Three-component response of transient electromagnetic method

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Abstract. Based on the three-component TEM forward simulation, through varying the dip angle and strike of underground target, changing overburden conditions, three-component response characteristics were analyzed. According to the three-component responses, the geometric features (the position, size, and occurrence) of anomalous body can be determined. The extreme points of the X and Y component response curves reflect the boundary of the tabular body; the zero-crossing point of the curves corresponds to the center of the tabular body. According to the range size of X and Y component curves, and the position of extreme points and zero-crossing points, the dip angle and extension direction and the center of the tabular body can be determined.

1. Introduction

The current studies and applications of transient electromagnetic method generally only measure the vertical component (Z component). And the horizontal component (X component, Y component) are usually neglected. However, the three-component TEM can obtain more information about geoelectrical section. It is significant to study the characteristics of three-component TEM responses for the further research and achieve the comprehensive utilization of the three-component data. In practical applications, three-component transient electromagnetic detection has not been widely used due to the limitations of equipment and the complexity of three-component response interpretation.

Studying the characteristics of the transient electromagnetic three-component response can optimize the data processing and interpretation in the actual production process, and improve its efficiency and quality. At the same time, it can enrich the theoretical basis actual production work needed.

Niu [1] respectively studied three-component responses of TEM. Chen [2] found that multi-component interpretation is more effective than single-component in determining the range of anomalies and improving horizontal and vertical resolution. Qin [3] defined the apparent resistivity of the horizontal component.

Based on the former work, we performed the characteristics analysis of three-component response curve by TEM forward modeling. By varying the dip angle and strike of underground target and overburden conditions in the forward simulation, the change characteristics of the three-component
response were obtained. It further validated the method of observing the X and Y components in the transient field and provides effective detection of underground geological information.

2. Theory/Method

2.1. Forward Modeling analysis
Firstly, a target body model in the central loop system was built. Then the voltage response of half-space containing conductive bodies was calculated. The theoretical responses derived from these targets are inductively coupled [2]. Based upon frequency domain, integral equation thin sheet theory, a program Leroi to compute the combined EM effects of conductor in host rock was employed.

The Leroi algorithm based on the Maxwell software of the Australian EMIT Corporation was used to study the electromagnetic response of plate-shaped target bodies with different electrical parameters. The plate-shaped body generates current in the primary field. The eddy current induced is replaced by the intrinsic current, without considering the mutual inductance.

The X component is parallel to the survey line direction, the Y component is perpendicular to the survey line direction, and the Z component is perpendicular to the horizontal plane. Three-component directions satisfied the right hand criterion. The three-component detection helps to fully understand the underground situation and lays a foundation for realizing multi-dimensional inversion in the future.

Initial model. The resistivity of host rock (homogeneous half-space) is 1000 Ω·m. The resistivity of anomalous body is 5 Ω·m. Each Survey line consists of 21 measuring points. The distance between measuring points is 20 m. The depth of the anomalous body top interface is 100 m.

| Table 1. Parameters of the model |
|-------------------------------|-----------------|-----------------|
| Host rock | Size[m] | resistivity[Ω · m] |
| 500×500×300 | 1000 |
| Anomalous body | 100×100×20 | 5 |

Kaufman has given the electrical dipole field expression in the case of homogeneous half-space:

\[
\begin{align*}
\frac{\partial B_x}{\partial t} &= \frac{4\pi r}{4\pi^2}\rho \sin \theta \cos \theta u^2 \left[ I_1 \cdot \frac{u^2}{4} (u^2 + \theta) - I_0 \cdot \frac{u^2}{4} u^2 \right] e^{-u^2/4}, \\
\frac{\partial B_y}{\partial t} &= \frac{3\pi r}{4\pi^2}\rho u^2 \left[ I_0 \cdot \frac{u^2}{4} - I_1 \cdot \frac{u^2}{4} \right] \cos \theta e^{-u^2/4} + I_1 \cdot \frac{u^2}{4} \left( 2 - 4 \cos \theta \right) e^{-u^2/4}, \\
\frac{\partial B_z}{\partial t} &= -\frac{3\pi r}{4\pi^2}\rho \sin \theta \left[ \Phi(u) - \sqrt{\frac{2}{\pi}} u \left( 1 + \frac{u^2}{3} \right) e^{-u^2/2} \right],
\end{align*}
\]

\[ u = \sqrt{\frac{\theta_r}{(2\pi)t}}; \] \[ r \] is the distance from the receiving point to the dipole center; \( \theta \) is the angle between \( r \) and electric dipole; \( I \) is the emission current intensity; \( dx \) is the length of electric dipole; \( \rho \) is the regularly spatial resistivity; and \( I_0 \) and \( I_1 \) are the zero-order and first-order second-kind Bessel functions, respectively.

