Sensors & Transducers, Vol. 178, Issue 9, September 2014, pp. 111-116

Sensors & Transducers

http://www.sensorsportal.com

Study on the Effect of Frequency on Conductivity of Underground Strata in Coal Mine Through-the-earth Wireless Communication

[1] Jinyi TAO, [2] Yuchen ZHANG

[1] College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan 030024 China

[2] Institute of Control and Information, School of Automation, Northwestern Polytechnic University, Xi'an 710129 China,

[1] E-mail: taojinyi@tyut.edu.cn

Received: 15 June 2014 /Accepted: 29 August 2014 /Published: 30 September 2014

Abstract: The relationship of conductivity and the frequency, which is of decisive significance in through-the-earth wireless communication in coal mine, is closely related to the options of frequency range in coal mine wireless communication. When through-the-earth wireless communication is applied, the electromagnetic waves need to spread in the semi-conductive medium rocks. The main factors affecting the electromagnetic wave propagation in rocks is the rock strata electromagnetic parameters. These parameters are magnetic permeability μ (H/m), dielectric constant ε (F/m) and electrical conductivity σ (S/m). In these parameters, electrical conductivity is not constant. Under the influence of various factors, it will be great changes. This paper, for the specific circumstances of coal mine rock, discuses and conduct dada mining the effect frequency on the electrical conductivity of underground rock in coal mine with through-the-earth wireless communication. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Frequency, Underground rock conductivity, Through-the-earth wireless communication.

1. Introduction

When through-the-earth wireless communication is applied, the electromagnetic waves need to spread in the semi-conductive medium rocks. The distribution of its electromagnetic field cannot be accurately predicted, because coal mine composition of the overburden is complex and variable, and medium is anisotropy, as well as electromagnetic signal is attenuated significantly [6]. Rock gives an impact on electromagnetic waves, which is decided by the electromagnetic parameters. These parameters are magnetic permeability μ (H/m), dielectric constant ε (F/m) and electrical conductivity σ (S/m). In these parameters, electrical conductivity is not a constant, as it will change greatly under the influence of a variety of factors, such as frequency, temperature, humidity, porosity, pressure, rock mineral composition and polarization field strength [5]. Especially, the relationship between conductivity and frequency is of decisive significance in through-the-earth wireless communication in coal mine. It is closely related to the options of frequency range in coal mine wireless communication. Therefore, for the purpose of studying through-the-earth communication in mine, it is very important to discuss the effect of frequency on conductivity parameter of the communication region.

2. The Impact of Electromagnetic Parameters on Electromagnetic Wave Propagation

In the infinite homogeneous semi-conductive medium, the propagation of electromagnetic waves is:

$$\overline{E} = \overline{E}_0 e^{-\beta r} e^{-j\alpha r}, \quad (1)$$

where $\overline{E}_0$ is the constant vector. It shows that the initial amplitude of the electric field vector and the polarization direction. The r is propagation direction of the radius vector. As shown in (1), the amplitude is attenuator along the propagation direction of electromagnetic waves by e the exponential, in which

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right)}$$
$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}, \quad (2)$$

where μ (H/m) is for the magnetic permeability, ε (F/m) as the dielectric constant, σ (S/m) for the conductivity, ω (rad/s) sent waves of angular frequency [1-3, 9-10].

In coal mine through-the-earth communication, communication medium is the semi-conductive medium. In order to decrease the amplitude attenuation of electromagnetic waves in their transmittance (that is to make β as small as possible), lower frequency (i. e. the smaller ω, the better) and larger semi-conductive medium should be used, which meets the $\sigma \gg \omega\varepsilon$, $\sigma/\omega\varepsilon \gg 1$, α, β expression can be simplified as:

$$\alpha \approx \beta \approx \sqrt{\pi f \mu\sigma} \quad (3)$$

Obtained by (3), the frequency (f) and the conductivity (σ) are the main factors of the impact of electromagnetic wave propagation in the medium. They are the most important electromagnetic parameters for the through-the-earth wireless communication in coal mine [1-3].

