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Very Low Frequency Propagation Characteristics Analysis in Coal Mines

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ABSTRACT Electromagnetic wave penetration coal-rock communication is a significant part for the smart mine communication technology, there are great challenges for electromagnetic wave is rapidly attenuated by factors such as geology and coal seam structure. In order to provide a theory basis for wireless communication technology development in coal rock, based on the Maxwell's equations, this paper establishes a physical model of wireless communication under the conditions of coal seam. To characterize the performance of the electromagnetic wave propagation, we use the Maxwell's equations to derive the exact expression of attenuation coefficient. Also, the parameters of coal and other factors affecting the electromagnetic wave propagation are analyzed and discussed. To further obtain more insights, the attenuation coefficient and skin depth of the very low-frequency (VLF) electromagnetic wave in coal medium with different degrees of metamorphism are studied, as well as the influence of resistivity. This provides scientific theoretical support for the application of VLF communication in coal mines. Finally, our theoretical analyses are verified by computer simulation, and the simulated numerical results show that: 1) The range of frequency of electromagnetic wave suitable for coal medium propagation is $3\sim 3KH\text{z}$ (VLF); 2) The order of the electromagnetic waves attenuation coefficient in coal with different degrees of metamorphism is: anthracite > lignite > fat coal > coking coal > lean coal, and the order of skin depth is: lean coal > coking coal > fat coal > lignite > anthracite; 3) The resistivity of coal has little effect on the attenuation of electromagnetic wave when VLF is used for communication.

INDEX TERMS Coal medium, Very Low Frequency (VLF), Attenuation coefficient, Wireless communication

I. INTRODUCTION

The wireless communication technology of coal mines is always a hot spots, which has been attracted great interests from coal academia and industry [1–3]. The development of the modern mining industry requires the implementation of new communication solutions that can support automated machines and sensors in the underground environments [4]. However, due to the complex and harsh environment of the coal mine production, the electromagnetic waves are greatly depleted under such circumstances, resulting in the development of under mine wireless communication is relatively slow. Traditionally, underground communications are dominated by wired communications or other simple wireless communication devices, such as narrowband broadcasting intercom and ultra high-frequency leakage cable communications. The authors in [5] analyzed the problems of

current mine narrow band broadcasting intercom system, and proposed a design scheme of embedded mine broadcasting intercom system based on controller area network (CAN) bus. Based on the theory of leaky cable communication, the authors in [6] applied leaky cable technology to underground communication, which can realize the wireless data, image and voice transmission under mines. The communication system of wired transmission is relatively complete in functions, but due to the limitations of communication facilities, the reliable communication under mines are facing great challenges, such as high cost, poor flexibility, and poor anti-interference ability. Therefore, it is great practical significance to design the wireless communication systems of a coal mine for replacing the existing communication systems.

Recently, great number of researchers from all over the world have done a lot of works on underground wireless

communication. The authors in [7] studied the propagation characteristics of electromagnetic waves and analyzed the influence of environmental factors on their propagation characteristics. A statistical model was established in empty straight coal mine roadway at ultra high-frequency (UHF) in which the channel was carried out at 900 MHz, 1800 MHz and 2.4 GHz were established in [8]. The authors of [9] analyzed the effects of various complex environmental factors on the characteristics of wireless channels in coal mine roadways, and the channel model of roadway was established. For the long-wall mining tunnel, [10] built a scaled model and the propagation characteristics were measured in the presence of UHF radio waves. In [11], the electromagnetic wave propagation characteristics of the coal mine communication under the frequency of 900 MHz are analyzed. Some researchers also have done some research on the propagation characteristics of electromagnetic waves in geodetic layered medium. In [12], the authors studied the propagation characteristics of very low frequency electromagnetic waves in semi-conductor medium, and proposed an implementation scheme of the electromagnetic wave through-the-earth radio communication system for coal mine disaster relief. When the earth was regarded as the ideal uniform medium and the earth three-layer consumable model, authors in [13] deduced the transmission coefficient and reflection coefficient of electromagnetic waves propagating in the earth. It reveals that the low-frequency signal transmission is an important condition for ensuring the reliability of the ground-penetrating communication systems.

