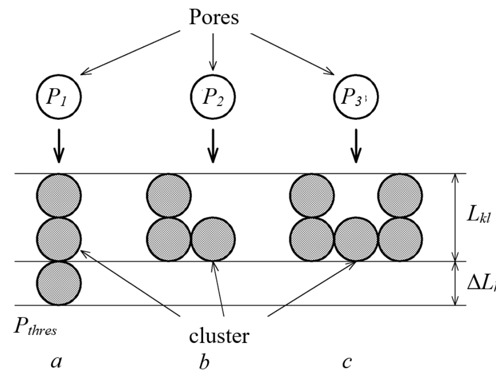


Fig. 3. The process of formation of the percolation conductive channels: *a* – formation of a current conductive percolation channel between the dielectric and current conductive structures of soil formed at probability P_{thres}; *b, c* – variants of percolation channels formation, which are insufficient for forming the current conductive pathways by the magnitude ΔL_{kl}

Thus, mass M_{kl} and density ρ_{kl} of the fractal percolation cluster depends on its size L_{kl} and on fractal dimensionality d_f.

The data obtained in determining the fractal dimensionality make it possible to determine the number of pores $N(L_{kl})$ with radius r_0 in the structure of a fractal cluster of radius L_{kl}. To this end, it is proposed to apply ratio (6):

$$N_{por}(L_{kl}) = \left(\frac{L_{kl}}{r_{0por}} \right)^{d_f}, \qquad (6)$$

where N_{por} is the number of pores; r_{0por} is the radius of an average pore; $2<d_f<3$ is the fractal dimensionality of the fractal percolation cluster of radius L_{kl}.

It is proposed to use expression (6) to determine the mean mass density of a volumetric electrolytic body $\rho(L_{kl})$ and the area of particle surface $S(L_{kl})$ in the volume of an electrolytic body of radius L_{kl}:

$$\rho(L_{kl}) = \rho_0 \left(\frac{r_0}{L_{kl}} \right)^{3-df}; \quad S(L_{kl}) = r_0^{\,2} \left(\frac{L}{r_0} \right)^{3-df}, \qquad (7)$$

where r_0 is the average radius (of pores) of the starting porous structure.

Thus, knowing ρ_0 and r_0 for the starting substances, that is, the threshold space of the inhomogeneous soil, it is possible, based on values ρ_0 and r_0, to determine the density of the fractal percolation cluster $\rho(L_{kl})$.

As noted above, the porous structure of a volumetric electrolytic body has a fractal structure in a certain domain of special scale $L_0<L<L_{ss}$; where L_0 is the minimum size of particles, clusters, pores, which form a fractal structure

(cluster), L_{ss} is the correlation length of self-similarity – the size of fractals that are similar to each other.

It is proposed to apply a model that makes it possible to describe the conductivity of the structure of a volumetric electrolytic body of inhomogeneous medium, if one knows the distribution function of structure elements (pores) based on the magnitude of their own conductivity.

Thus, we obtain the following expression (7) for a model of the cluster conductivity that forms an electrolytic grounding electrode

$$\sigma_{kl} = 2\gamma_3 \nu_3 l^{-2} \int_0^{\sigma_c} \left[\int_{\sigma_1}^{\sigma_c} f_0(\sigma) d\sigma \right]^{\nu} \times \\ \times f_0(\sigma_1) \frac{d\sigma_1}{\left[\int_{\sigma_1}^{\infty} f_0(\sigma) \frac{d\sigma}{\sigma} \right] \left[\int_{\sigma_1}^{\infty} f_0(\sigma) d\sigma \right]^{-1}}, \quad (7)$$

the numerical coefficient γ_3 (the order of unity) is employed to correct the fact that overflows between conducting parallel chains were not taken into consideration.

