Application of transient electromagnetic method in coal mine fire detection

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Abstract
Detecting the location of coal mine fire zone accurately is a hot subject today in coal mine safety discipline. Based on the transient electromagnetic method, the apparent resistivity of the roadway ahead were calculated, and advanced detection and cross-section detection were studied. The results show that the mine transient electromagnetic method is a fast, efficient and convenient detection technology which can locate underground coal mine fire area accurately. It can also provide a scientific basis for the subsequent mine fire prevention project of this coal mine.
Keywords: SPONTANEOUS COMBUSTION AREA, TRANSIENT ELECTROMAGNETIC METHOD, ADVANCED DETECTION, CROSS-SECTION DETECTION, APPARENT RESISTIVITY

1. Introduction

Coal mine spontaneous fire usually refers to the non-control burning disaster occurred in the vicinity of underground mine or near the wellhead[1]. Mine fire accident is one of the major coal mine disasters and safety threat. There are a large number of mine fires happened in many countries, such as United States[2], Australia[3], and China[4]. Mine fire will burn a lot of coal resources and equipment, and emit a large amount of toxic plume harmful gases which are dangerous to the health and safety of coal miners seriously. It can even induce gas and coal dust explosion that expand its catastrophic.

The key issue of controlling coal spontaneous combustion is that how to accurately determine the location of spontaneous combustion area[5]. Then fire could be extinguished fast and efficiently in the next. However, underground coal spontaneous combustion takes place in the hidden area, and its development is relatively slow at the initial stage which makes the detection of combustion area cannot be judged by human senses and it should resort to some appropriate detection equipment and methods. Accurate detection of spontaneous combustion of coal in the region has always been the focus of the world's coal mining enterprises and researchers. Until now, coal mine fire detection method commonly include infrared assays and assay temperature coal or surrounding rock, radon measuring method, resistivity method, gas measurement, remote sensing method, radar detection method, radio wave method, and transient electromagnetic method (TEM)[6-13]. These methods are mainly used to detect the hidden high-temperature region of spontaneous combustion in open pit and coal seam. However, there is no one economical and reliable fire detection technology or equipment, even if there are early signs of spontaneous combustion in tunnels. That leads to a lower success rates of extinguishment of coal mine fire, and seriously affect the safety of coal production. Therefore, we adopt transient electromagnetic method based on advanced detection and profiling techniques to locate the precise location of the fire area and its range, and hope to provide a reliable geological basis for the fire extinguishment work.

2. Detection principle and method

2.1 Detection principle of TEM

Transient electromagnetic technique is a time-domain method[14]. The basic working principle is to send pulse current to the ground by using a stable electromagnetic coil, and shutdown current of a magnetic field will suddenly disappear at this time. This action will cause distinct changes of underground magnetic field and will form an inductive eddy current field in a good conductor of ground substance. The induced electromagnetic field slowly decay over time. We also call this approach as time domain electromagnetic method (TEM). This principle is shown in figure 1. Because of the limitation of space range in coal mine tunnels, the transmitting and receiving frames laid in the roadway are subject to the particular space. The measurement space includes four directions - front, back, left and right side of frame surface. Therefore, the whole space is in a valid range, and it is also called the whole space transient electromagnetic method. The earth can be seen as a homosexual conductor when the pulse current through the transmit coils. Thus the expression of current $I(t)$ can be written as the following equation:

$$I(t) = \begin{cases} I & t \le 0 \\ 0 & t > 0 \end{cases} \quad (1)$$

The current generated by the transmitter coil is a stable primary electromagnetic field before the current is turned off. The flow of current in the transmitter coil suddenly disappeared when *t* equals 0 and *I* equals 0. After the primary electromagnetic field immediately disappear, dramatic changes of the current generated by dramatic changes in the magnetic field will inspire induced current to maintain the current before disconnecting the electromagnetic field.in the vicinity of the conductive rock. After the disappearance of this field, the induced current will slowly decay and not disappear immediately. Induced current and induced electric field will pass down until the energy runs out by means of continuous transformation. Receiving coil receive magnetic field information of secondary magnetic field which is the secondary induced voltage *V (t)*. Secondary field properties with geological information will be received by the receiving coil. Different materials will reflect different electrical information. If there is a good conductor, the induced current will be generated in it and the coil is energized. The induced currents size is determined by the electrical characteristics of the geology, which can be fed back to determine the composition of the ground substance the magnetic field.