In order to solve the transient electromagnetic response problem of conductive thin plates, the commonly used numerical solution is to use the “equivalent model” for calculation. In the “intrinsic current model”, Gallagher simulates the electromagnetic response of a thin-plate conductor with 15 intrinsic current circles without considering the mutual inductance between the intrinsic currents:

\[
\begin{align*}
\text{Early stage:} \frac{dB}{dt} &= \sum_{n=1}^{15} C_n \exp(-t/\tau_n) \\
\text{Late stage:} \frac{dB}{dt} &= C_0 \exp(-t/\tau_1)
\end{align*}
\]

\( \tau_n \) is the time constant of the n-th intrinsic current; \( c_n \) is the amplitude coefficient, which is related to the time constant and the size of the body.

For the electromagnetic field of any measuring point, it can be seen that a plurality of horizontal electric dipoles are accumulated at this point.

Total magnetic field:
\[ qB_n = \sum_{k=n}^{K} dB_k \frac{dt}{t_k} \]

Through forward simulation of transient electromagnetic method, the electromagnetic response (normalized voltage) \( dB/dt \) is measured (in uV/A). The EM response (magnetic induction \( B \)) is obtained (in pT/A). X, Y, and Z components correspond to \( B_X \), \( B_Y \), and \( B_Z \), respectively. \( qB \) is an approximation to \( B \) field.

2.2. The response of different component

Inclination Angle. The dip range of the low-resistivity tabular body is \( \alpha \). By changing Inclination Angle \( \alpha \) (Let \( \alpha = 0°, 15°, 30°, 45°, 60°, 75°, 90° \)) (Figure 1), the characteristics of three-component responses are analyzed. It is selected that the responses at the same time channel (\( t = 0.0304 \) ms) for comparison.

![Figure 1. Tabular body with dip angle \( \alpha \) model map](image)

![Figure 2. X component TEM response curves](image)

![Figure 3. Y component TEM response curves](image)

![Figure 4. Z component TEM response curves](image)

From figure 2-4, it can be seen that: (1) the shape of the X-component curve varies with the change of \( \alpha \). In addition, it abnormal peaks appear. The zero-crossing point corresponds to the center of the anomalous body, which changes with \( \alpha \) increasing. The tabular body tends to be vertical. At the same time, the interval between positive and negative peaks is getting narrower. As \( \alpha \) closes to 90°, the
amplitude of the curve becomes larger. (2) When the dip angles are 0° and 90°, respectively, the Z component response curve is symmetrically distributed on both sides of the plate, and the single peak value of the curve corresponds to the projection position of the center of the plate body on the ground. When the inclination changes between 0° and 90°, the curve shape is relatively flat. As the dip angle increases, the Z-component response curve gradually changes from an upwardly convex abnormal peak to a downwardly low valley. Therefore, the peak can be used to determine the dip of the tabular body. (3) Along the line, the model is symmetric in the Y direction and the value of the Y component curve is zero.

Strike. The angle (β) between the anomalous body and the survey line is changed to achieve the purpose of changing the strike, and the characteristics of the X, Y, and Z components can be analyzed. As shown in figure 5, β = 0°, 15°, 30°, 45°, 60°, 75°, 90°; t = 0.0304 ms.

![Figure 5. Tabular body with angle β model map](image)

The positive and negative peaks of the X component are concentrated in the range of 150 m to 350 m. As the projection location of the tabular body changes, the shape of multiple instrument channels curve changes. According to figure 6-7, by analysis of the zero-crossing point of X and Y component response curves, we can identify the center of the tabular body. When the tabular body is parallel to
the survey line (the direction of the X component), the X component response is relatively small and the curve varies gently; when the anomaly tabular body is perpendicular to the line (parallel to the Y component), the Y component response is relatively small and the curve varies gently. As \( \beta \) increases, the amplitudes of the X and Z component responses increase. When \( \beta = 45^\circ \), the amplitude of the Y component reaches its maximum.

3. Conclusions
In this paper, we have demonstrated numerically that three-component TEM measurements can potentially give access to conductor information. The three-component forward modeling results are compared by changing the dip angle of the tabular body. The X component response curve presents abnormal peaks, and the lateral range of the anomalous body can be determined by the positive and negative peaks of the curve. The zero-crossing point reflects the position of the center point of the anomalous body; the Z component response curve varies gently, and its peaks correspond to the center of the plate; the comprehensive analysis of the three-component responses can determine the dip angle.

Analyze the response characteristics by changing the angle between the tabular body and the survey line: when the tabular body is parallel to a horizontal component, the voltage response of this component is relatively small and the curve is relatively flat. When the tabular body and the survey line are not parallel, for Z component and the X component, the larger the \( \beta \), the greater the magnitude of the response curve. When \( \beta = 45^\circ \), the amplitude of the Y component response presents the maximum. By observing the three-component characteristics and analyzing the response of multiple lines, we can judge the extension direction of the anomalous body.

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