Under the assumption that all conductive channels have identical conductivity at $l=L_{kl}$ and, by expressing the probability values for conductivity of connection P_c^b via the cluster size L_{kl} and the percolation threshold x_c, formula (7) takes the form of the critical percolation dependences and takes the following form (8):

$$\sigma_{kl} \sim \frac{L_{kl} \left(x - x_c \right)^{\Delta d_{fr}}}{L_0}. \quad (8)$$

Hence, the size of the fractal percolation cluster

$$L_{kl} = \frac{\sigma_{kl} L_0}{\left(x - x_c \right)^{\Delta d_{fr}}}.$$

(8) shows that the percolation conductivity model of a volumetric electrolytic body is defined by the size of the fractal percolation cluster L_{kl} (electrolytic grounding electrode) and depends on a change in the fractal dimensionality of a porous structure of the heterogeneous soil medium by the magnitude Δd_f at achieving the percolation threshold x_c.

4. 2. Improvement of the method for calculating the resistivity of soil for electrolytic grounding electrodes of autonomous mobile electrical installations

Based on modeling the process of electrolytic grounding in the porous structure of an inhomogeneous medium of structures of various soils, we considered in this work the structures of an infinite percolation cluster in the volume of an electrolytic body. It has been shown that its size L_{kl} is the size of the volumetric electrolytic body $L_{ob.t}$.

In order to provide the conductivity channels from the dielectric layers to the conductive layers of soil, it is proposed to accept, as depth H of the electrolyte flow through the structure of an electrolytic body, the size of a percolation cluster size L_{kl}, that is $L_{kl}=H$.

It is also necessary to draw attention to the fact that, according to the theory of percolation, in order to ensure conductivity, it will suffice to form even a single channel for the electrolyte percolation. In this case, it will suffice to consider the calculation of resistance to current spread along one percolation channel R_g^{1chan} (in a single r-chain), as shown in Fig. 4.

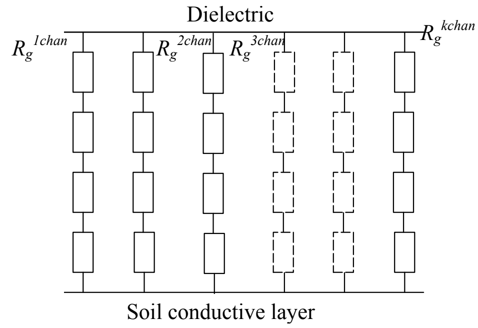


Fig. 4. Schematic of calculation of the current spread resistance in a single percolation channel

Known methods for calculating the grounding resistance are based on the following quantities: soil resistivity ρ, magnitude of the linear size of grounding electrode L, as well as the coefficients that depend on the shape of a grounding electrode and the conditions for its penetration.

To calculate the grounding resistance R_g of a single grounding electrode, the following expression (9) is typically used:

$$R_g = \frac{\rho}{\pi L} C, \quad (9)$$

where L is the main greatest linear size of a grounding electrode, m; C is the dimensionless coefficient that depends on the shape of a grounding electrode and conditions for its penetration.

For a problem on the electrolyte percolation along a single conductivity channel, we shall determine R_g accepting that the resistivity in a percolation channel ρ_{pch} is equal to the electrolyte resistivity, that is $\rho_{pch}=\rho_{el}$.

Then we obtain expression (10) in order to determine the current spread resistance R_g^{1chan} for a single percolation channel:

$$R_g^{1chan} \sim \rho_{el} \frac{\ell_{chan}}{S_0}, \quad (10)$$

where ℓ_{chan} is the correlation (meandering) length of a percolation channel; S_0 is the surface contact area.