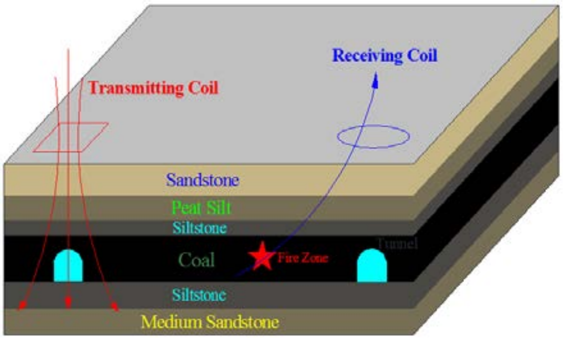


Figure 1. Detection principle of transient electromagnetic method

The apparent resistivity of transient electromagnetic method is often calculated by late-defined formula, or by the final curve synthesis. Under the stimulation of pulse current, transient response of the half-space dipole apparatus with time rate change is represented by the following equations:

$$B_z(t) = \frac{\mu m}{4\pi r^3}\left[\left(\frac{9}{2Z^2} - 1\right)erf(Z) - \frac{1}{\sqrt{\pi}}\left(\frac{9}{Z} + 4Z\right)e^{-Z^2}\right] \quad (2)$$

$$\frac{dB_z(t)}{dt} = -\frac{m\rho}{2\pi r^5}\left[-9erf(Z) + \frac{2Z}{\sqrt{\pi}}(9 + 6Z^2 + 4Z^4)e^{-Z^2}\right] \quad (3)$$

$$Z = \frac{r}{2}\sqrt{\frac{\mu}{\rho t}} \quad (4)$$

where μ is the half-space magnetic conductivity; *m* is magnetic moment; *N* is emit loop turns; *I* is current intensity; *S* can be considered as the area of the coils; *erf (Z)* represents the error function.

Eq. (4) yields:

$$\rho = \frac{r^2\mu}{4t}\frac{1}{Z^2} \quad (5)$$

Substituting Eq. (5) into Eq. (3), we obtain Eq. (6) as follows:

$$\frac{dB_z(t)}{dt} = -\frac{\mu m}{8\pi t r^3}\frac{1}{Z^2}\left[-9erf(Z) + \frac{2Z}{\sqrt{\pi}}(9 + 6Z^2 + 4Z^4)e^{-Z^2}\right]$$

(6)

Introducing the vertical component of the magnetic induction:

$$F_B(Z) = \left[\left(\frac{9}{2Z^2} - 1\right)erf(Z) - \frac{1}{\sqrt{\pi}}\left(\frac{9}{Z} + 4Z\right)e^{-Z^2}\right] \quad (7)$$

$$F_D(Z) = \frac{1}{Z^2}\left[-9erf(Z) + \frac{2Z}{\sqrt{\pi}}(9 + 6Z^2 + 4Z^4)e^{-Z^2}\right]$$
(8)

Eq. (7) and Eq. (8) yields:

$$B_Z(t) = \frac{\mu m}{4\pi r^3}F_B(Z) \quad (9)$$

$$\frac{dB_Z(t)}{dt} = -\frac{\mu m}{8\pi t r^3}F_D(Z) \quad (10)$$

By staging the final iteration, apparent resistivity under half-space conditions dipole device can be obtained in full space condition. The transient dipole response is expressed as follows:

$$\frac{dB_Z(t)}{dt} = -\frac{\mu m \theta^3}{\pi^{3/2} t}(1 - \theta^2 r^2)e^{-\theta^2 r^2} \quad (11)$$

$$Z = \theta r = \frac{r}{2}\sqrt{\frac{\mu}{\rho t}} \quad (12)$$

$$\rho = \frac{r^{2\mu}}{4tZ^2} \quad (13)$$

where ρ is called the apparent resistivity.

2.2 Detection method of TEM

Transient electromagnetic method is divided into the advanced detection and the profile detection and measuring point spacing is from 2 to 20 m when it is used in the detection in coal mine underground roadway. According to the direction of the multi-turn small wire frame transmitting electromagnetic field, the normal direction of frame plane is considered as the direction of transient detection.

During profile detection, the normal direction of transmitting frame is aligned respectively with the direction of the roof coal seam, the bottom plate or the parallel seam. The plane of the receiving frame is coincident with the plane of the transmission frame, the connection of the two frame center is parallel to the horizontal line simultaneously. Due to the wastage of the induced current in the process of detection, the center line distance should not exceed 5 meters in order to ensure detection accuracy. Profile detection can reflect the geological anomaly of the roof coal seam, the rock, and the floor strata or the parallel seam. The angle between the plane and the bottom plate is determined by the detection requirement and the dip angle of the coal seam. The detection method is shown in figure 2.