So far, there are some research works on the electromagnetic waves transmission of coal-rock media in coal mines. Electromagnetic waves propagating characteristic in the process of coal rock outburst is analyzed by theory in [14]. Authors in [15] studied the attenuation characteristics of electromagnetic waves in coal-rock media and various geological anomalies by radio wave perspective forward modeling. The wireless communication attenuation model of coal-rock media and the roadway was established in [16]. The results indicate that the communication frequency band must be less than 1MHz when the skin depth is more than 5 meters in coal rock. The electromagnetic waves propagation loss is affected by many factors, and the penetration loss of electromagnetic waves of different frequencies is different. Regarding to medium-high frequency electromagnetic waves, authors of [17] investigated the propagation characteristics under the conditions of coal medium and derived the amplitude attenuation constant related to the angle of incidence. The authors in [18] discuss the propagation attenuation modeling for wireless communication in underground channels. It is concluded that the optimum frequencies of electromagnetic waves in depending on the conductivity of the rock and the distance ranges are determined. The authors in [19] take a circular tunnel and a rectangular tunnel as examples, the influence of electrical parameters on UHF radio waves propagation are analyzed. The conclusion gives a reference for design the wireless communication system in tunnels. Apart

the aforementioned works, [20–23] also studied coal mine safety aspects and environmental monitoring, but most of the research focused on wireless communication in the roadway.

Motivated by the above discuss, we first analyze the effects of various factors on the propagation of electromagnetic waves in coal medium and derive the exact expression of attenuation coefficient based on Maxwell's equations. Then we establish the physical model of wireless communication in coal medium and analyze the frequency suitable for electromagnetic wave propagation. Finally, we simulate the attenuation coefficient and skin depth of the very low-frequency (VLF) electromagnetic wave in coal mediums with different degrees of metamorphism by computer simulation. Furthermore, the influence of resistivity on the attenuation coefficient is analyzed. The results show that 1) The frequency of electromagnetic wave suitable for coal medium propagation is 3~3KHz (VLF) ; 2) The order of the electromagnetic waves attenuation coefficient in coal with different degrees of metamorphism is: anthracite> lignite> fat coal> coking coal> lean coal, and the order of skin depth is: lean coal > coking coal > fat coal > lignite > anthracite; 3) The resistivity of coal has little effect on the attenuation of electromagnetic wave when VLF is used for communication.

The remainder of this paper is organized as follows. In Section 2, we introduce the electrical parameters of coal and the factors that can affect the propagation of electromagnetic waves. In Section 3, we use the basic theory of electromagnetic wave propagation to analyze the influence of electrical parameters on the attenuation coefficient. In Section 4, we establish the physical model of wireless communication in coal medium and analyze the range of frequency suitable for electromagnetic waves propagation. Then we simulate the propagation characteristics of the VLF electromagnetic wave in coal mediums with different degrees of metamorphism. Finally, we analyse the influence of resistivity on the attenuation coefficient by computer simulation. Conclusion and outlook are given in Section 5.

II. FACTORS AFFECTING ELECTROMAGNETIC WAVE PROPAGATION IN COAL MEDIUM

The transmission environment of electromagnetic waves in the coal medium is relatively complex. In this section, the parameters of coal and other factors affecting the electromagnetic waves propagation are analyzed and discussed.

A. ELECTROMAGNETIC PARAMETERS OF COAL MEDIUM

The electric parameters, porosity, temperature and humidity of coal all affect the propagation of electromagnetic waves. The electrical parameters of coal include magnetic permeability, permittivity and conductivity. In terms of magnetism, coal rocks are typical anti-magnets, and they contain few magnetic substances. The magnetic permeability is almost the same as that of vacuum [24]. The magnetic permeability can be set to a constant $\mu = 4\pi \times 10^{-7} H/m$. The permittivity is another important electromagnetic parameter of

TABLE 1: The conductivity of different coal media

Coal medium	Conductivity(S/m)
anthracite	$10^{-2} \sim 10^{-1}$
lignite	$5 \times 10^{-3} \sim 10^{-1}$
fat coal	$10^{-4} \sim 10^{-2}$
coking coal	2×10^{-3}
lean coal	$3 \times 10^{-3} \sim 10^{-1}$

coal medium that changes with many factors. It includes the physicochemical components, temperature, humidity, and the various components constituting the medium.

