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Computational Modeling of the Electromagnetic Field Distribution of a Horizontal Grounded Antenna in Rock for TTE Communication

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Abstract. The article investigates the spatial distribution of the electromagnetic (EM) field of an antenna in the form of a long grounded cable in a rock with the corresponding electrophysical parameters. The frequency dependences of the emitted EM fields (300 Hz – 30 kHz) on the depth of the receiver position are determined. This is of practical importance for the problems of wireless mine communications.

Keywords: wireless communication, mine communication, magnetic antenna, grounded antenna, electromagnetic field, ULF, VLF.

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Wireless transmission of signals through rocks is possible by using low frequency electromagnetic waves. The article investigates the magnetic component of the electromagnetic field in a continuous medium with the properties of mountain ranges for the frequency range 300 Hz – 30 kHz. Signal transmission through the rock is possible using a long grounded cable located on the surface of the mine field or in mine roadway as a transmitting antenna. To receive the signal, it is proposed to use a compact magnetic antenna in the form of a coil with a ferrite core.

1. Theoretical assessment

The currently existing wireless communication systems in underground mine workings can be conditionally divided into low-frequency (VLF–LF) and HF and VHF systems [1–8]. As an additional channel for operational communication with personnel, a system of wireless emergency notification and communication through the Earth (TTE) is used. A separate type of connection is wireless magnetic-inductive or near-field magnetic connection (NFMC) in the frequency range of 30–100 kHz. Such systems use an antenna in the form of a magnetic loop with a radius of 10–200 m to transmit a signal through the Earth to mine workings. Studies are being carried out on the possibility of using long conductors in mines to increase the range of low-frequency (400 Hz – 9 kHz) channels [4, 6, 7].

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The Radius-2 wireless notification and personnel search system for mines, developed by the "Radius" company (Krasnoyarsk). It is based on the transmission of a useful signal through a mountain range using an antenna-feeder device in the form of a long feeder line grounded into the ground on the daylight surface [8].

To analyze the energy potential of a wireless channel, it is necessary to estimate the distribution of the magnetic field emitted by a transmitting grounded antenna in a continuous medium with the physical properties of a rock (resistivity ρ, dielectric permittivity ε and magnetic permeability μ). Each of the two grounds is a point source A (see Fig. 1a), directing the current into the ground.

For the case of a homogeneous medium, the current $\overline{j}$ flows uniformly in all directions of the half-space in the form of direct rays from point A. The hemisphere S with radius r is set at some distance from the source to determine the current density in the half-space around it. This will determine the current density at point M on the surface of the hemisphere:

$$j = \frac{J}{2\pi r^2}, \tag{1}$$

where r is equipotential surface radius; J is total current flowing through equipotential surfaces.

The electric field intensity E at point M is defined as:

$$E = \rho \cdot j = \frac{J \cdot \rho}{2\pi r^2}. \tag{2}$$

In an isotropic medium, the orientation of the current and electric field vectors is the same. The distribution of the electric field and currents between the two grounds of the dipole source is shown in Fig. 1b. The current flow of such a source is closed, and the equipotential surfaces on which the potential U is constant, as in the case of a point source, are perpendicular to the current lines and have a hemispherical shape. For a homogeneous medium, the field E of two point electrodes has an almost constant level (see Fig. 1b).

