Distribution Characteristics and Edge Detection of Electromagnetic Field in Two Beds Formation Based on Analytical Solution

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Abstract. After decades of development of the Chinese petroleum industry, complex oil and gas reservoirs have become the main battlefield for oil and gas field detection and development, which pose severe challenges to geosteering drilling technology that uses integrated logging and conventional logging-while-drilling tools to locate and predict formation interfaces. Based on the developed software for the distribution of forward and lateral detection electromagnetic fields, this paper calculates and analyzes the distribution characteristics of electromagnetic fields at different distances in front, and studies the lateral detection characteristics based on the half-coil of the electric field. The results show that the influence of boundary on the field is revealed according to the distribution characteristics of electromagnetic fields at different distances in front. The 1-3m receiving-transmitting short-pitch half-coil have approximately the same edge detection distance, and when the frequency is less than 20 kHz, the edge detection distance is more than 30m in two beds formation of 0.01S/m and 1.0S/m.

1. Introduction

In the field of oil drilling, logging-while-drilling (LWD) technology is the key to geosteering and real-time formation comparison evaluation in intelligent drilling, and it is an important development direction of logging technology. The geosteering should address two key technologies of drill bit front and side detection [1]. Forward detection can provide effective help for determining geological reservoirs and adjusting drilling trajectories by understanding the formation structure amplitude, reservoir distribution range, and formation properties, etc. [2,3]. Lateral detection, on the one hand, confirms the upper and lower boundaries of the reservoir and guides drilling along the best trajectory of the reservoir [4,5]; on the other hand, determines the geological reserves and oil-bearing areas of the oil and gas reservoirs, and recognizes and evaluates the oil and gas reservoirs [6]. Currently the electromagnetic remote detection technology is mature. Schlumberger respectively introduced electromagnetic wave resistivity instruments such as VDR in 2003, PeriScope HD in 2008, and DDR in 2010, which used tilt or quadrature coil technology to achieve the formation interface and orientation within a range of 1 to 6 m near the wellbore probe. VDR does not have the capability of azimuth measurement. PeriScope HD and DDR have real-time mapping function of multiple interfaces above and below the borehole, whose formation boundary detection distance can reach 30 m, and have a certain forward-looking prospecting capability. In 2014, Schlumberger launched a new generation of Geosphere reservoir mapping and other high-end logging-while-drilling technologies and services, which achieved well logging Long-range detection of formation and geological
structures 30m near the eye by adopting long-distance drilling-while-drilling electromagnetic resistivity logging tools DDR, using multi-frequency multi-component array antennas and segmented modular design as well as real-time inversion algorithms[7,8]. The half-coil has the capability for a long-distance detection, and its open-loop half-coil design is used to realize the electric field measurement under the condition of drilling. Based on the software developed for forward and lateral detection of electromagnetic field distribution characteristics, this paper calculates and analyzes the electromagnetic field distribution characteristics at different distances in front studies the lateral detection characteristics based on the electric field half-coil, and thus provides theoretical basis for the design and application of electromagnetic remote detection instrument.

2. Methods

2.1. Forward detection electromagnetic field distribution theory
In order to study the distribution characteristics of the forward detection electromagnetic field, taking two beds as an example, considering the ideal case, the transmitting coil faces the boundary of the target intervals in front of the detection. The origin of the cylindrical coordinate system is taken on the interface, upwards are positive, the upper dielectric conductivity is $\sigma_2$ and lower is $\sigma_1$, the permeabilities are $\mu_2$ and $\mu_1$ respectively, the dielectric constants are $\varepsilon_2$ and $\varepsilon_1$ respectively, the transmission and reception distance is $L$, and the distance from the transmitting coil to the interface is $h$. Suppose that the transmitting coil is in $\sigma_1$ medium, and the simplified schematic diagram of the two beds formation vertical coil system is shown on the left of Figure 1.