3. General Characteristics of Rock in Coal Mine

With coal sedimentary rock composed mainly by a multi-layer-like structure, respectively belong to different strata layers. Department generally has several layers of each layer of coal and rock. Therefore, in the transmitting antenna of the electromagnetic field within the reach of the communication area, it can include some belonging to different geological rock formations. Since the existence of tectonic movements, each very different angle buried rock, coal and rock angle from 0° to 90°. The shape of a gently inclined rock and steep, and its angle is not buried in stone. The same rock, in some areas may be gently inclined, while in other regions may be tilted or inclined, the most common are sloping gently inclined rock and rock. Meanwhile, the spacing of the seam there is a large difference in the thickness of the rock apart. Extension direction in their likely, rock is thickening or thinning or even pinch bifurcation and fracture. Coal in the form of rock lines, sandstone is most common. The rock and the broad, along the strike of up to hundreds of kilometers to tens of meters in thickness 0.1 m, followed by shale and mudstone, mostly in their thickness between 0.1 to tens of meters, and the extension of a large range [6].

In the process of establishing of through-the-earth communication, the most crucial task is to acquire the electromagnetic parameters of the coal seam used for wireless communication and the surrounded roof and floor. The roofs of coal seams are generally made of mudstone and sandstone, as well as conglomerate; the floor can be made of carbon-bearing clay, mudstone, and rare sandstone.

3.1. The Earth Formation of the Electromagnetic Parameter

The effect of rock strata on the electromagnetic waves is determined by the strata's electromagnetic parameters. These parameters are magnetic permeability μ (H/m), dielectric constant ε (F/m) and electrical conductivity σ (S/m). By Magnetic, the sedimentary rock is a typical anti-magnet –namely that they are not magnetic. The magnetic permeability μ is approximately equal to the magnetic permeability in vacuum (i. e. the value of μ is approaching $4\pi\times10^{-7}$ H/m). Rock's dielectric constant ε relates to frequency of the polarization field, the relationship between ε and frequency is decided by the water content of rocks. The dielectric constant ε of dry sedimentary rock is fixed for all frequencies. Rock's humidity mostly influences audio and sub-audio frequency. The difference of dielectric constant ε between dry and the moistest rocks can reach several orders of magnitude. As for the electrical conductivity σ, the sedimentary rocks are semiconductors, its conductivity is not constant. Under the influence of various factors, such as temperature, humidity, porosity, pressure, rock mineral composition, frequency and polarization field strength, there will be great changes in conductivity.

3.2. The Impact of Frequency on the Conductivity of Rock

The relationship between conductivity σ and the frequency is of decisive significance in through-the-earth wireless communication in coal mine. It is closely related to the options of frequency range in coal mine wireless communication. The frequency offset coefficient ξ can be used to describe the frequency offset of the electrical conductivity in the electromagnetic fields. The conductivity coefficient of the frequency offset can be expressed as:

$$\xi = 1 - \frac{\sigma(\omega)}{\sigma(0)}, \tag{4}$$

where σ(ω) and σ(0) are the conductivity with frequency ω and 0. If ξ =0, it means that the conductivity and frequency are independent. When there is ω→∞, the limit of the frequency offset coefficient is $\xi(\infty) = -\frac{\sigma(\infty)}{\sigma(0)} = -0.25n\sqrt[3]{m}$. n is the valence of the electrolyte and m is the concentration of the electrolyte (mol / l).

In order to measure the conductivity, the electromagnetic field need be established in the rocks. With the raising of the electromagnetic wave frequency, its shock energy loss will increases and the penetration depth of electromagnetic waves in rocks will be reduced.

3.3. Other Factors that Affect the Electrical Conductivity

3.3.1. The Effect of the Rocks' Porosity on the Electrical Conductivity

Sedimentary rock formations may be electrically conductive, and may also have ionic conductivity. Electronic conductivity depends on the existence of free electrons in the mineral crystals. The number of free electrons is closely related to impurities in the crystal. Less than one percent of impurities in the semiconductor rocks can lead to the concentration change of free electrons or holes up to several orders of magnitude. The ionic conductivity of the rock is mainly due to the ionic in the salts saturated solution. When rock is dry, it is perfect dielectrics. When rock is damp, the conductivity will change up to several orders of magnitude. The formation of rock electrolytic conductivity mechanism is very complex. With the enhancement of degree of dispersion of rock porosity, along with the function of water penetrating into rock layers, the number of ions in the crystal and the amount of minerals integrated into the water are rising, then causing the increase in the conductivity of rock. On the contrary, with the improvement of the degree of the rock water's mineralization and grinding, the adsorption capacity of minerals of ions in the water will be strengthened. In addition, the electrical conductivity of water in the rock will be reduced.