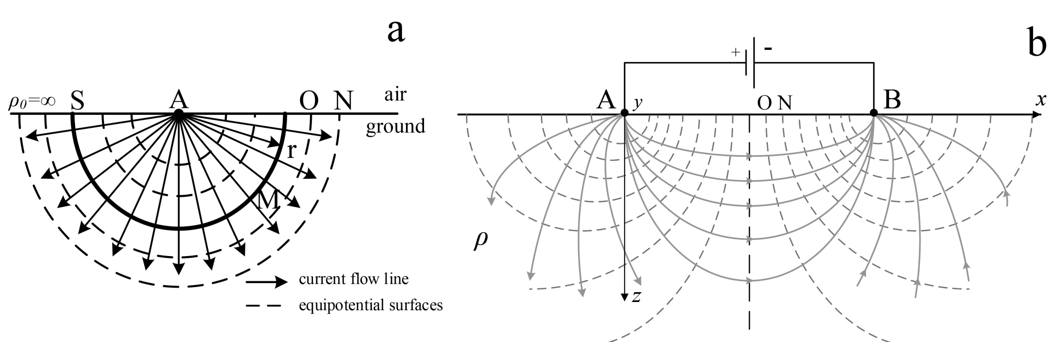

Fig. 1. Scheme of distribution of the field and currents of the current source in a homogeneous half-space: a — point source, b — dipole source

The vector $\overline{E}$ is directed along the radius vector connecting the points AO. In this case, expression (2) takes the form:

$$\overline{E} = \frac{J \cdot \rho}{2\pi r^2} \cdot \frac{\overline{r}}{r}, \tag{3}$$

where $\dfrac{\overline{r}}{r}$ is unit radius vector.

An electric dipole source is an emitter, because there is a periodic change in the electric moment $\overline{p}$ in the process of oscillation of charges q in the wire:

$$\overline{p} = \overline{p_0} \sin(\omega t), \tag{4}$$

where $\overline{p}_0 = J_0 l \overline{d}$; l is wire length; $\overline{d}$ is unit vector indicating wire orientation.

Consider the electromagnetic field of a straight cable of length l with current J located at the boundary of a conducting half-space with electrical conductivity σ_2. The cable is connected to a power source and grounded at the ends. It is necessary to determine the magnetic field at the depth z1 at the point M, which is formed as the sum of the fields of two opposite charges located at grounding points. It is necessary to determine the magnetic field at the depth z_1 (point M), which is formed as the sum of the fields of two opposite charges located at grounding points. In the work of M. S. Zhdanov [9], a solution was obtained for this problem to determine the current density in a conducting half-space. The current density has three components (j_x, j_y, j_z), let's analyze the distribution of currents in the XZ plane (see Fig. 2):

$$\overline{j}_x = \frac{\overline{J}}{2\pi} \left[\frac{x}{(x^2 + y^2 + z^2)^{3/2}} + \frac{l - x}{((l - x)^2 + y^2 + x^2)^{3/2}} \right], \tag{5}$$

$$\overline{j}_z = \frac{\overline{J}}{2\pi} \left[\frac{z}{(x^2 + y^2 + z^2)^{3/2}} + \frac{z}{((l - x)^2 + y^2 + x^2)^{3/2}} \right], \tag{6}$$

where $\overline{J}$ is current in the cable.

The magnetic field at point M is represented by the sum of the fields created by the main current of the antenna and the elementary currents flowing in the half-space of rocks. To do this, we divide the entire region $z > 0$ into elementary sections located at a distance Δz from each other, through which the current flows as through an equivalent conductor with electrical conductivity σ_2 and radius a (see Fig. 2).

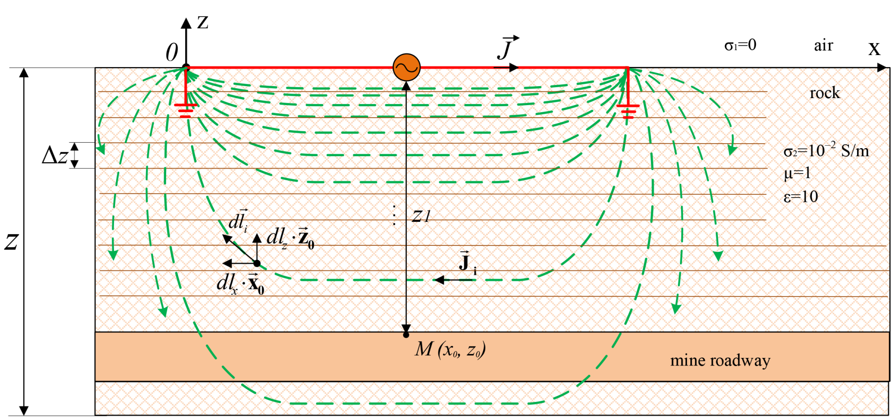

Fig. 2. Scheme of distribution of current density in the rock for a grounded cable with current

The magnetic field at point M is determined by the sum of three components:

$$\overline{H} = \overline{H}_0 + \sum_{i=1}^{k_1} \overline{H}_i + \sum_{i=k_1+1}^{k_2} \overline{H}_i, \tag{7}$$

where $\overline{H}_0$ is the field created by the current $\overline{J}$ flowing in the wire between the grounds on the surface of the half-space.