The coil source is a magnetic dipole. The magnetic dipole moment $M = N_I A_T$, $N_I$ is the number of turns of the transmitting coil, $I_T$ is the current of the transmitting coil, and $A_T$ is the cross-sectional area of the transmitting coil. The coil source is rotationally symmetric, so only $E_\varphi$ and $H_z$ in the cylindrical coordinate system are analyzed. The expression of electric field and magnetic field in each bed of medium is given in Reference 9. Based on the expression, “the analysis software for detecting the distribution of electromagnetic fields in front of two beds of formation V1.0” is developed, which can analyze the distribution of electromagnetic fields at different positions from the front boundary.

\[
E_{1\varphi} = -\frac{i\omega M}{4\pi} \int_0^\infty \frac{\xi^2}{\lambda_1^2} \left[ e^{-\lambda_1 |z+h|} - F_{12} e^{-\lambda_1 (h-z)} \right] j_1(\xi \rho) \, d\xi
\]

(1)

\[
E_{2\varphi} = \frac{i\omega M}{4\pi} \int_0^\infty \frac{\xi^2}{\lambda_1^2} (1 - F_{12}) e^{-\lambda_1 h - \lambda_2 z} \cdot j_1(\xi \rho) \, d\xi
\]

(2)

\[
H_{1z} = \frac{M}{4\pi} \int_0^\infty \frac{\xi^2}{\lambda_1^2} \left[ e^{-\lambda_1 |z+h|} - F_{12} e^{-\lambda_1 (h-z)} \right] j_0(\xi \rho) \, d\xi
\]

(3)

\[
H_{2z} = \frac{M}{4\pi} \int_0^\infty \frac{\xi^2}{\lambda_1^2} (1 - F_{12}) e^{-\lambda_1 h - \lambda_2 z} j_0(\xi \rho) \, d\xi
\]

(4)

Where $\lambda = \sqrt{\xi^2 - k^2}$, $F_{12} = \frac{\lambda_2 - \lambda_1}{\lambda_2 + \lambda_1}$, $F_{12}$ is the reflection coefficient of the electromagnetic wave when it is transmitted from the medium $\sigma_1$ to $\sigma_2$, $(1 - F_{12})$ is the transmission coefficient when the electromagnetic wave is transmitted from the medium $\sigma_1$ to $\sigma_2$.

2.2. Theory of electromagnetic field distribution in lateral detection
Compared with the calculation of the vertical magnetic dipole response, the calculation of the horizontal magnetic dipole requires the use of a cylindrical coordinate system and a rectangular coordinate system. The horizontal magnetic dipole points to the x-axis direction at (0,0,0). The two dielectric conductivities are $\sigma_1$ and $\sigma_2$ respectively, the permeabilities are $\mu_1$ and $\mu_2$, the dielectric constants are $\varepsilon_1$ and $\varepsilon_2$, and the distance from the transmitting coil to the interface is $h$. Assuming that the transmitting coil is in the $\sigma_1$ medium, a simplified schematic diagram of a two beds formation horizontal coil system is shown on the right of Figure 1.
In horizontal wells, formations do not have rotational symmetry. Therefore, the expressions of $E_\rho$, $E_\varphi$ and $H_z$ in the two beds medium are given in reference 10. Based on the expressions, the "three-beds formation horizontal well electromagnetic field distribution characteristics analysis software V1.0" is developed, which can analyze distribution characteristics of electromagnetic fields at different positions. The formulas for calculating the electromagnetic field distribution characteristics of the two beds formation horizontal coil system is shown in Table 1. The parameters of the formulas for calculating the electromagnetic field distribution characteristics of the two beds formation horizontal coil system are shown in Table 2.

Table 1. Calculation formulas of the electromagnetic field distribution characteristics of the horizontal coil system in two beds.

