Design of Electromagnetic Wave Resistivity Logging Tool for Underground Coal Mine

Zhang Jiguan
CCTEG XI’AN Research Institute, Xi’an, Shaanxi, 710077, China
E-mail: 285272186@qq.com

Abstract: Electromagnetic wave resistivity logging is an important method in oil logging, but it has not been applied in underground coal mine due to special working conditions and explosion-proof requirements. In this paper, through theoretical analysis and simulation, an electromagnetic wave resistivity logging tool is designed, which is suitable for underground coal mine. The detection of amplitude ratio and phase difference of weak signal is realized, and its performance index meets the actual working conditions.

1. Introduction
With the progress of technology, the drilling construction of underground coal mine has realized the leap from "geometric guided drilling" to "geological guided drilling", but at present, "geological guided drilling" only has a logging parameter, the natural gamma, the logging method is single, and the measurement depth is small.

Electromagnetic wave resistivity logging is an important method in oil logging. It uses the propagation effect of electromagnetic wave in the medium to measure the relative changes of two characteristic parameters (phase difference and amplitude ratio) of electromagnetic field to obtain the resistivity of stratum. It does not rely on drilling fluid as a conducting medium and is suitable for dry hole because of high resolution and large detection depth. In the near horizontal drilling of underground coal mine, combined with natural gamma logging, the geological parameters are measured together, which can better divide the geological section of borehole and determine the depth, thickness and structure of coal seam.

At present, the electromagnetic wave resistivity logging technology has developed rapidly in the field of oil drilling, but for the underground coal mine, due to the size and explosion-proof requirements, the technology has not been applied. In this paper, the electromagnetic wave resistivity logging tool for underground coal mine is designed.

2. Design principle
The theoretical basis of electromagnetic wave resistivity logging is the propagation effect of electromagnetic wave. Due to the different geological parameters of different strata, their responses to medium- and high-frequency electromagnetic field are also different. The amplitude of the electromagnetic wave emitted by the logging tool through the transmitting antenna decreases with the increase of the propagation distance in the stratum. When the propagation distance is the same, the attenuation is related to the resistivity of stratum. At the same time, because the propagation speed of the electromagnetic wave is different in strata with different resistivity, if the propagation distance is the same but the resistivity of stratum is different, the phase change is different. Therefore, by
measuring the phase (difference) and amplitude (attenuation) of the electromagnetic wave with the receiving antenna, the apparent resistivity of the stratum can be inversed.

The basic tool structure of electromagnetic wave resistivity measurement while drilling is a three-coil sonde structure with single transmitter and double receiver, as shown in Figure 1. T1 is a transmitting antenna around the drill pipe, R1 and R2 are two receiving antennas. T1 transmits high-frequency electromagnetic wave which propagates through the stratum and is received by R1 and R2. The phase difference or amplitude ratio of the electromagnetic wave detected by R1 and R2 is related to the resistivity of the nearby stratum. When the current of different frequency passes the transmitting coil, the stratum characteristics are identified by the amplitude ratio and phase difference of the two receiving coils’ signals, and the measuring point is the midpoint of the two receivers[1-2].

![Figure 1. Principle Block Diagram.](image)

2.1 Selection of working frequency

The phase and amplitude changes of electromagnetic wave in the process of stratum propagation are mainly affected by the following physical parameters of the stratum:

- Electrical conductivity (\( \sigma \))
- Permittivity (\( \varepsilon \))
- Permeability (\( \mu \))

When the frequency is greater than 10MHz, the permittivity dominates the wave propagation, and the measured phase shift and attenuation are more dependent on the permittivity of the stratum and less dependent on its resistivity. The propagation of electromagnetic wave with frequency less than 0.1MHz in the stratum is mainly affected by the conductivity of stratum. As the drill pipe is a conductor, a surface current will be formed on the drill pipe. The current will be transmitted between the transmitter and the receiver, resulting in the “short circuit” of measurement tool. In addition, if the working frequency is too low, the amplitude ratio and phase difference range obtained by the instrument will be reduced, affecting the accuracy of the instrument.

In order to eliminate the influence of the permittivity, the lower working frequency of the instrument is required. At the same time, it can greatly reduce the response abnormality caused by the eccentricity of the instrument and the irregular borehole. However, the higher working frequency can improve the measurement accuracy of the instrument. Therefore, the measurement of electromagnetic wave resistivity of pup joint generally adopts two working frequencies: high frequency and low frequency, 1 MHz ~ 2MHz for high frequency and 250 kHz ~ 500KHz for low frequency.