The second two elements (7) are the sum of the magnetic fields induced by elementary currents located above the observation point M. The total number of such elementary currents is k_1, therefore, $\Delta z \cdot k_1 \leqslant z_1$. The second sum determines the contribution of elementary currents, below the observation point M. The total number of such elementary currents is k_2, which means that $\Delta z \cdot k_2 \leqslant z_1 + z$, where z is the total depth of the studied spaces. The magnetic field of the current element is determined by the Biot-Savart law:

$$\overline{H}_i = \left(\frac{\overline{J}_i}{2\pi} \int\limits_{l_i} \frac{\left[d\bar{l}_i \cdot \bar{l}_r \right]}{r_i^2} \right) \cdot e^{-\alpha r_i}, \tag{8}$$

where $d\bar{l}_i$ is length of the current element $\overline{J}_i$;

$d\bar{l}_r$ is the unit vector of the radius of the vector r_i;

r_i is distance between current element and point M;

l_i is the length of the elementary conductor;

$\alpha = \omega \sqrt{\frac{\varepsilon\mu}{2} \cdot \left[\sqrt{\left(\frac{\sigma}{\omega\varepsilon} \right)^2 + 1} + 1 \right]}$ is the attenuation coefficient (the real part of the wave number);

$\omega = 2\pi f$ is radian frequency;;

$\varepsilon = \varepsilon_0 \varepsilon_r$ is dielectrical constant of the medium;

$\mu = \mu_0 \mu_r$ is magnetic permeability of the medium;

σ is electrical conductivity.

The current distribution structure is determined by expressions (5), (6). Fig. 3 shows the dependence of j_x and j_z on x for a z value of 500–800 m. The main difference between j_x and j_z current components is that the current density j_z has a value of 0 under the center of the current vector in the cable (see Fig. 3b). This shows a change in the direction of the vector j_z to the opposite and reaches the maximum and minimum extremum under the ground points of the antenna. The current density for the j_x component reaches its maximum under the central part of the antenna (see Fig. 3a). The ratio of these components forms the current flow vector between the grounding points at a sufficiently large depth, while the current density decreases with depth due to the strong divergence of the current vectors over the volume of the half-space.

The magnetic field in the XZ plane is determined based on the ratio:

$$[d\bar{l}_i \cdot \bar{l}_r] = [\overline{x}_0 dx \bar{l}_{ir}] + [[\overline{z}_0 dz \bar{l}_{ir}]]. \tag{9}$$

The magnetic field at the point of observation $M(x_0,\, z_0)$ has an orientation along $\overline{y}_0$. The current field J_{xi} of the current component is determined from the equation:

$$\overline{y}_0 \cdot \overline{H}_i^x = \left[\frac{1}{2\pi} \int\limits_a^b J_{xi} \left(-\frac{(z_0 - z)dx}{r^3} \right) \right] \cdot e^{-\alpha r}. \tag{10}$$

where $r = \sqrt{(x_0 - x)^2 + (z_0 - z)^2}$ is distance between element $dl_i = dx$ and observation point M with coordinates x_0, z_0;

J_{xi} is current density at depth z, estimation of relations (5) and (6).

