Research on 3D Location Method of Underground Cable

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Abstract. Power cable is one of the most widely used electrical equipment in distribution system. Due to some historical reasons, the accidents such as cut or damage cables during construction often occur. In this paper, the calculation model of power cable power frequency magnetic field under different laying conditions is established. Based on the analysis of magnetic flux density around power cable, a positioning method of underground cable based on electromagnetic method is proposed. Three horizontal magnetic field sensors are used to locate the path of the cable, two vertical magnetic field sensors are used to locate the depth of the cable, so as to realize the three-dimensional positioning of the power cable. The simulation results of MATLAB show that the average absolute error of the method is about 0.03 m when the sensor array is 0.35 m around the cable in path positioning, and it can accurately locate the location of underground cable in depth location.

1. Introduction
Power cable have become one of the largest electrical equipment in distribution system. However, in recent years, cut or damage cables cables has often occurred during the construction of the project, causing unnecessary economic losses to users [1]. Therefore, it is necessary to check whether there is cable underground before construction. The traditional cable path detection methods are roughly electromagnetic method, pulsed magnetic field method, ground penetrating radar method, etc., and the electromagnetic method is currently the most commonly used method in the field of cable detection [2-4]. Reference [5] transmits a signal through a signal transmitting device, and accurately detects the path by receiving the strength of the induced signal and calculating the phase difference, but the cable to be tested must have a bare point. Literature [6] proposed to use 7 measuring coil arrays to measure the distribution of power frequency magnetic field, but there are many sensors and the detection process is more complicated. In this paper, a new detection scheme is proposed based on the principle of electromagnetic method, and the accuracy of the method is verified by Matlab simulation.

2. Calculation Model of Magnetic Field Around Cable
According to ampere circuital theorem [7], the magnetic flux density at any point outside the infinitely long current-carrying wire is:

\[ B = \frac{\mu_0 I}{2\pi r} \]  \hspace{1cm} (1)

Where \( r \) is the vertical distance from the point outside the wire, \( I \) is the current intensity in the wire, \( \mu_0 \) is the magnetic permeability of the medium in vacuum (\( \mu_0 = 4\pi \times 10^{-7} \, H / m \)).
In three-phase system, assuming that the coordinates of the A phase are \((x_1, y_1)\), B phase \((x_2, y_2)\), and C phase \((x_3, y_3)\), the currents passing through the ABC three phases are \(I_1, I_2, I_3\), and P point \((x, y)\) is any point outside the cable, as shown in Figure 1.

![Figure 1. Three-phase magnetic field calculation model.](image)

From equation (1), we can see that the magnetic flux density generated by the A-phase cable at point P is \(B = \frac{\mu_0 I_1}{2\pi r_{p1}}\), and the components along the x and y directions are:

\[
B_{Ax} = \frac{\mu_0 I_1 (y - y_1)}{2\pi r_{p1}^2}
\]  
(2)

\[
B_{Ay} = \frac{\mu_0 I_1 (x - x_1)}{2\pi r_{p1}^2}
\]  
(3)

\[
r_{p1}^2 = (x - x_1)^2 + (y - y_1)^2
\]  
(4)

According to the superposition theorem, the magnetic flux density at point P are:

\[
B_{Px} = \sum_{i=1}^{3} \frac{\mu_0 I_i (y - y_i)}{2\pi r_{pi}^2}
\]  
(5)

\[
B_{Py} = \sum_{i=1}^{3} \frac{\mu_0 I_i (x - x_i)}{2\pi r_{pi}^2}
\]  
(6)

\[
r_{pi}^2 = (x - x_i)^2 + (y - y_i)^2
\]  
(7)

\[
B = \sqrt{B_{px}^2 + B_{py}^2}
\]  
(8)

Where \(I_i\) is the current through each phase cable core, \((x_i, y_i)\) is the coordinate of each phase core, and \(r_{pi}\) is the vertical distance from point P to each phase cable.

3. Distribution Law of Magnetic Field Around the Cable

3.1. Single-core Cable

Generally, the wiring of single-core cables is mainly divided into horizontal layout, vertical layout and triangular layout, as shown in Figure 2. Taking YJV-26/35kV-1*630 mm2 as an example, assume that the effective value of symmetrical three-phase current is 960A, the frequency is 50Hz, and the cable spacing is 100mm. Taking 0.001s as the calculation step, the magnetic field distribution at 1m above the cable is simulated, and the relationship between the magnetic flux density and the horizontal
distance in one cycle of the three wiring methods is shown in Figure 3. Different colors represent different moments.

Figure 2. Typical single-core cable routing.

Figure 3. Horizontal magnetic field strength distribution under typical wiring of single-core cable. It can be seen from the simulation results that, no matter which wiring mode the single-core cable has, there is always a quadratic polynomial function relationship between the magnetic flux density and the distance above the cable level, and the magnetic flux density is the largest when it is directly above the cable.

3.2. Three-core Cable
Taking the currently commonly used YJV22-8.7/10-3*240mm² three-core cable as an example, the simulation model shown in the figure 4 is established. It is easy to know according to the cable parameters: the phase A coordinate is (0,17.8), the phase B coordinate is (-15.415, -8.9), and the phase C coordinate is (15.415, -8.9). Suppose the effective value of the symmetrical three-phase current is 300A and the frequency is 50Hz. Taking 0.001s as the calculation step, the relationship between the magnetic flux density and the horizontal distance of 0.7m above the cable in one cycle is shown in Figure 5. The curves of different colors on the simulation diagram represent different moments.

Figure 4. Three-core cable simulation model.
From the simulation results, it is not difficult to find that the relationship between the magnetic flux density of the three-core cable and the distance above the cable level is similar to that of the single-core cable arranged in a positive triangle, and they are distributed like a quadratic polynomial function, and the magnetic flux density has a maximum value directly above the cable.