Coal is a conductive medium and the structure is very complicated. Electrical conductivity is also affected by a number of factors. It includes humidity, temperature, pressure, porosity, electromagnetic wave frequency and the physical and chemical composition of the medium, which will cause the conductivity of the medium to change. The research shows that [25, 26]: the conductivity of coal rocks with different porosities is also different. The conductivity of low porosity coal and rock masses is low. Conversely, the conductivity of high porosity formations is high. Table 1 shows the conductivity of different coal medium [16].

B. TEMPERATURE AND HUMIDITY

The temperature can change the electrical parameters of coal. With the increase of temperature, the attenuation coefficient, permittivity and conductivity of the electromagnetic waves were decreased [27]. As the humidity of the coal medium increases, the amount of electromagnetic waves reflection was increased and the transmission energy was decreased, which is not conducive to the propagation of electromagnetic waves.

III. ELECTROMAGNETIC FIELD IN COAL MEDIUM

In this section, we derive the exact expression of attenuation coefficient based on the Maxwell's equations and the influence of various parameters on the attenuation coefficient is studied.

A. MAXWELL'S EQUATIONS

Electric and magnetic fields with the same phase and perpendicular to each other, propagating outward in the form of waves to form electromagnetic waves. Its propagation direction is perpendicular to the plane formed by the electric field and the magnetic field, thereby effectively transmitting energy. The Maxwell's equations are a set of partial differential equations that Maxwell's derived in the 19th century. Maxwell's equations presents the basic laws of electromagnetic phenomena [28]. The equations are as follows:

$$\begin{cases} \nabla \times H = J + \frac{\partial D}{\partial t} \\ \nabla \times E = -\frac{\partial B}{\partial t} \\ \nabla \cdot B = 0 \\ \nabla \cdot D = \rho \end{cases}, \quad (1)$$

where H represents the strength and direction of the magnetic field, whose unit is A/m; E represents strength and direction of the electric field with its unit V/m^2 ; D represents the electric displacement, whose unit is C/m^2 ; B denotes the magnetic induction intensity, whose unit is Wb/m^2 ; J is the current density A/m^2 ; ρ represents the charge density in C/m^3 .

Maxwell's equation comprehensively reflects the basic properties of electric and magnetic fields, and clarifies the relationship between electric and magnetic fields with a unified view. In addition to the above four equations, the constitutive relationship of the medium is also required to solve the solution problem. In the next section, based on Maxwell's equations and the constitutive relationship of the medium, we obtain the exact expression of the attenuation coefficient, and analyze the parameters that affect the attenuation coefficient in theory.

B. ATTENUATION PARAMETERS OF ELECTROMAGNETIC WAVES IN COAL MEDIA

The propagation of electromagnetic waves in a lossy medium can produce attenuation. The main reason is the presence of free electrons. When electromagnetic waves propagate in the medium, the electric field interacts with the magnetic field to form a conduction current, and the change of the electromagnetic field causes energy loss in the transmission of the electromagnetic wave. The coal medium can be regarded as a conductive medium [15]. In order to make the calculation simple, this paper considers the coal medium as a linear medium with uniform isotropic (the same below). In the passive region, its constitutive relationship is as follows:

$$\begin{cases} D = \varepsilon E \\ B = \mu H \\ J = \sigma E \end{cases}, \quad (2)$$

where ε and μ are the permittivity and the magnetic permeability of coal medium with unit F/m and H/m, respectively, while σ is the conductivity of coal medium with unit S/m. Substituting (2) into Maxwell's equations, we can obtain the following as:

$$\begin{cases} \nabla \times H = \sigma E + \varepsilon \frac{\partial E}{\partial t} \\ \nabla \times E = -\mu \frac{\partial H}{\partial t} \\ \nabla \cdot H = 0 \\ \nabla \cdot E = 0 \end{cases}, \quad (3)$$