Based on the above analysis, the system uses the electromagnetic wave with the frequency of 2MHz and 400kHz to measure the stratum. In these two frequencies, we can get better phase response, and ignore the influence of the permittivity and the surrounding rock on the measurement, which has good performance in the actual logging.
2.2 Measurement of amplitude ratio

The signal amplitude of electromagnetic wave passing through conductive stratum will appear exponential attenuation, and the attenuation speed is proportional to the conductivity of stratum. The amplitude ratio is the amplitude ratio of the signal detected in the two receiving coils.

If the electromotive force of receiving coils R1 and R2 is $V_1$ and $V_2$ respectively, the amplitude ratio is:

$$E_{ATT} = 20 \log \left( \frac{|V_1|}{|V_2|} \right)$$

(1)

Where: $|V_1|$ and $|V_2|$ are the modules of the electromotive force $V_1$ and $V_2$ of the near receiver and the far receiver, respectively.

In the high conductivity stratum, the signal amplitude difference between the two receiving coils is large, and the signal amplitude of the far receiving coil is significantly smaller than that of the near receiving coil. In the high resistivity stratum, the signal amplitude difference between the two receiving coils is small, and the specific conversion situation is referred to Figure 2.

![Figure 2. Amplitude Resistivity Conversion Template.](image)

2.3 Measurement of phase difference

The phase of electromagnetic wave propagating through two receiving coils is different, which is directly related to the resistivity of stratum. The propagation speed of electromagnetic wave in the resistive stratum is greater than that in the conductive stratum, and the wavelength of electromagnetic wave in the resistive stratum is greater than that in the conductive stratum. Therefore, the greater the resistivity of stratum is, the smaller the phase difference between the two receiving coils is. For the specific transformation, please refer to Figure 3.

The formula of phase difference measurement is:

$$\Delta \Phi = \Phi_1 - \Phi_2$$

(2)

Where: $\Phi_1$ and $\Phi_2$ are the phase angles of the electromotive force $V_1$ and $V_2$. 
3. Design of coil sonde

On the layout of the coil sonde, this system refers to the MPR instrument of Baker Hughes company, and sets up double transmitting and double receiving coils. The structure of the coil sonde is shown in Figure 4. This symmetrical compensation structure can effectively eliminate the influence of temperature and various electronic errors, with good accuracy, large measuring range and simple instrument scale.

3.1 Determination of spacing \( \Delta L \) of receiving coil

The spacing \( \Delta L \) is the distance between two receiving coils. In order to ensure that the phase difference \( \Delta \Phi \) of the electromotive force \( V_1 \) and \( V_2 \) varies from 0° to 360°, the spacing \( \Delta L \) should be less than the minimum wavelength \( \lambda_{\text{min}} \) that may occur in the stratum.

From the phase difference \( \Delta \Phi = \frac{360 \Delta L}{\lambda} \), it can be seen that, when the wavelength is fixed, the smaller the spacing \( \Delta L \) is, the smaller the phase difference \( \Delta \Phi \) that the instrument can measure is. When the phase difference is too small, the measurement error of the instrument becomes larger, which affects the measurement accuracy. Therefore, if the minimum phase difference that can be resolved by the instrument is \( \Delta \Phi_{\text{min}} \), the spacing \( \Delta L \) needs to meet the following requirement\(^{[3-4]}\):

\[
\Delta L > \frac{\lambda_{\text{max}} \Delta \Phi_{\text{min}}}{360} \quad (3)
\]

The spacing \( \Delta L \) also affects the resolution of the instrument to the thickness of longitudinal stratum \( d \). The smaller the spacing \( \Delta L \) is, the higher the resolution is, that is, the smaller thickness of the stratum can be resolved. Therefore, in order to ensure the resolution of the longitudinal stratum, the spacing \( \Delta L \) needs to be smaller than the designed resolution index \( d \).

To sum up, the coil sonde spacing needs to meet:

\[
\frac{\lambda_{\text{max}} \Delta \Phi_{\text{min}}}{360} < \Delta L < \min (\lambda_{\text{min}}, d) \quad (4)
\]

According to the performance index, it is assumed that the main concerned variation range of the resistivity of stratum is 0.1~100 \( \Omega \cdot m \), and the resolution of the instrument is 0.3m. From the
calculation of formula (4), it can be seen that the spacing ΔL should meet the requirement of 0.0016 m<ΔL<0.3 m. In order to give consideration to both the measurement accuracy and resolution, the spacing can be 0.2m.