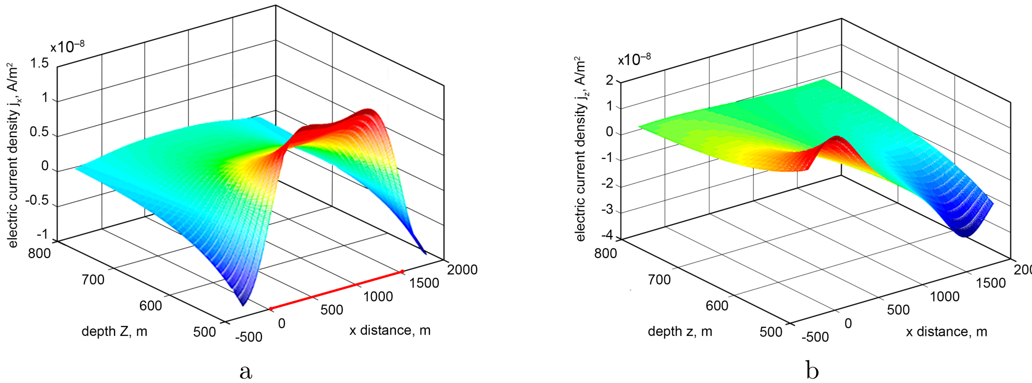

Fig. 3. Current density distribution in the conducting half-space: a — j_x at a depth of 500–800 m; b — j_z at a depth of 500–800 m

The current component J_{zi} creates a magnetic field at the observation point M:

$$\overline{y}_0 \cdot \overline{H}_i^z = \left[\frac{1}{2\pi}\int_a^b J_{zi}\left(-\frac{(x_0 - x)dx}{r^3}\right)\right] \cdot e^{-\alpha r}. \tag{11}$$

The current density J_i at depth Z is determined by expression (5, 6) and the equivalent cross section of the conductor d in the form of a section of rocks (equivalent diameter):

$$J_i = j_{x,z} \cdot \frac{\pi d^2}{4}. \tag{12}$$

where d is cross-sectional diameter of the equivalent wire.

Computational modeling will provide a more accurate solution for analyzing the distribution of magnetic fields. This will make it possible to select the channel parameters depending on the properties of the medium in order to increase the efficiency in terms of the magnetic field level and the coverage area of the rock volume.

2. Computational modeling

Modeling the distribution of currents and magnetic field in an isotropic and anisotropic medium requires extensive computational resources. To analyze these processes, the finite element method (FEM) is proposed as one of the mathematical tools for numerical solution, including physical problems [9, 10]. The method is based on the division of the modeling object into subdomains (finite elements) and the approximation of an unknown function in each element as a combination of basic functions.

For the study, a model with dimensions of 4000×2000×1600 m was created, which includes an air layer (h_1=100 m) and a rock layer (h_2=1500 m). Propagation medium properties: electrical conductivity σ=10^{-3} S/m; dielectric constant ε=10; magnetic permeability μ=1. On the surface of the rock there is a radiating antenna with grounding, formed by a cable with a length l=1400 m and a current of J=5 A. The boundary conditions for the current and magnetic field are determined by the properties of the outer boundaries of the model $n \cdot J = 0$ and $n \times H = 0$ to take into account the absorption of currents and the magnetic field incident on the boundaries. This is done to simulate an infinite space around the model.

To analyze the model by the finite element method, the solution of Maxwell equations and full-current equation is implemented, which show the interaction of currents and electromagnetic fields in an absorbing medium [9, 10]:

$$\operatorname{rot}\overline{H} = \overline{J}, \tag{13}$$

$$\overline{B} = \operatorname{rot}\overline{A}, \tag{14}$$

$$\overline{E} = -j\omega\overline{A}, \tag{15}$$

$$\operatorname{div}\overline{J} = Q_{j,v}, \tag{16}$$

$$\overline{J} = \overline{J}_{cond} + \overline{J}_{EI} + \overline{j}_e, \tag{17}$$

where $Q_{j,v}$ is the density of the bulk current source; j_e is the density of electric current, external source (antenna current); V is the electric potential; σ is electrical conductivity; E is the electric field strength; $D = \varepsilon_0\varepsilon_r E$ is electrical induction; $J_{EI} = j\omega D$ is electric induction current; $J_{cond} = \sigma E$ is conduction current; H is the magnetic field strength; B is magnetic induction; A is the vector potential; J is the electric current density.