Hence, from expression (10), we obtain for $\ell_{chan} \sim (R_{kl})^{dkl}$ or $\ell_{chan} \sim (H)^{dkl}$, and $S_0=\pi r^2$ (where r_0 is the radius of the pore), then, by substituting values ℓ_{chan} and S_0 in (10), we obtain expression (11):

$$R_g^{1chan} \sim \rho_{el} \frac{\left(R_{kl} \right)^{d_{kl}}}{\pi r_0^2} \sim \rho_{el} \frac{\left(H \right)^{d_{kl}}}{\pi r_0^2}. \quad (11)$$

Taking into consideration expression (10) and the schematic of calculation of resistance to current spread along a single percolation channel (Fig. 4), it follows that the total resistance of electrolytic grounding $R_{\Sigma g}$ for all percolation channels is derived from expression (12):

$$\frac{1}{R_{\sum g}} = \frac{1}{R_g^{1chan}} + \frac{1}{R_g^{2chan}} + \frac{1}{R_g^{3chan}} + \ldots + \frac{1}{R_g^{Nchan}}. \quad (12)$$

In determining the electrical resistance of an electrolytic cluster, we consider a volume unit of a given body, confined to a parallelepiped with a base area of S and height L (Fig. 5).

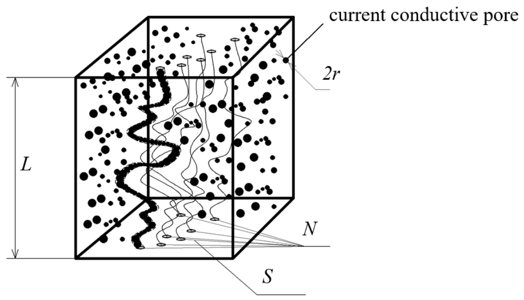


Fig. 5. Structure of electrolytic body

The resistance of soil in the volume of a percolation cluster, confined to a site of area S, is determined by the resistance of a single channel and the number of channels that form parallel circuits and can be determined from formula (13):

$$R_{kl} = \frac{R_{1chan.ekv}}{N_{k.ekv}}, \tag{13}$$

where $N_{chan.ekv}$ is the number of parallel percolation channels placed at a site of the cross-section of the percolation cluster of area S, $R_{1chan.ekv}$ is the equivalent resistivity of a single channel, Ohm, derived from formula (14):

$$R_{1chan.ekv} = \left(\rho_{el} \cdot \frac{L}{\pi \cdot r^2}\right)^{d_3+\xi_3-d_f}, \tag{14}$$

where ρ_{el} is the electrolyte conductivity, Ohm, L is the axial percolation channel length (excluding meandering and unevenness of the way the channel is filled with the electrolyte), m; r is the radius of the structural element of the cluster (pore), m, d_3 is the dimensionality of the Euclidean space equal to 3; ξ_3 is the base indicator of sinuosity equal to 1, $d_{fchan.}$ is the fractal dimensionality of space in which the percolation channel is formed, equal to (15):

$$d_{f\,chan} = \frac{\ln\left(n \cdot k_{com.por}\right)}{\ln l}, \tag{15}$$

where l is the scale of the spatial dimensionality, n is the number of structural elements (pores) in a cluster, $k_{com.por}$ is the filling factor of the electrolyte for a pore space, equal to (16):

$$k_{com} = \frac{V_{el}}{V_{por}} = \frac{V_{el}}{V_{geom} \cdot k_{por}}, \tag{16}$$

where V_{geom} is the geometrical body volume, m^3, V_{el} is the electrolyte volume, m^3; k_{por} is the coefficient of soil porosity.

The number N can be determined from formula (17):

$$N_{chan.ekv} = \left(\frac{S}{\pi \cdot r^2}\right)^{d_{f\,sq}-1}, \tag{17}$$

where S is the area of the site of the cross-section of a percolation cluster; m^2,

$$d_{f\,sq} = \frac{\ln\left(n \cdot k_n\right)}{\ln l}$$

is the fractal dimensionality of the site's plane.