3.2 Determination of source distance L

Source distance L is the distance from the midpoint of receiving coils R1 and R2 to the transmitting coil. The source distance will directly affect the strength of the signal on the receiving coil. If the source distance is too large, the receiving coil cannot receive the electromagnetic wave signal. The induced electromotive force V2 on the far receiving coil R2 is relatively small, and its induced electromotive force is:

\[ V_2 = 2πr_2E_2 = -\frac{jωμ_0α^2}{2L_2^2} \cdot A e^{-jB} \quad (5) \]

where

\[ A = -\frac{jωμ_0α^2}{2L_2^2} e^{-βL_2} \sqrt{(1 + βL_2)^2 + (βL_2)^2} \]

\[ B = βL_2 - \frac{1}{tg^{-1} \frac{βL_2}{1+βL_2}} \quad (6) \]

Given the minimum receiving sensitivity of the instrument, the upper limit value of the source distance L can be determined by formula (5). At the same time, the source distance L will also affect the longitudinal detection characteristics of the instrument. The larger the source distance L is, the greater the radial detection depth is. Therefore, in order to detect a longer distance, the source distance L should be as large as possible under the condition that the received signal is strong enough. After calculation, the system takes L = 0.9m to meet the demand.

3.3 Determination of coil turns

Using coil sonde with more turns cannot increase the magnetic dipole moment much. In order to reduce the loss of the coil, maintain the strength of the drill pipe and increase the service life of the instrument, the number of coil turns should not be too much, and one turn is used in foreign countries. Based on the results of similar products at home and abroad, the coil diameter of the system is 1mm and the number of turns is 5-10.

4. Circuit design

Electromagnetic wave resistivity logging system while drilling is generally composed of transmitting and receiving parts.

The internal working principle block diagram of the whole logging tool is shown in Figure 5. Its working process is: under the control of DSP, the signal transmitting circuit (including DDS module and power amplification module) provides a certain-power alternating current to the transmitting antenna installed on the pup joint of the tool, then the electromagnetic wave is generated to spread to the stratum. Some of these electromagnetic waves pass through the stratum and are received by two receiving coils on the drill pipe at a certain distance. Then the low-frequency difference-frequency output signal is generated by pre-amplification and mixing filtering in the receiving circuit, and then sent to the subsequent circuit for sampling, processing and storage.
5. Structure design

The structure design is as shown in Figure 6, in which the left side is the circuit part, the middle is the pup joint of transmitting and receiving coil, and the right side is the adapter. Due to the small hole diameter of the borehole in the coal mine, the single-layer collar structure is adopted, and the water passes through the middle. The high-strength outer collar structure is obtained by optimizing the antenna layout, and the high-strength antenna protective cover is further designed. At the same time, the wear of the collar body at the antenna is reduced, so as to increase the overall life of the outer collar.

For structural strength simulation, the results show that the maximum stress value of the drill pipe is between 900MPa and 1000MPa when the drill pipe bears 18000N•m torque. According to the table, the yield stress of beryllium copper is 1250-1500MPa, and the yield stress of non-magnetic stainless steel is equivalent to that of beryllium copper. That is to say, the structure design can bear 18000N•m torque. The final structure of the logging tool is shown in Figure 7.

6. Conclusion

Through theoretical analysis and simulation, the coil sonde, circuit and mechanical structure of the electromagnetic wave resistivity logging tool suitable for the underground coal mine are designed, and the amplitude ratio and phase difference detection of weak signal are realized. Its performance index meets the design requirements and the actual working conditions.
Funded Projects
Major National Science and Technology Special Tasks in the 13th Five-Year Plan (2016ZX05045-003-001).

References
[1] Li Huiyin, Su Yinao, Sheng Limin, et al. A logging while drilling tool for multi-depth electromagnetic wave resistivity measurement [J]. Journal of China University of Petroleum (Edition of Natural Science), 2010, 34(3): 38-42.
[2] Huang Zhongfu, Huang Ruiguang, Chen Peng. Development of MWD Resistivity Logging Tool [J]. Well Logging Technology, 2002, 26(2): 172-175.
[3] Zhao Yuan, Dun Yueqin, Yuan Jiansheng. On Coil System Design for MWD Electromagnetic Wave Logging Tools [J]. Well Logging Technology, 2011, 35(3): 224-229.
[4] Fan Cun. Study on Measurement Technology of Resistivity While Drilling [D]. Northeast Petroleum University, 2010.