Taking the curl of formula (3) can obtain the wave equations of E and H as follows:

$$\nabla^2 E - \mu\varepsilon \frac{\partial^2 E}{\partial t^2} - \mu\sigma \frac{\partial E}{\partial t} = 0, \quad (4)$$

$$\nabla^2 H - \mu\varepsilon \frac{\partial^2 H}{\partial t^2} - \mu\sigma \frac{\partial H}{\partial t} = 0, \quad (5)$$

The electromagnetic wave is a simple harmonic, and the complex expressions of E and H are $E = |E| e^{j\omega t}$ and $H =$

$|H|e^{j\omega t}$, where $|E|$ and $|H|$ are complex amplitudes, and ω is angular frequency. Then equations (4) and (5) can be re-expressed as:

$$\nabla^2 E + (\mu\epsilon\omega^2 - j\mu\sigma\omega) E = 0, \quad (6)$$

$$\nabla^2 H + (\mu\epsilon\omega^2 - j\mu\sigma\omega) H = 0, \quad (7)$$

It can also be re-written as:

$$\nabla^2 E + K^2 E = 0, \quad (8)$$

$$\nabla^2 H + K^2 H = 0, \quad (9)$$

$$K^2 = \mu\epsilon\omega^2 - j\mu\sigma\omega = \mu\omega^2 \left(\epsilon - j\frac{\sigma}{\omega} \right) = \mu\omega^2 \epsilon_k, \quad (10)$$

Equations (8) and (9) are Helmholtz equations [10], where K is complex wave number, ϵ_k is called the complex permittivity of coal medium. Let $K = \beta - j\alpha$ ($\beta > 0, \alpha > 0$), bring into equation (10).

$$\begin{cases} \beta^2 - \alpha^2 = \mu\epsilon\omega^2 \\ 2\beta\alpha = \mu\sigma\omega \end{cases}, \quad (11)$$

α and β are calculated as follows:

$$\beta = \omega \sqrt{\frac{\mu\epsilon}{2} \left[1 + \sqrt{1 + (\sigma/\epsilon\omega)^2} \right]}, \quad (12)$$

$$\alpha = \omega \sqrt{\frac{\mu\epsilon}{2} \left[\sqrt{1 + (\sigma/\epsilon\omega)^2} - 1 \right]} \quad (13)$$

where α is the attenuation coefficient, indicating the attenuation of the amplitude per unit length along the propagation direction; β is the phase coefficient. The formula (12) and (13) show that the amplitude of the wave is attenuated and the phase is delayed when electromagnetic waves propagate in a lossy medium. During the propagation of electromagnetic waves, the phase coefficient and attenuation coefficient are affected by the electrical parameters (σ, μ, ϵ) and frequency (f) of the coal medium. When σ is very small, ie $\sigma/\omega\epsilon \ll 1$, $\alpha = \frac{\sigma}{2} \sqrt{\mu/\epsilon}$, the attenuation coefficient is proportional to the conductivity and inversely proportional to the square root of the dielectric constant, and it has little to do with the frequency of the electromagnetic waves. When σ is very large, ie $\sigma/\omega\epsilon \gg 1$, $\alpha = \sqrt{\mu\omega\epsilon/2}$, the attenuation coefficient is related to the frequency and conductivity of the electromagnetic waves with almost independent of the dielectric constant. In general, ie $\sigma/\omega\epsilon \approx 1$, $\alpha = \omega \sqrt{\mu\epsilon/2}$, the attenuation coefficient is proportional to the frequency and is related to the dielectric constant.