Taking this into consideration, the resulting formula for the magnitude of soil resistivity in the volume of a percolation cluster takes the form (18):

$$R_{kl} = \frac{\left(\rho_{el} \cdot \frac{L}{\pi \cdot r^2}\right)^{d_3+\xi_3-\frac{\ln\left(n \cdot \frac{V_{el}}{V_{por} \cdot k_{por}}\right)}{\ln l}}}{\left(\frac{S}{\pi \cdot r^2}\right)^{\frac{\ln\left(n \cdot \left(V_{por}/V_{body}\right)\right)}{\ln l}-1}}, \tag{18}$$

where

$$L_{kl} = 2r_{por}\left(\frac{3V_{el}}{4\pi r_{por}^3}\right)^{\frac{1}{d_f}}$$

is the cluster size;

$$\rho_{geom} = \rho_{el}\left(\frac{r_{kl}}{r_{por}}\right)^{d_f-d_3}$$

is the density of the volumetric geomet-rical body; ρ_{el} is the mass density of the electrolyte; r_{kl} is the radius of a cluster; r_{por} is the average size of a pore; d_f is the fractal dimensionality of the percolation cluster; d_3=3 is the geometrical Euclidean dimensionality of a volumetric body

$$V_{geom} = V_{el}\left(\frac{r_{kl}}{r_{por}}\right)^{d_3-d_f}.$$

The derived analytical expression (18) relates the electrophysical and geometrical parameters of a volumetric body of the electrolyte in soil and takes into consideration a change in the properties of space at a change in its structural-phase characteristics with fractal properties.

In addition, we have examined and demonstrated that the size of cluster L_{kl} can be considered as depth H_{dep} of the electrolyte penetration into a heterogeneous soil, that is, $L_{kl} \approx H_{dep}$.

The method that follows from formula (18) implies determining the electrophysical parameters based on a fractal-percolation model of a volumetric electrolytic body, which, in contrast to those known, makes it possible to express and relate the electrophysical parameters to the structure's percolation parameters, and the geometrical characteristics (L_{kl}, r_{por}, H_{dep}, S) to the fractal dimensionality d_f.

5. Experimental research into electro-physical properties of surface electrolytic grounding electrodes

In the course of experiment, in order to confirm a theoretical study, we investigated an electrolytic grounding electrode depending on the shape and volume of the electrolytic body in the form of a percolation cluster.

To determine the electrophysical parameters of the electrolytic grounding electrode, we proposed a procedure of experimental research, designed and constructed a laboratory installation whose schematic is shown in Fig. 6.

Laboratory study has allowed us to obtain actual dependences of ohmic resistance of circuits "model of an electrolytic grounding electrode – sensor" for the for layerwise and point sensors in different soil structures and for various electrolytes. Ohmic resistance curves demonstrate three distinctive zones.