The expression of conductivity of the rock soaked in the water σ_W is

$$\sigma_W = \sigma_r \frac{1 - \sqrt[3]{(1 - k_\xi)^2}}{1 + 0.25\sqrt{1 - k_\xi}}, \tag{5}$$

where σ_r is the conductivity of aqueous solutions, k_ξ is the porosity of the rock. Visibly, the conductivity of the water-saturated rock depends largely on its porosity. The curves are shown in Fig. 1.

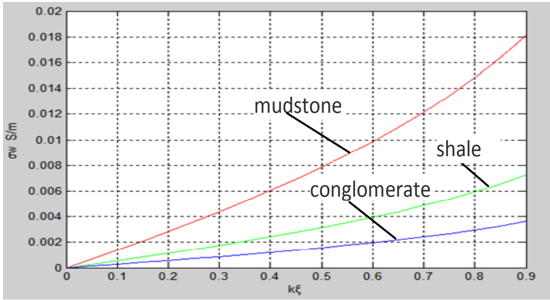

Fig. 1. The change of vary soaking rock conductivity σ_W with porosity k_ξ .

3.3.2. The Effect of the Temperature of the Rock on the Electrical Conductivity

The conductivity σ is also related to the temperature of the rocks, because the conductivity of the solution in the rocks relates to the temperature to a great extent. The relationship of the conductivity and temperature of the solution is:

$$\sigma_t = \sigma_0 [1 + \rho_t (t - t_0)], \tag{6}$$

where σ_t and σ_0 is conductivity of the solution separately at the temperature of t and t_0. ρ_t is the temperature coefficient.

In coal mine, the temperature change is little on the same level of rock. However, along with the increase of the depth, the temperature of the rock formations will raise. In general, if the depth of mine increases 100 m, the temperature will raise 3 ºC.

4. The Design of a Measurement Method of the Conductivity in Underground Coal Mine

4.1. The Connecting Methods of Coal Mine Underground Grounding Electrode

The connecting methods of coal mine underground grounding electrode are shown in Fig. 2.

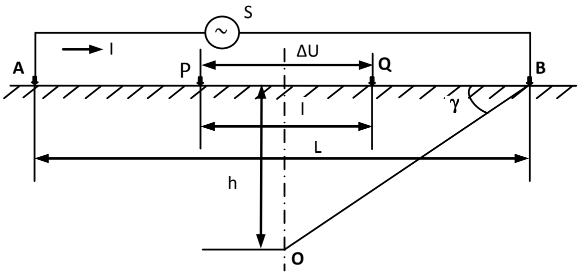

Fig. 2. The connecting methods of coal mine underground grounding.

Where the A and B is the emission grounding electrode. By the signal source S, a current I in the rocks can be generated in the A and B loop. The P and Q is the receiving grounding electrode. The four grounding electrodes are arranged symmetrically along a straight line. The distance between the receiving electrodes P and Q to the emission electrode A and B is equal. That is $r_{AP} = r_{BQ}$. At the same time, the distance to the AB center is equal too. If it meets that the size of the measured rock is much larger than the size of the electrodes, the electrodes can be regarded as a point electrode. On the surface of the rock, the voltage between the receiving electrodes P and Q is:

$$\Delta U = U_P - U_Q = \frac{I}{2\pi\sigma}\left(\frac{1}{r_{AP}} - \frac{1}{r_{AQ}} + \frac{1}{r_{BN}} - \frac{1}{r_{BP}}\right), \quad (7)$$

where I is the current of the emission electrode circuit, $r_{AP}, r_{AQ}, r_{BQ}, r_{BP}$ are the distance from the emission electrodes A and B to the receiving electrode P and Q. In the symmetric setting, there are $r_{AP} = r_{BP}, r_{AQ} = r_{BQ}$. When the distance of the emission electrodes A and B is L and the distance of receiving electrodes P and Q is l, the Formula (7) change into (8).

$$\Delta U = \frac{4Il}{\pi\sigma(L^2 - l^2)} \quad (8)$$

The general requirement is to take $l = 0.2\ L$, it can get Formula (9):

$$\sigma = \frac{I}{1.2\Delta U\pi L} = \frac{1}{K}\frac{I}{\Delta U}, \quad (9)$$

where $K=1.2\pi L$ is called the apparatus coefficient of the measuring apparatus. It is obvious that in order to measure the conductivity σ, the measurement of the current I in the emission electrodes A and B loop and the voltage ΔU between the receiving electrode P and Q must be conducted.