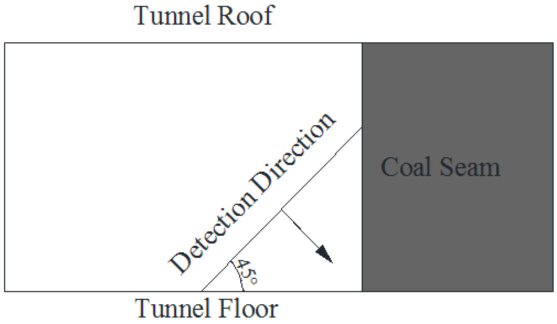


Figure 2. Cross-section detection direction in transient electromagnetic method

During advanced detection, the plane of the receiving frame is coincident with the plane of the transmission frame, and the normal direction of them is aligned with the head-on tunnel. It can reflect the geological anomaly of the head-on roof coal seam, and the floor strata or the parallel seam. The angle between the plane and the bottom plate is determined by the detection requirement and the dip angle of the coal seam. The direction of the mine transient electromagnetic method in head-on advanced detection can be divided into three different positions, as shown in figure 3, upper inclined, bedding and down inclined of heading face. Specific angle should be decided by geological data and field exploration. Seven angles in each direction are fan-shaped layout. The angles between the direction and the normal of the heading face are 0 °, ± 15 °, ± 30 °, ± 45 °, as shown in figure 3.

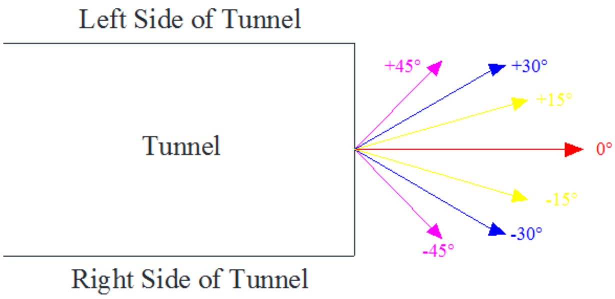


Figure 3. Layout of frontal advanced detection angle

3. Case detection and analysis

No. 9 coal seam in a coal mine has a grade I spontaneous combustion tendency. The spontaneous combustion period is about 30 days. A roof fall accident occurred on the right side of the heading face about 251m distance from the main transport roadway during the digging process of transport tunnel of a working face. The coal fallen from the roof had a surface temperature of 110℃. Carbon monoxide (CO) concentration was beyond the safety index at the heading face many times.

These phenomena indicates that spontaneous combustion and high temperature region occurred in the upper part of the coal seam.

3.1 Detection results

Advanced detection and profile detection of the roadway roof, floor rocks and the coal region were detected by YCS150 mine intrinsically safe design TEM instrument with 2A emission current and 20 Hz frequency. The transmitter coils were installed in a 2m × 2m × 20 square frame, and the receiving coils in a circular frames with a diameter of 0.6m. They are independent and did not have the same number of turns, so as to generate optimal coupling response with the coal seam abnormal body.

Data collected in situ is drawn into an apparent resistivity 2D map in the detecting direction. Figure 4 is the 2D map of the transient electromagnetic advanced detection of the mine hidden high temperature area. Coordinate (0, 0) is the test position and the vertical axis is the distance of detecting ahead. The horizontal and probing direction are vertical. The negative represents the left side of the probe and positive represents right.

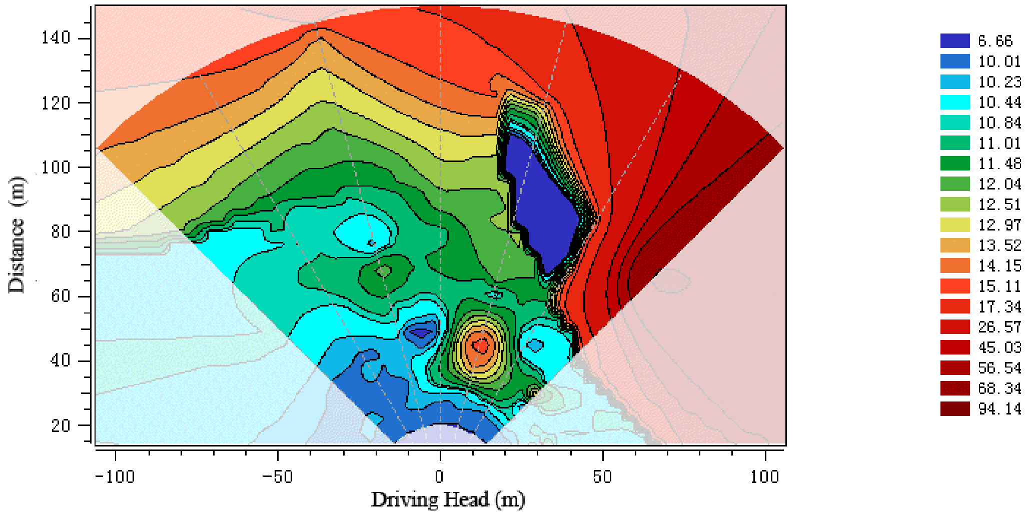
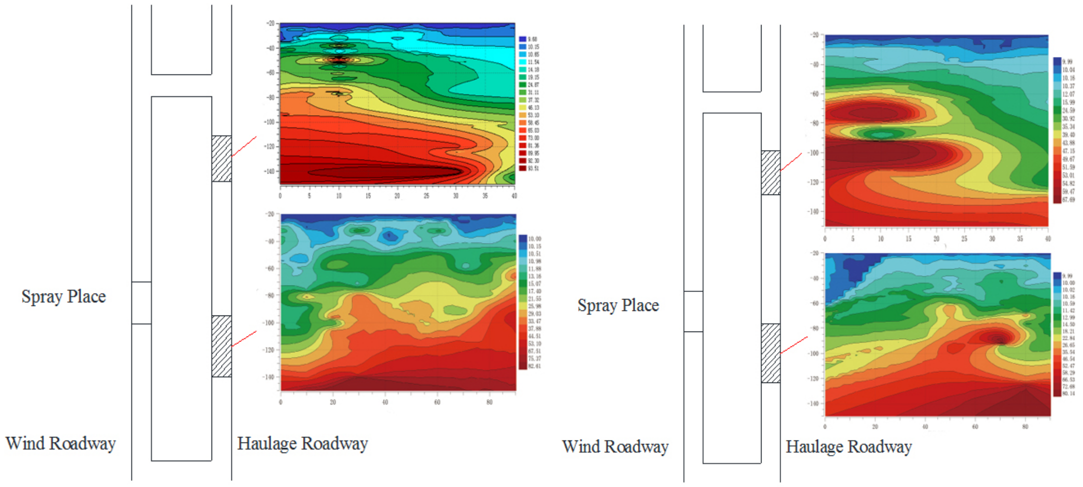