Since the conductivity of coal medium is generally in the range of $10^{-5} \sim 10^{-1}$ S/m, and its permittivity has almost the same effect on the propagation of electromagnetic waves. To satisfy $\sigma/\omega\epsilon \gg 1$, only the lower frequency can

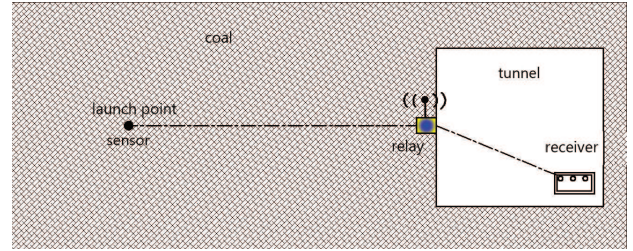


FIGURE 1: Physical model of wireless communication in coal medium

be used to make the attenuation coefficient small enough. Coal belongs to the category of semi-conducting medium with a small dielectric constant, $\sigma \ll \omega\epsilon, \sigma/\omega\epsilon \gg 1$, substituting $\omega = 2\pi f$ into $\alpha = \sqrt{\mu\epsilon\omega/2}$ yields a simplified form of the attenuation coefficient α .

$$\alpha = \sqrt{\mu\omega\sigma/2} = \sqrt{\pi\mu f\sigma}, \quad (14)$$

IV. SIMULATION ANALYSIS OF VERY LOW FREQUENCY ELECTROMAGNETIC WAVE IN COAL MEDIUM

In this section, we verify the accuracy of the theoretical analysis results by computer simulation. Unless otherwise stated, all simulation parameters are set as: $\mu = 4\pi \times 10^{-7} H/m$, $\sigma_1 = 5 \times 10^{-3} S/m$, $\sigma_2 = 3 \times 10^{-2} S/m$, $\sigma_3 = 2 \times 10^{-1} S/m$, $f_1 = 50 Hz$, $f_2 = 100 Hz$, $f_3 = 200 Hz$, $f_4 = 3000 Hz$, $f_5 = 10000 Hz$, $f_6 = 30000 Hz$, $\rho_1 = 1000 \Omega \cdot m$, $\rho_2 = 1500 \Omega \cdot m$, $\rho_3 = 2000 \Omega \cdot m$, $\epsilon = 3.0 \times 10^{-12} F/m$.

A. ESTABLISHMENT OF COAL MEDIUM PHYSICAL MODEL

Due to the complexity of the coal medium structure, in order to simplify the calculation conditions, the physical model is assumed as follows: 1) The structure and electrical parameters of the medium in different directions are constant; 2) The coal medium is regarded as an ideal transmission medium, regardless of temperature, humidity, porosity and other factors. The relay is buried in the tunnel wall and the information detected by the sensor is transmitted to the receiver by wireless communication. The established physical model of wireless communication is shown in Fig.1. We can use this model to monitor the stress and failure in the coal mines.

B. SELECTION OF ELECTROMAGNETIC WAVE FREQUENCY

Coal belongs to the category of the semi-conducting medium. When electromagnetic waves propagate in a semi-conducting medium, the expression of the attenuation coefficient $\alpha = \sqrt{\pi\mu f\sigma}$, where f represents the frequency of the electromagnetic waves. The magnetic permeability is a constant $\mu = 4\pi \times 10^{-7} H/m$. σ is conductivity of the medium. In order to analyze the transmission performance of electromagnetic waves with different frequencies in the coal medium,

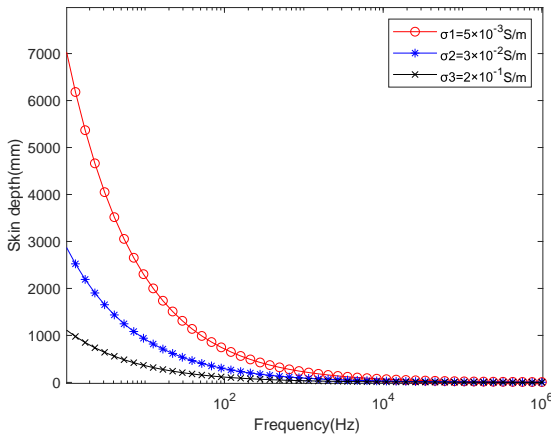


FIGURE 2: Curve of skin depth and frequency at different conductivity

the concept of skin depth is introduced, and the expression of it is as follows.