In Fig. 2, point O is on the symmetry axis of the four buried electrodes and the depth from the rock surface to the point O is h, the expression of current density j of the point O is:

$$j = \frac{4I}{\pi L^2\left[\sqrt{1+\left(\frac{2h}{L}\right)^2}\right]^3} = j_0\frac{1}{\left[\sqrt{1+\left(\frac{2h}{L}\right)^2}\right]^3}, \quad (10)$$

when the h = L, j≈0.09j_0 and h=3L, $j = \frac{1}{194}j_0$.

Be made $H_0 = \frac{2h}{L} = tg\gamma$, there will be

$$\frac{I(H_0)}{I} = \frac{2}{\pi}arctgH_0 \quad (11)$$

To guarantee that the measurement deviation is less than 10 %, there will be $I(H_0)/I=0.9$, $H_0=6.3$, L=h/3.15. Obviously, it must be ensured that the distance L between the emission electrode A and B is less than 1/3.15 of the thickness of rock h. If the requirements of the measurement deviation is less than 5 %, there will be $I(H_0)/I=0.95$, $H_0=12.7$, L=h/6.35. If the multi-layer rocks of different conductivities exist within the measured region, the final measurement results are the average conductivity of the multi-layer mediums.

4.2. The Frequency Selection of the Signal Source S in the Conductivity Measurement Circuit

The high-frequency cut-off frequency depends on the equivalent capacitance of the electrode and the setting size of the ground electrode. If the medium to be measured mainly has high frequency conducting current, the high-frequency cut-off frequency of the four-electrode device is met:

$$f \le 8.14^4\frac{4}{\sigma(L+l)^2} \quad (12)$$

It can be obtained that the range of the measured conductivity is 2~10^{-4} S/m, the size of buried electrodes: *l*=200 mm, *L*=1000 mm, the range of the highest cut-off frequency of the four-electrode device is 6 kHz~121 MHz.

4.3. Design of Measurement Circuit of the Conductivity of Underground Rock

The technical parameters of the rock conductivity measurement circuit are as followed:

1) The sending frequency range: 1 kHz ~ 120 kHz,
2) The measured conductivity range: 10^{-4}~2 S/m,
3) The size of buried electrodes: *l*=200 mm, *L*=1000 mm,
4) The electrodes' diameter is 20 mm,
5) The apparatus coefficient: $K=1.2\pi L=3.76$,
6) The input resistance of the differential amplifier R>2 MΩ.

The block diagram of the measurement circuit is as follows:

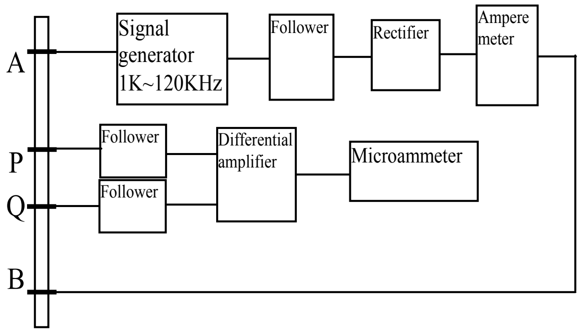

Fig. 3. The block diagram of the measurement circuit.

5. The Method of Certifying the Effect of Frequency on Conductivity of Rocks

In the measurement process, the signal frequency should be selected. An electromagnetic field in the rock will be excited. In the area of the fluctuating electromagnetic field, r_1 and r_2 are the two selected measurement points, H_{r1} and H_{r2} respectively represent the amplitude of the magnetic field strength of these two points. The measurement diagram is shown in Fig. 4.

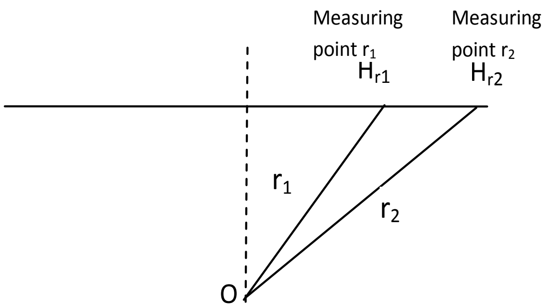

Fig. 4. The measurement diagram.