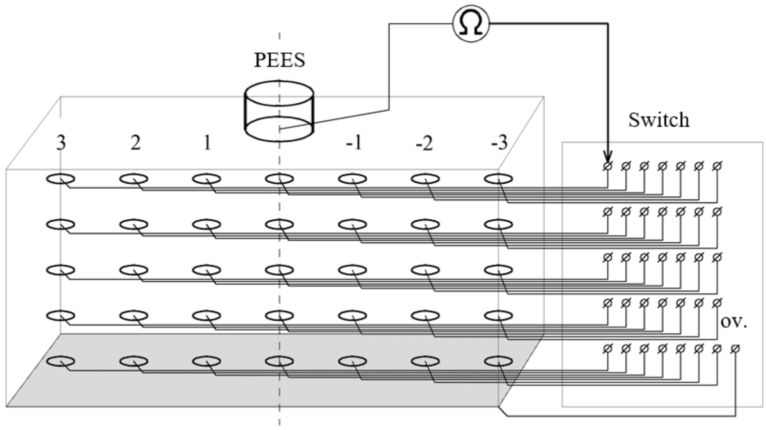


Fig. 6. Schematic of the laboratory installation to conduct the experiment

During experimental study aimed at determining the electro-physical parameters of the conductivity cluster, we used sandy soil with a faction of structural elements (sand – pores) with a radius of 0.07 mm, soil porosity coefficient is k_n=0.375, applying copper sulphate as the electrolyte (ρ_{el}=0.35 Ohm·m). It was found that the degree of filling the space of soil with the electrolyte varies in the range from 0 to 0.375 c.u., for an ideal dry sand, which corresponds to the full saturation of the soil with the electrolyte. Therefore, the calculations were carried out specifically for this range and for the linear dimensions of the sample of a sandy soil with the height, width, and depth of 1 m. In order to obtain soil resistivity, we examined a change in the increment of fractal dimensionality of the percolation channel Δd_{fchan} and the site of the cross-section of cluster Δd_{fsq} of conductivity due to a volumetric concentration of the electrolyte in pores x_c and the fill factor for the volume of an electrolytic body k_{oc}.

We have derived a dependence of the resistance of a percolation cluster on the volumetric concentration of electrolyte in pores x_c and the fill factor for the volume of an electrolytic body k_{op} (Fig. 7).

The computational experiment has allowed us to derive dependences of change in the basic electrophysical quanti-

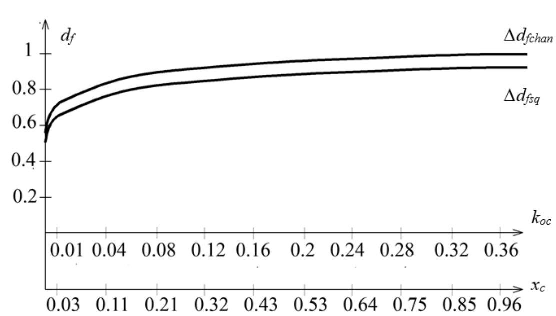


Fig. 7. Change in the gain of fractal dimensionalities of percolation channel Δd_{fchan} and the conductivity cluster's cross-sectional site Δd_{fsq} on volumetric concentration of the electrolyte in pores x_c and the fill factor of the electrolytic body's volume k_{oc}

ties of PEES at an increase in the electrolyte content in the volumetric body of soil (Fig. 8). Fig. 8 shows that a change in the degree of filling the soil pore space leads to a change in the fractal dimensionality increment. Values for critical concentration x_c of the electrolyte in a porous space of soil coincides with the qualitative changes in ohmic resistance of the percolation cluster.

Fig. 8 shows that a sharp fall in ohmic resistance occurs within the range of change in the values for volumetric electrolyte concentration x_c from 0.11 to 0.43, that is, at the time of formation of the conductive percolation pathways. The lower bound of this range, x_c=0.11, is near the values for the probability of initial formation of percolation pathways while the upper bound, x_c=0.43, is close to the values for the unambiguous overcoming of the percolation threshold.

The results of computational experiment reveal that when the soil is filled with the electrolyte the space of the electrolytic cluster changes its properties, resulting in a sharp change in electrical resistance, from dozens kOhm to units Ohm. Thus, the soil medium becomes conductive in nature.

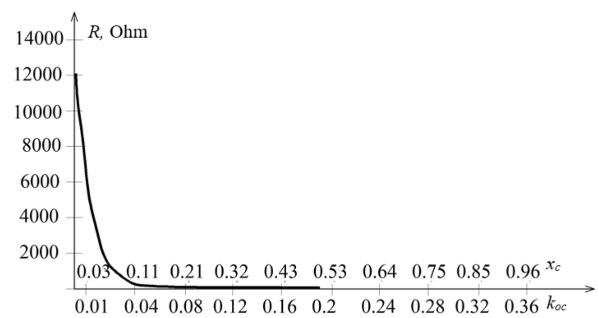


Fig. 8. Dependence of percolation cluster resistance on volumetric concentration of electrolyte in pores x_c and the fill factor of an electrolytic body's volume k_{oc}

Results of the laboratory study and the field tests are shown in Fig. 9. The experiment was conducted to establish the dependence of resistance of a soil sample on the volume of electrolyte used, and the dependence of resistance to current percolation on the electrolyte's volume.