$$\delta = \frac{1}{\alpha} = \frac{1}{\sqrt{\pi \mu f \sigma}}, \quad (15)$$

The relationship between electromagnetic wave propagation frequency and skin depth at different conductivity is simulated. The skin depth essentially describes the distance of electromagnetic waves transmission. As can be seen from Fig.2, the transmission frequency of electromagnetic waves is inversely proportional to the skin depth. In other words, The transmission distance was raised with an decreasing frequency of electromagnetic waves. Conversely, the transmission distance was decreased with an increasing frequency of electromagnetic waves.

Through the above analysis, the electromagnetic waves with lower frequency not only attenuate slowly but also have longer transmission distance, which is more conducive to the transmission of wireless communication in coal mines. Based on this conclusion, we choose VLF (3~3KHz) electromagnetic waves as the communication frequency band in the coal medium. The very low-frequency electromagnetic waves not only can propagate stably in the coal rocks but have a strong penetration ability to coal rocks. The strong anti-interference ability makes it less affected by uncertain environment.

C. ATTENUATION CHARACTERISTICS OF VERY LOW FREQUENCY ELECTROMAGNETIC WAVES IN DIFFERENT COAL MEDIUM

Fig.3 shows the relationship between the attenuation coefficient and conductivity at different frequencies. The electromagnetic wave attenuation coefficient also increases as the conductivity of the coal medium increases. In addition, the attenuation gradually decreases as the value of σ decreases, and the influence of the conductivity on the electromagnetic wave is relatively decreased. When the conductivity increases to a critical point of 10^2 , the attenuation begins to increase

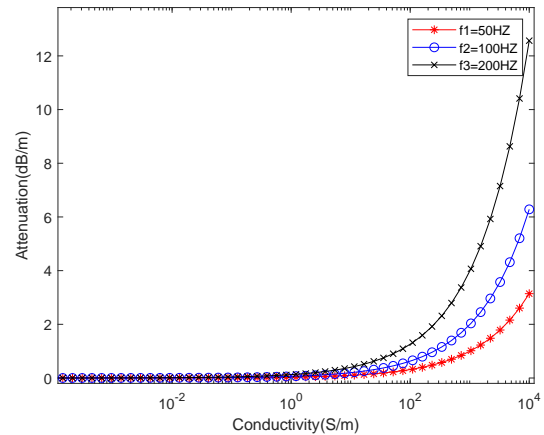


FIGURE 3: Curve of conductivity and attenuation coefficient at different frequency

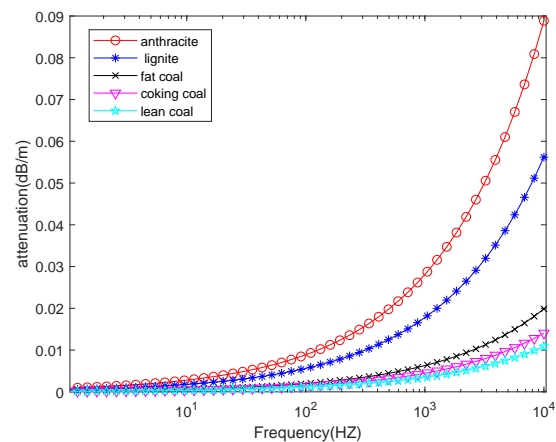


FIGURE 4: Attenuation coefficient of different frequencies in different coal medium

abruptly. Since the conductivity of the coal seam is about 10^{-5} S/m to 10^{-1} S/m, which is much less than 10 S/m. Therefore, the lower frequency is more suitable for communication in coal mines.