Then, there is the following formula:

$$H_{r2} = H_{r1} e^{-\alpha(r_2 - r_1)}, \tag{13}$$

where r_1 and r_2 are the distances from the measuring point to the origin point O separately, and $r_1 < r_2$. α is the attenuation coefficient.

$$\alpha = \frac{\ln \frac{H_{r2}}{H_{r1}}}{r_2 - r_1} \tag{14}$$

During the measurement process, two different frequencies f_1 and f_2 are selected to measure**,** and then get two attenuation coefficient α_1 and α_2 are obtained. Thus, we can obtain a conductivity of:

$$\sigma = \frac{2\alpha_1\alpha_2}{\omega_1\omega_2\mu}\sqrt{\frac{\alpha_1^2\omega_2^2 - \alpha_2^2\omega_1^2}{\alpha_2^2 - \alpha_1^2}}, \tag{15}$$

where ω_1 and ω_2 are the angular frequencies which are corresponding to the frequencies f_1 and f_2 respectively. μ is the formation permeability.

6. Conclusions

In the underground coal mine, the relationship between conductivity and frequency of natural-buried rocks is quite complex. Due to a variety of different factors and burial conditions, the conductivity will be varied within a wide range

1) Under the influence of a variety of factors, such as frequency, temperature, humidity, porosity, pressure, rock mineral composition and polarization field strength, the conductivity measurement results will change greatly. Therefore, in the measurement, different frequencies should be chose.

2) In the actual measurement, a few measuring points should be selected; several measurements can be done in the different directions of the rock and then note the average of the measurement results.

3) When the conductivity is measured in the coal mine, it is better to try to choose the roadway without any metal, cable, wire rope to lay the measuring electrode. However, in the highly mechanized modern mines, it is not easy to achieve the conditions mentioned above. These issues should be considered when the actual measurement is conducted in the future.

4) The offset and dispersion of conductivity of multi-layer structure rocks is greater than uniform rocks. If the seam around the coal is relatively uniform, the rock can be regarded as a uniform rock to study. The anisotropy coefficient should not be more than 1.3~ 1.5. If the structure of rocks is multi-layer, the influence of anisotropy on the measurement results is still very serious.

Acknowledgements

We want to thank the Natural Science Foundation of Shanxi Province of China (2013011019-2) for supporting the project, as well as the authors of references for their contributions to many of the results and ideas illustrated here.

References

[1]. Jinyi Tao, The analysis of the measurement method of conductivity of underground rock with through-the-earth wireless communication in coal mine, *Journal of Computational Information Systems, Binary Information Press*, Vol. 8, Issue 20, 2012, pp. 8389-8396.

[2]. Jinyi Tao, Research on electromagnetic wave through-the-earth wireless communication for coal mine disaster, in *Proceedings of the International Conference on Web Information Systems and Mining (WISM 2011 part I LNCS 6987)*, Taiyuan, China, 2011, pp. 1-10.

[3]. Wendong Liu, Zhijun Zhang, Zhenghe Feng, Bidirectional rectangular ring antenna for coal mine /tunnel communication, *Microwave and Optical Technology Letters*, Vol. 55, No. 6, June 2013, pp. 1412-1416.

[4]. Warren L. Stulzman, Gary A. Thiele, S. Zhu, Antenna Theory and Design (2nd Edition), *Posts and Telecom Press*, China, 2006.

[5]. Ian A. Glove, Peter M. Grant, Keng Li, Jian Dong, etc., Digital Communication (2nd Edition), *China Machine Press, China,* 2006.

[6]. Zengxue Li, Coal Geology, *China Coal Industry Publishing House*, 2009.

[7]. Jiping Sun, Technologies of monitoring and communication in the coal mine, *Journal of the China Coal Society,* Vol. 35, No. 11, November 2010, pp. 1925-1929.

[8]. Yanfeng Wang, Hongzhen Yu, Shen Zhang, Guangguo BI, Analysis of the characteristic of monocycle waveform in coal mine UWB communication system, *Journal of China University of Mining and Technology,* Vol. 35, No. 2, March 2006, pp. 167-172.

[9]. Baowei Lv, Zhensong Wang, Theory of Radio Wave Propagation and Applications, *Science Press*, China, 2003.

[10]. Junhua Chen, Xiaozhou Chen, Study on coal mine safety monitoring system with emergency voice communication based on wireless sensor network, *Applied Mechanics and Materials*, Vol. 195-196, 2012, pp. 956-961.