Fig. 4 shows the distribution of the spatial components of the magnetic field (H_x, H_y, H_z) for a grounded antenna 1400 m long. The H_x component is concentrated in the upper part of the model closer to the antenna itself. It has an extremely low level below the center, which makes it the least useful for reception at great depths. The H_z component has a similar depth distribution, but a higher intensity, contributing to the total magnetic field H. The most useful and dominant component in the total field is the H_y component. Possessing the highest tension and coverage area, this component allows you to register it in any area in the emitter area. In the antenna ground region, the Hz and H_y components compensate each other, maintaining an acceptable level of magnetic field strength. An analysis of the distribution of the components shows that the orientation of the receiving magnetic antenna along the Z and Y axes is the most effective for registering a useful signal.

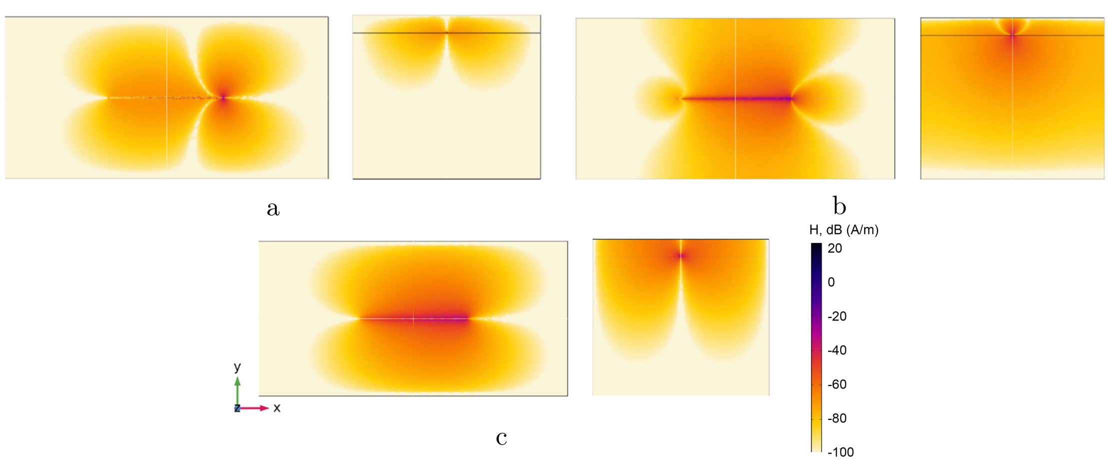

Fig. 4. Distribution of the magnetic field components for a grounded antenna 1400 m long: a — H_x; b — H_y; c – H_z

In practice, signal reception occurs using a ferrite antenna that converts the magnetic field into EMF. In this case, the signal voltage at the receiver input is calculated by the formula [11]:

$$U = \omega \cdot \mu_0 \cdot H \cdot S_{AEA}, \tag{18}$$

where $S_{AEA} = \mu_c ore \cdot S_{core} \cdot n = 1\text{m}^2$ is the antenna-effective area; $n = 1000$ is number of turns; $\mu_{core} = 8000$ is magnetic permeability of the core; $S_{core} = 1.25 \cdot 10^{-7}$ m^2 is the cross-sectional area of the core; $\mu_0 = 4\pi 10^{-7}$ H/m is the magnetic constant; H is the magnetic field strength.

As a result of the simulation, estimates of the level of the magnetic field and the voltage induced on the receiving antenna at a maximum depth of 1000 m were obtained. Analysis in the frequency range of 0.5–30 kHz indicates a general trend of attenuation of the electromagnetic field with increasing frequency due to the absorbing properties of the rock mass, being an electrically conductive medium. For grounded antenna of medium length 1400 m, the simulation shows a level of 1.32 μV at a frequency of 2 kHz (Fig. 5).