4. Model Establishment

4.1. Path Locationing Model

From the simulation results, it can be seen that whether it is a single-core cable or a three-core cable, at any time in a cycle, the magnetic flux density and the distance above the cable level have a quadratic polynomial function relationship, and the magnetic flux density is the largest when it is directly above the cable. To this end, a hypothesis is proposed: the horizontal distance and magnetic induction intensity directly above the cable have a quadratic polynomial distribution. There is:

$$y = ax^2 + bx + c$$

(9)

Where \( y \) is the magnetic flux density, and \( x \) is the horizontal distance to the cable directly above.

![Horizontal magnetic field sensor arrangement.](image)

Figure 6. Horizontal magnetic field sensor arrangement.

Assume that the cable path positioning sensors are arranged as shown in Figure 6, and that the cable is located directly under the No. 2 sensor at this time, and the distance between the sensors 1, 2 and 2, 3 is \( k \). Using sensor 2 as a reference point to establish a detection model, then the magnetic flux density of sensor 1 is: \( y_1 = k^2a - kb + c \). Similarly, the magnetic flux density of sensor 2 is: \( y_2 = c \), and the magnetic flux density of sensor 3 is: \( y_3 = k^2a + kb + c \).

Thus the following matrix can be obtained:

$$
\begin{bmatrix}
y_1 \\
y_2 \\
y_3
\end{bmatrix} =
\begin{bmatrix}
k^2 & -k \\
0 & 0 \\
k^2 & k
\end{bmatrix}
\begin{bmatrix}
a \\
b
\end{bmatrix} + c
$$

(10)

Where \( y_i \) represents the magnitude of the magnetic flux density measured by the \( i \)-th magnetic field sensor. Through the magnetic flux density \( y_1, y_2, y_3 \) measured by the magnetic field sensors 1, 2, and 3, the quadratic polynomial parameters \( a, b, \) and \( c \) can be obtained. From the function nature of the quadratic polynomial, when \( x = -b/(2a) \), the function obtains the maximum value, so that the position of...
the underground cable can be determined according to the value of $X_{\text{max}}$. When $X_{\text{max}}=0$, the cable is located directly under No. 2 sensor; when $X_{\text{max}}>0$, the underground cable is located to the right of No. 2 sensor; when $X_{\text{max}}<0$, the cable is located to the left of No. 2 sensor. The value of $|X_{\text{max}}|$ also reflects the relative position of the underground cable and No. 2 sensor.

4.2. Depth Positioning Model

The depth of the cable to the ground is generally not less than 0.7m. After the underground cable path is determined by the No. 1, 2, and 3 sensors, the dual sensor is used to set the depth of the underground cable. This paper presents a scheme for dual-sensor detection of cable burial depth. Its schematic diagram is shown in Figure 7. The vertical distance between the two magnetic sensors is $h$, and the buried depth of the power cable is $R$. Assume that the magnetic flux density of the cable under test in the vertical direction satisfies the function $B(x)$, where $x$ is the vertical distance of the sensor from the cable. There are:

\[ B_2 = B(R) \]  
\[ B_4 = B(R + h) \]  
\[ \frac{B_2}{B_4} = B\left(\frac{R}{R + h}\right) \]

After the magnetic flux density of the No. 2 and No. 4 sensors is known, the deep buried $R$ can be derived according to equation (13).

5. Analysis of Simulation Results

5.1. Analysis of Cable Path Simulation Results

In order to verify the reliability of the cable path positioning method, this paper takes a three-core cable as an example to establish a detection model. Assuming that the sensor array moves from left to right above the three-core cable, the simulation results shown in Figure 8 are obtained. Different colors represent the distance $k$ between different sensors.

It can be seen from the simulation results that when the detection model is about 0.35m near the cable, the method in this paper has high accuracy, and $X_{\text{max}}$ is consistent with the above assumption. When $k$ is 0.5, the average absolute error of path positioning is about 0.03 meters. $|X_{\text{max}}|$ can reflect the relative distance from the cable very well. Some results are shown in Table 1.
Figure 8. Simulation results of cable path positioning.

Table 1. Relationship between $X_{\text{max}}$ and cable position when $k$ is 0.5.

| Left side of the cable | Above the cable | Right side of the cable |
|------------------------|-----------------|-------------------------|
| Cable location         | 0.34 0.26 0.16  | 0 0.08 0.16 0.23        |
| $X_{\text{max}}$      | -0.494 -0.263 -0.123 | 0 0.045 0.13 0.22       |
| Absolute error         | 0.15 0.003 0.037 | 0 0.035 0.03 0.01       |

5.2. Analysis of Cable Embedding Depth Simulation Results

When the cable path is determined, we can use dual sensors to locate the buried depth. Assuming that the buried depth of the three-core cable is 0.7m, the detection model shown in Figure 7 is established. When the distance $h$ between the No. 2 sensor and the No. 4 sensor is different, the simulation result is shown in Fig. 9. As shown in Figure 9, when the distance between the vertical sensors is between 0.3 and 0.55 meters, the cable depth positioning error is about 14%. When the distance is about 0.4 meters, the cable depth positioning error is 2%, fully meet the requirements of depth positioning.

6. Conclusion

(1) Regardless of the laying method of a single-core cable, the magnetic flux density and the distance above the cable have a quadratic polynomial function relationship, and the magnetic flux density directly above the cable is the largest, and the three-core cable also has this relationship;

(2) A new method for locating underground cables is proposed. The simulation results show that the average absolute error of the method is about 0.03 m when the sensor array is 0.35 m around the cable with path positioning, and in depth location, this method can accurately locate the location of underground cable.
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