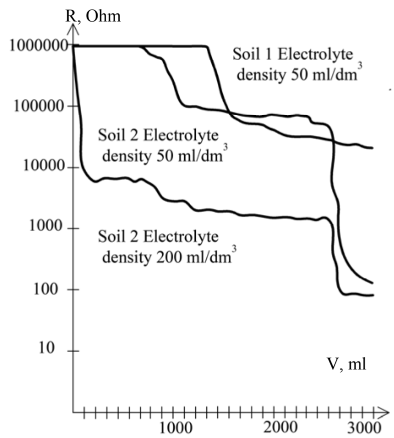
Fig. 9 shows three main stages of change in the magnitude of electrical resistance:

– a stage of initial fall of electrical resistance due to the creation of a reliable contact "electrolytic grounding electrode – soil structure" by wetting the upper layers of the soil and the further growth of the volume and surface of the electrolytic cluster of conductivity. Within this zone, the fall of the ohmic resistance does not result in that the soil acquires the properties of a conductor;

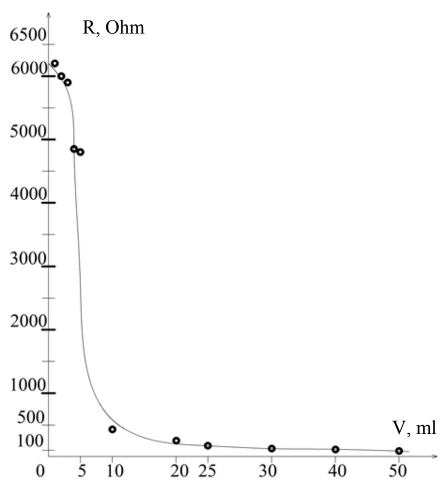
– a stage a sharp fall in electrical resistance due to the creation of a totality of percolation channels that connect the electrolytic grounding electrode to the layers of good conductivity. The boundaries of this zone are near the percolation threshold values and correspond to establishing the critical electrolyte concentration in soil;

– a stage of stable low ohmic resistance, which practically does not change depending on the volumetric concentration of the electrolyte.

Field tests (measurement of grounding resistance of the electrolytic grounding electrode using a method of ammeter-voltmeter) that were performed employing a specially designed full-sized sample have confirmed the results of theoretical study and laboratory tests. A significant drop in ohmic resistance of the electrolytic grounding electrode coincides with the formation of the electrolytic conductivity cluster. The total volume of the cluster is defined by its main linear size that matches the laying depth of the well-watered layers of soil structure.



a



b

Fig. 9. Results of laboratory study and field tests: *a* – experimental dependence of resistance of the soil sample on volume of the electrolyte used; *b* – dependence of resistance of current spread from the electrolytic grounding electrode on the electrolyte's volume (field testing)

6. Discussion of results of studying the processes of electrolytic grounding

In order to calculate the basic electrophysical resistance characteristic of spreading the electrolytic grounding for grounding the autonomous mobile electrical installation, the percolation theory was applied. This theory allowed us to simulate the process of conductivity in heterogeneous porous media in the structures of various soils.

The constructed percolation model has made it possible to consider the physical process of formation of the structure of conductive paths through electrolytic grounding electrodes (the electrolyte's volumetric body) – the conductive layer of soil. However, it has been obtained that the conductivity of the volumetric electrolyte's body is predetermined by the formation of the conductivity cluster in the structure of porous space of soil and is defined by the parameters of a given cluster and the electrolyte's conductivity in the percolation channels of the cluster.

It is shown that the conductivity cluster of the system "soil – electrolyte" has fractal properties that are accounted for via the fractal dimensionality with a stage character of change.

The percolation channels' sinuosity and the heterogeneity of their filling with the electrolyte, as well as the filling degree of space in the volumetric electrolytic body, was in general accounted for via fractal dimensionality.