We simulate the attenuation of very low-frequency electromagnetic waves in different coal mediums [29], as shown in Fig 4. It can be seen that the attenuation coefficients of electromagnetic waves in coal medium with different degrees of metamorphism are different, and the order of attenuation coefficient is: anthracite > lignite > fat coal > coking coal > lean coal. It can be seen from Fig.4 that the attenuation coefficients of electromagnetic waves in different coal media are different. However, they all show the same properties as electromagnetic waves propagating in a medium. That is, the electromagnetic attenuation is rapidly attenuated as the frequency of the electromagnetic wave increases. However, in the very low-frequency (3 ~ 3KHz) range, the attenuation coefficient does not change much, only between 0 and 0.04. Therefore, we use VLF(3 ~ 3KHz) electromagnetic waves

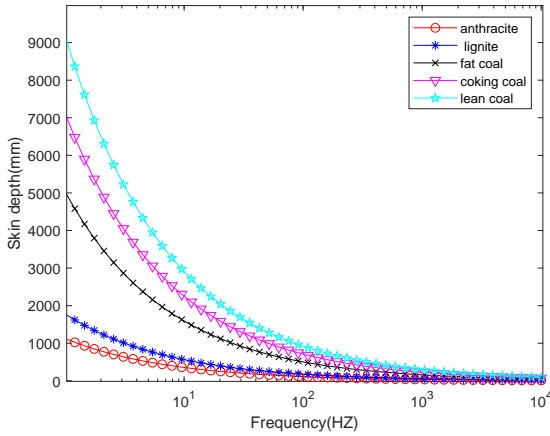


FIGURE 5: Skin depth of different frequencies in different coal medium

for coal mine communication. Fig.5 is a plot of the frequency and skin depth in different coal mediums.

Fig.5 plots the skin depth of electromagnetic waves versus frequency in coals with different degrees of metamorphism is ranked as: lean coal > coking coal > fat coal > lignite > anthracite, which is the opposite of the law of attenuation coefficient. It can be concluded that the distance of signal transmission continues to shrink with the increase of frequency. Therefore, it is best to use the lower frequency band for underground communication. Through the above analysis, for a certain coal medium, its electrical parameters play a decisive role. In order to reduce the attenuation coefficient of electromagnetic waves and make electromagnetic signals transmit farther, it is necessary to use VLF (3~3KHz) electromagnetic waves for communication.

D. RELATIONSHIP BETWEEN ATTENUATION COEFFICIENT AND RESISTIVITY

The electrical resistivity of coal is mainly determined by the degree of coal metamorphism. As the metamorphic degree of coal is higher, the carbon content of the coal increases and the resistivity of the coal becomes smaller. In addition, the electrical resistivity of coal is closely related to humidity. With the raise of the moisture and humidity, the electrical resistivity was decreased and the attenuation of the electromagnetic wave was increased [15]. We express ω and σ in Equation 3 as follows by frequency f and resistivity ρ , respectively.

$$\alpha = \sqrt{2\pi f \sqrt{\mu\epsilon} \sqrt{\left(\sqrt{1 + \left(\frac{1}{2\pi f \epsilon \rho} \right)^2} - 1 \right)}}, \quad (16)$$

According to formula (16), assuming a dielectric constant $\epsilon = 3.0 \times 10^{-12} F/m$, a theoretical relationship diagram of resistivity ρ and attenuation coefficient α at different frequencies can be plotted. When the permittivity is a constant, the

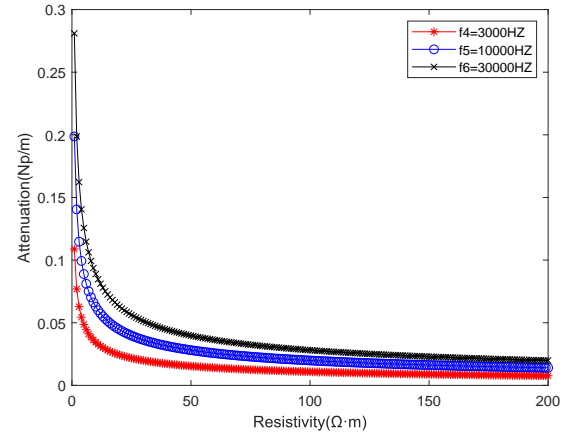


FIGURE 6: Curve of resistivity and attenuation coefficient at different frequency