Figure 4. The apparent resistivity of advanced detection in 2D map

It can be seen that an obvious banded low-resistance abnormal body exists in front of the probe about 60-120m along the two o'clock direction and the abnormal area is larger and differs from the surrounding rock environment obviously. Especially the apparent resistivity in 65-100 m region is lower than 6.66 $k\Omega \cdot m$, and the abnormal body is obvious. By comparison, there is a low resistivity region in front of the right side of detection position about 60-120 m, and it is inferred that this region is a high temperature area.

To further infer the location of the hidden high temperature area, profile detection was conducted in the corresponding section of transport roadway and other areas. The angles between transmitting frame and coal wall were 9 ° and 25 °. High temperature detection area is located in 27 to 36 air duct area of transport tunnel. The Specific engineering layout is shown in Figure 5.



(a) Angle profile detecting in 9°. (b) Angle profile detecting in 25°.

Figure 5. Apparent resistivity in cross-section detection outside the fire source area

3.2 Location of high temperature region

It can be seen that an obvious part of the low resistance in the area of horizontal coordinates from (0,100) to vertical coordinates (20, 40) in figure 4. This area is likely a water rich area or water mining fissure. It is related to the damp roof and bottom water in the 25 to 28 air duct place of transport tunnel. The measured data is a mixture resistivity values of rock in aqueous. But the apparent resistivity value of this region is gradually increasing with the deepening of measuring depth in the area of horizontal coordinates from (0, 80) to vertical coordinates (40,100), and it is related to the structure of the underground rock. No obvious low resistivity anomaly region is observed in this area. Moreover, there is an obvious part of the low resistance in the area of horizontal coordinates from (0,100) to vertical coordinates (20, 40) in figure 5. But in the area of horizontal coordinates (90, 100) and vertical coordinates (40, 50), there is a high level of resistance variation. The blue area indicates the low resistivity zone and it is in agreement with the position of the advanced detection. So it is assumed that the position is a hidden high temperature region.

By comprehensive comparison, there is no obvious variation of the high and low resistance in the angle profile detecting of 9°. But in the angle profile detecting of 25°, there is a high level of resistance variation area in horizontal coordinates from (90, 100) to vertical coordinates (40,50). It is in agreement with the position mentioned above by the advanced detection method and it is convinced that this area is a hidden high temperature region.

4. Conclusion

Compared with other methods of mine geophysical prospecting method, using transient electromagnetic method to probe fire areas of mine roadway roof (TEM) is more convenient, fast, deep prospecting and more sensitive to low resistivity objects in the limit space of mine tunnel. With the help of the advanced and profile apparent resistivity figure formed by inverse calculation, it can locate the underground coal fire scope accurately.

Receiving frame of TEM instrument can receives signals from the whole space rock electrical properties of the comprehensive reflection emitted by the transmitter frame. Meanwhile, it also needs a combination of geological data based on the detected direction of the frame plane and comprehensive analysis to eliminate interference various in determining the spatial location of the combustion area. The TEM has optimistic prospect of application in coal mine fire detection and will provide a scientific basis for the subsequent mine fire extinguishment projects.

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