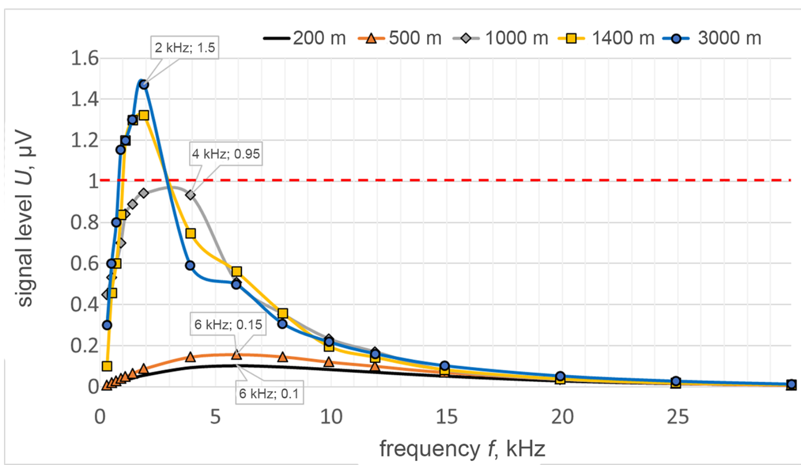

Fig. 5. Dependence of the signal level at the receiver input on the frequency for the depth Z = 1000 m under the center of the antenna, at $\sigma = 10^{-3}$ S/m, and a number of lengths of the transmitting antenna

To analyze the distribution of the EM field under the antenna, simulation data were obtained at a depth of 1000 m in a continuous medium. At the limiting distance at a frequency of 2 kHz, the voltage level above 0.5 μV is maintained in a continuous medium over a length of 1700 m for a grounded current dipole (Fig. 6a). This indicates the advantage of a grounded long antenna for mines located at depths of 200–800 m and having a large extent.

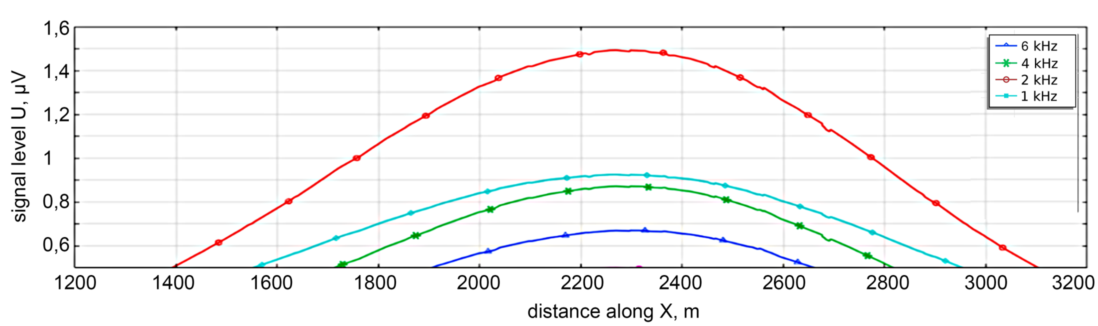

Fig. 6. Distribution of the signal level under the transmitting antenna at a depth of 1000 m

Conclusion

As a result of the study, the magnetic field components that are most suitable for using a receiving magnetic antenna were determined. The components H_y and H_z are predominant at depths greater than 100 m. The optimal operating frequencies of the transmitter are determined depending on the depth of the receiver position. For depths up to 1000 m, with an electrical conductivity of rocks of 10^{-3} S/m, these frequencies are in the range of 1–3 kHz. To increase the coverage area and the maximum depth of signal transmission, it is necessary to increase the length of the transmitting antenna.

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Вычислительное моделирование распределения электромагнитного поля горизонтальной заземленной антенны в горной породе

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Аннотация. В статье исследовано пространственное распределение электромагнитного поля антенны в виде длинного заземленного кабеля в горной породе с заданными электрофизическими параметрами. Определены частотные зависимости излучаемых сигналов (300 Гц – 30 кГц) от глубины положения приемника, что имеет большое прикладное значение для задач шахтной радиосвязи.

Ключевые слова: беспроводная связь, шахтная связь, магнитная антенна, заземленная антенна, электромагнитное поле, инфранизкие частоты, очень низкие частоты.