attenuation coefficient will decrease as the resistivity increases. It can be seen from the Fig. 6 that the difference between the three curves of different frequencies become more and more smaller with the resistivity increases, and there is a tendency to merge into a curve. This characteristic indicates that it is not easy to distinguish different types of high-resistance coal rocks using multiple frequencies. Therefore, electromagnetic waves of different frequencies can be used to study geological bodies with low resistivity.

According to formula (16), it is assumed that the permittivity ϵ of coal is constant and the resistivity ρ takes three different values. The relationship between frequency and the attenuation coefficient is shown in Fig.7. It can be seen from Fig.7 that the different resistivity has little effect on the attenuation of electromagnetic waves in the range of very low-frequency. When the frequency in the range of $10^5 Hz$ to $10^8 Hz$, the attenuation rises sharply until the attenuation coefficient reaches a maximum at a frequency of about $10^8 Hz$. The resistivity of the medium is different, and the maximum value of the attenuation coefficient is also different. The attenuation maximum becomes smaller with the increase of resistivity. From this, it can be concluded that the attenuation coefficient increases but does not change much with the increase of frequency in the very low-frequency band. When the frequency of electromagnetic wave exceeds $10^8 Hz$, the attenuation coefficient α reaches a maximum value and tends to be saturated. However, the resistivity of coal has little influence on the attenuation of electromagnetic wave, when using very low-frequency electromagnetic wave for communication.

V. CONCLUSION

In this paper, the propagation characteristics of very low-frequency electromagnetic waves in coal media is studied. Specifically, we use Maxwell's equations to derive the exact expression of attenuation coefficient. Based on the derived formula, the various parameters of coal and other factors

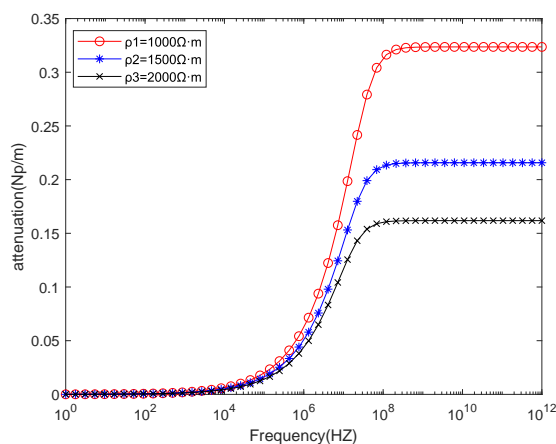


FIGURE 7: Curve of frequency and attenuation coefficient at different resistivity

affecting the electromagnetic wave propagation are analyzed and discussed, and a physical model of wireless communication under the conditions of coal seam is established. we also carry out propagation characteristics analysis for the coal with different degrees of metamorphism through computer simulation. The present paper main research conclusion is as follows: 1) The best frequency range for electromagnetic wave propagation in coal seams is VLF(3~3KHz); 2) The order of the electromagnetic waves attenuation coefficient in coal with different degrees of metamorphism is: anthracite > lignite > fat coal > coking coal > lean coal, and the order of skin depth is: lean coal > coking coal > fat coal > lignite > anthracite; 3) The resistivity of coal has little effect on the attenuation of electromagnetic wave when VLF is used for communication. Because of the complexity of coal seam geological structure, electromagnetic waves will encounter faults, fracture zones, collapse columns and other structures in the coal seam, and there may be water filling, which will affect the propagation of electromagnetic waves [30]. This paper fails to analyze the more complex factors, so we will work on wireless communication under the complex structure of coal seams in the future. Even so, our research provides a theoretical basis for optimizing the optimal communication frequency for coal mine communications. This is of great significance for further research on the propagation mechanism of VLF electromagnetic waves in coal mines.

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