| Range | Formula |
|-------|---------|
| $E_\rho$ | $z>h$ \(-\mu_1 \sin \Theta M_h (4\pi)^{-1} \int_0^h \left[ \xi_1 P_2 e^{-\xi_1 (z-h)} + \xi_2 P_3 e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| | $|z|<h$ \(-\mu_1 \sin \Theta M_h (4\pi)^{-1} \int_0^h \left[ \xi_1 P_2 e^{-\xi_1 (z-h)} + \xi_2 P_3 e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| $E_\varphi$ | $z>h$ \(-\mu_1 \cos \Theta M_h (4\pi)^{-1} \int_0^h \left[ \left( \xi_1 P_2 + \lambda S_3 \right) e^{-\xi_1 (z-h)} + \left( \xi_2 P_3 + \lambda S_3 \right) e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| | $|z|<h$ \(-\mu_1 \cos \Theta M_h (4\pi)^{-1} \int_0^h \left[ \left( \xi_1 P_2 + \lambda S_3 \right) e^{-\xi_1 (z-h)} + \left( \xi_2 P_3 + \lambda S_3 \right) e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| $E_\varphi$ | $z<0$ \(-\mu_1 \cos \Theta M_h (4\pi)^{-1} \int_0^h \left[ \left( \xi_1 P_2 + \lambda S_3 \right) e^{-\xi_1 (z-h)} + \left( \xi_2 P_3 + \lambda S_3 \right) e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| | $|z|>h$ \(-\mu_1 \cos \Theta M_h (4\pi)^{-1} \int_0^h \left[ \left( \xi_1 P_2 + \lambda S_3 \right) e^{-\xi_1 (z-h)} + \left( \xi_2 P_3 + \lambda S_3 \right) e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| $H_z$ | $z>h$ \(\mu_1 \cos \Theta M_h (4\pi)^{-1} \int_0^h \left[ \left( \xi_1 P_2 + \lambda S_3 \right) e^{-\xi_1 (z-h)} + \left( \xi_2 P_3 + \lambda S_3 \right) e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| | $|z|<h$ \(\mu_1 \cos \Theta M_h (4\pi)^{-1} \int_0^h \left[ \left( \xi_1 P_2 + \lambda S_3 \right) e^{-\xi_1 (z-h)} + \left( \xi_2 P_3 + \lambda S_3 \right) e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
| $H_z$ | $z<h$ \(\mu_1 \cos \Theta M_h (4\pi)^{-1} \int_0^h \left[ \left( \xi_1 P_2 + \lambda S_3 \right) e^{-\xi_1 (z-h)} + \left( \xi_2 P_3 + \lambda S_3 \right) e^{-\xi_2 (z-h)} + \lambda J_0 (\lambda \rho) d\lambda \right]\) |
3. Results

3.1. Distribution characteristics of forward detection electromagnetic field

Heterogeneous formation parameters are showed as follows: the conductivity of the target intervals is 0.01 S/m, the conductivity of the surrounding rock is 1 S/m, the frequency is 200 kHz, the emission current is 1 A, the number of coil turns is 1 turn, the coil radius is 0.1 m. The distance from the coil to the interface is 2 m. Draw the electromagnetic field distributions of homogeneous formations with electrical conductivity of 0.01 S/m, other parameters are the same as above, and compare them with heterogeneous formations. In the figure below, the real part is on the left and the imaginary part is on the right. Two pictures on the left shows the distribution of electromagnetic fields in heterogeneous formations, two pictures on the right shows the distribution of electromagnetic fields in homogeneous formations with a conductivity of 0.01 S/m.

3.1.1. $E_\phi$ distribution characteristics of forward detection.

Figure 2. $E_\phi$ distribution characteristics of forward detection in heterogeneous formations (left) and homogeneous formation with conductivity of 0.01 S/m (right).

By comparing, it can be seen that the real part of the heterogeneous formation $E_\phi$ shows significant numerical changes at the interface boundary (mainly due to the change in boundary conductivity) besides changing obviously at the source emission position. But there is almost no difference in the trend and amplitude of imaginary part change (the main reason is that the direct coupling signal is strong and the small changes are submerged).
3.1.2. $H_z$ distribution characteristics of forward detection.

![Figures 3](image1)

Figure 3. $H_z$ distribution characteristics of forward detection in heterogeneous formations (left) and homogeneous formation with conductivity of 0.01S/m (right).

By comparison, we can see that the imaginary part of $H_z$ in heterogeneous formations changes significantly at the source emission position as well as at the interface boundary, while the real part has almost no difference in trend and amplitude.

3.2. Distribution characteristics of lateral detection electromagnetic field

3.2.1. $E_\varphi$ distribution characteristics of lateral detection.

![Figures 4](image2)

Figure 4. $E_\varphi$ distribution characteristics of lateral detection in heterogeneous formations (left) and homogeneous formation with a conductivity of 0.01S/m (right).