We have determined the critical volumetric concentration of the electrolyte, which, in line with theoretical calculations, was 0.34, which provided for a condition to form percolation channels and, therefore, conductive paths of conduction.

To determine the electrophysical parameters of the electrolytic body in the formation of the electrolytic grounding electrode in the structure of soil during operation of an autonomous electrical installation, the derived analytical expressions made it possible to relate the structural-phase characteristics of space to the geometrical sizes of the conductivity cluster.

It has been shown that at a qualitative fall in the ohmic resistance of soil structure, at the time of overcoming the percolation threshold, one should observe the formation of an infinite electrolytic cluster between a grounding object and the conductive phase of soil's structure. In addition, near the percolation threshold the soil's structure demonstrate changes in the structural-phase soil characteristics expressed by a change in its quantitative magnitude of a pore space – fractal dimensionality. The fractal dimensionality of the soil pore space can act as its power function of spatial scale.

Overcoming the percolation threshold is observed at a volumetric concentration of the electrolyte in pores in the region of certain values; in this case, there is a change in the fractal dimensionality of an inhomogeneous space of the electrolytic cluster. The process of change in the fractal dimensionality is observed in the region of the cluster's border.

It was established that the percolation threshold value (a sharp fall in electrical resistance) almost does not depend on the type of an electrolyte, and is defined by the structure of the soil.

We have established the interval of change in the magnitude of fractal dimensionality of the system electrolyte – soil (for example, for sand of fraction 0.07 mm) and determined that its change reflects the degree of heterogeneity (filling) of the pore space in the soil's structure and corresponds to a change in the volumetric concentration. Therefore, fractal dimensionality can be represented as a spatial scale of a power function.

We have accepted the following limitations and assumptions during study:

– the resistivity of soil in the percolation channel of electrolyte spread is equal to the electrolyte's resistivity;

– a skeleton of the porous structure of soil is not conductive and the spreading of current in soil is predetermined by the ionic conductivity of the electrolyte;

– the depth of process investigation could not be limited to the surface layer; it propagates throughout the entire volume of an electrolytic body and further in the soil;

– a soil structure has a random nature of formation and cannot be described as being homogeneous; it relates to the dissipative self-organizing systems;

– a parabolic shape of the electrolytic body in soil was adopted in calculations;

– the fractal dimensionality of the electrolyte was taken to equal three, that is, the electrolyte's phase was accepted conditionally homogeneous.

The assumptions made, and the constraints accepted, during modeling of the processes of electrolytic grounding do not significantly affect the description of these processes, but they are important in order to enable the application of the percolation model to describe the processes of soil conductivity.

The disadvantage of the present study that must be noted is the complexity of the experiment for different multicomponent complex soils and their structures, as well as the use of a rather large volume of the electrolyte.

A promising direction for the development of this research is the process of creating the electrolytic grounding electrodes of modular type for stationary electrical installations.

7. Conclusions

1. We have constructed a physical model of the electrolytic grounding process that takes into consideration the soil structure properties when changing the fractal dimensionality of a cluster in the interval from 2.56 to 3.00, forming the grounding electrode, with the normalized resistance of up to 4 Ohm.

2. We have improved a method for calculating the ELG electro-physical parameters, based on accounting for the main linear size of an electrolytic volumetric body, which coincides with the electrolyte penetration depth for various soil structures. The analytical expressions have been derived to relate the normalized resistance of electrolytic grounding electrodes and the resistivity of soil to the fractal dimensionality, the volume of electrolyte, the number of pores with the electrolyte, the density of geometrical volumetric body.

3. During the experiment, we have confirmed the dependence of soil resistivity on the shape and volume of the electrolytic body. It has been established that the formation of conductivity channels, that is, electrolytic grounding electrodes with the penetration depth of the electrolyte, is confirmed by a sharp decrease in ohmic resistance in the range of values for a volumetric electrolyte concentration from 0.11 to 0.43.

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