By comparing, it can be seen that the real part of the heterogeneous formation $E_\varphi$ shows a significant value change at the source emission position as well as at the interface boundary. But there is almost no difference in the trend and amplitude of imaginary part change.

3.2.2. $E_\rho$ distribution characteristics of lateral detection.

![Figures 5](image3)

Figure 5. $E_\rho$ distribution characteristics of lateral detection in heterogeneous formations (left) and homogeneous formation with a conductivity of 0.01S/m (right).
By comparison, we can see that the real part of the heterogeneous formation $E_\rho$ has significant changes in value besides at the source emission position, and also shows significant numerical changes at the boundary of the interface. Compared with the lateral detection $E_\phi$, the change trend and amplitude of the two are almost as same as each other.

3.2.3. $H_z$ distribution characteristics of lateral detection.

![Figure 6. $H_z$ distribution characteristics of lateral detection in heterogeneous formations(left) and homogeneous formation with a conductivity of 0.01S/m(right).](image)

By comparing, it can be seen that the imaginary part of $H_z$ in heterogeneous formations changes significantly at the source emission position as well as at the interface boundary, while the change trends of the real part of $H_z$ are almost as same as each other.

4. Discussion

The research is based on the electric field half-coil edge detection characteristics. In this paper, it is to study the effect of changes in edge detection distance and transmit and receive distance on apparent conductivity. The x-axis is the edge detection distance, the y-axis is the receiving and transmitting distance, and the z-axis is the apparent conductivity. The left part is the real part of apparent conductivity, and the right part is the imaginary part of apparent conductivity. The parameters are shown in Table 3.

| Parameter                              | First group | Second group | Third group |
|----------------------------------------|-------------|--------------|-------------|
| Frequency (kHz)                        | 200         | 200          | 20          |
| Target layer conductivity (S/m)        | 0.01        | 0.1          | 0.01        |
| Conductivity of surrounding rock (S/m) | 1           | 1            | 1           |
| Probe distance (m)                     | 1,1.5,2,2.5,3,3.5,4,4.5,5,6,7,8,9,10,15,20,25,30,35,40 |              |             |
| Receiving and transmitting distance (m)| 1,1.2,1.4,1.6,1.8,2,2.2,2.4,2.5      |              |             |
Figure 7. Three groups of data graphs.

It can be seen from the first two sets of data graphs that when the frequency is 200 kHz, the real part of the apparent conductivity shows a negative value, and the edge detection distance is very short. Therefore, it is best to work at low frequency; According to the third set of data graphs, when the frequency is 20kHz, the change of the transmitting-receiving distance has little effect on the apparent conductivity amplitude, while the apparent conductivity varies monotonically with the edge detection distance. In general, when the formation conductivity is less than $10^{-3}$ S/m (the resistivity is greater than 1000Ω·m), the measurement signal is very small and cannot be accurately measured. If the apparent conductivity is equal to $10^{-3}$ S/m, the minimum measurement value is $10^{-3}$ S/m, it can be seen from the calculation data that under the condition of a frequency of 20kHz, the maximum detectable distance is 35m, and the receiving and transmitting distance can be realized at 1-3 m, which shows that a short distance half-coil of 1m can realize a long-distance detection of 30m.

5. Conclusions
(1) The distribution characteristics of $E_\phi$ real part and $H_z$ imaginary part at different distances from the two beds formation reveal the field change regularity in the boundary area of the front formation, which can be used to study the influence regularity of electromagnetic forward detection instruments,
judge the state of the front formation, and provide theoretical basis for determining geological reservoirs and adjusting drilling trajectories:

(2) The $E_\varphi$ real part, $E_\rho$ real part and $H_z$ imaginary part of the horizontal coil system in the two beds formation reveal the change characteristics of the lateral boundary region, which can be used to study the lateral formation influence regularity of the edge detection instrument and guide drilling along the optimal trajectory of the reservoir;

(3) In the half-coil edge detection instrument, the edge detection distance is little affected by the receiving and transmitting distance, and the frequency has a great influence on the edge detection distance. For the formation with 1S/m surrounding rock and 0.1S/m target intervals, if the minimum apparent conductivity is 0.001S/m when the frequency is 20kHz, the receiving-transmitting distance is 1-3m and the edge detection distance can reach up to 35 m.

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