Development of Multi-layer Soil Model for Yanmenguan Converter Station Based on Wenner and Magnetotelluric Method

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Abstract. In order to assess the effects of Yanmenguan HVDC grounding electrode on buried metal facilities, it is necessary to build up the soil model of Yanmenguan converter station. Soil resistivity was measures by Wenner and magnetotelluric method. Then the soil structure of Yanmenguan converter station was inversed based on the experimental data. It was shown that the soil structure of Yanmenguan converter station was three-layer horizontal soil. The resistivity of three layers was 101.7Ω·m, 1037.5Ω·m and 76.4Ω·m. The thickness of three layers was 400m, 4600m and infinite.

1. Introduction

Ultra-high voltage grid is the main part of global energy interconnection. Interconnection of global large clean energy center and load center can only be achieved by ultra-high voltage grid [1]. As an important part of Chinese ultra-high voltage grid, ±800kV Yanmenguan-Huaian HVDC transmission system plays an important role in ensuring energy security. However, as the land use problems have become more intense, there are many AC substations, windfarms and pipelines inevitably nearby Yanmenguan converter station. In order to assess the electromagnetic influence of Yanmenguan converter station on the buried metal facilities of AC substations, windfarms and pipelines, it is necessary to build up the soil model of Yanmenguan converter station [2].

In section 2 the measuring methods of soil resistivity such as Wenner and magnetotelluric method are described. The inversion method of soil structure is also provided. In section 3 the soil structure of Yanmenguan converter station was inversed based on the experimental data. We conclude this paper with a discussion in section 4.

2. Measuring and Inversion Method

2.1. Wenner Method

Resistivity of shallow soil can be measured by Wenner method [3]. The basic principle of Wenner method is that current is flowed through the soil and two poles, and the potential difference is measured by two other poles. The schematic diagram of Wenner method is shown in Figure 1. Two current poles are C₁ and C₂, and two potential poles are V₁ and V₂. Four poles are equal spacing.
When current $I$ is injected into the soil through pole $C_1$, the potential generated of pole $V_1$ is

$$V_1' = \frac{\rho I}{2\pi a} \tag{1}$$

When current $I$ is exported from the soil through pole $C_2$, the potential generated of pole $V_1$ is

$$V_1' = -\frac{\rho I}{4\pi a} \tag{2}$$

According to the superposition principle, the overall potential of pole $V_1$ is

$$V_1 = V_1' + V_1' = \frac{\rho I}{4\pi a} \tag{3}$$

Similarly, the overall potential of pole $V_2$ is

$$V_2 = V_2' + V_2' = -\frac{\rho I}{4\pi a} \tag{4}$$

The indicated value of the voltmeter is

$$V = V_1 - V_2 = \frac{\rho I}{2\pi a} \tag{5}$$

The soil resistivity can be obtained by

$$\rho = 2\pi a \frac{V}{I} \tag{6}$$

![Schematic diagram of Wenner method](image)

**Figure 1.** Schematic diagram of Wenner method.

### 2.2. Magnetotelluric Method

Resistivity of deep soil can be measured by magnetotelluric method [4-6]. The basic principle of magnetotelluric method is that electromagnetic waves with different frequencies have different skin depth in soil, so the electrical structure of the soil from shallow to deep can be obtained by measuring the electromagnetic response sequence from high frequency to low frequency. Schematic diagram of magnetotelluric method is shown in figure 2. The system consists of a master, two electric field detectors (Ex and Ey), and three magnetic field detector (Hx, Hy and Hz).

It is assumed that the field source is an electrical source polarized along the $X$ direction and there is no lateral change in the geological model. The induced secondary field has only $H_y$ and $H_x$ components.

$$E = (E_x, 0, 0), \quad H = (0, H_y, 0) \tag{7}$$

Then the wave vector equation degenerates to

$$\frac{d^2E_x}{dy^2} + \frac{d^2E_x}{dz^2} + k^2E_x = 0, \quad H_y = \frac{-1}{io\mu} \frac{dE_x}{dz} \tag{8}$$

The solution of (8) is
The impedance of TE mode is

\[ Z_{\text{TE}} = \frac{E_x}{H_y} = \frac{\omega \mu}{k_z} = \sqrt{i \omega \mu \rho} \]  

Similarly, the impedance of TM mode is

\[ Z_{\text{TM}} = \frac{E_y}{H_x} = -\frac{\omega \mu k_z}{k^2} = -\sqrt{i \omega \mu \rho} \]  

**Figure 2.** Schematic diagram of magnetotelluric method.

### 2.3. Inversion Method

When the soil is not uniform as shown in figure 3, the soil resistivity measured by Wenner method is not the actual resistivity of the soil, but an apparent resistivity considering the heterogeneity of the soil comprehensively. The apparent resistivity changes with the soil structure and electrode spacing. The apparent resistivity of the soil is

\[ \rho_a = 2a \rho_1 \left[ \int_0^\infty \alpha_1(\lambda) J_0(\lambda a) e^{-\lambda h_1} d\lambda - \int_0^\infty \alpha_1(\lambda) J_0(2\lambda a) e^{-2\lambda h_1} d\lambda \right] \]  

where \( J_0 \) is the first kind of zero order Bessel function.

**Figure 3.** Schematic diagram of horizontal layered soil.

The Prony method is used to approximate \( \alpha_1(\lambda) \) in equation (12), then the apparent resistivity can be approximated by
\[ \rho_i \approx 2a\rho \sum_{j=1}^{n} c_i \left[ \frac{1}{d_i^2 + d_j^2} - \frac{1}{(2a)^2 + d_j^2} \right] \]  \hspace{0.5cm} (13)

Change the pole spacing \( a_j \) \( (j=1,2,...M) \) of Wenner method, \( M \) apparent resistivities \( \rho_m \) are obtained by Wenner method, and \( M \) apparent resistivities \( \rho_c \) are calculated from equation (13). When judging the number of soil layers \( N \), the following objective function is established by using the least square method

\[ f(\rho_1,\rho_2,\cdots,\rho_N,h_1,h_2,\cdots,h_{N-1}) = \sum_{j=1}^{M} \left[ \frac{\rho_m^j - \rho_c^j(\rho_1,\rho_2,\cdots,\rho_N,h_1,h_2,\cdots,h_{N-1})}{\rho_m^j} \right]^2 \]  \hspace{0.5cm} (14)

with the constraints

\[
\begin{align*}
\rho_i &> 0, i=1,2,\cdots,N \\
h_j &> 0, i=1,2,\cdots,N-1
\end{align*}
\]  \hspace{0.5cm} (15)

The inversion of soil structure is to solve the minimum of (14). The constrained nonlinear optimization problem can be solved by the variable scale quasi Newton method [7-8].

3. Results and Discussions

Resistivity of deep soil of Yanmenguan converter station measured by magnetotelluric method is shown in table 1. It can be seen that the resistivity at the depth from 400m to 1000m is 1292.0Ω·m, and the resistivity at the depth from 1000m to 5000m is 783.0Ω·m. The resistivity at the depth from 0 and 400m and at the depth from 5000m to \( \infty \) is smaller than 100Ω·m. It is indicated that the soil at the depth from 400m to 5000m has many gravels and rocks.

| Depth of upper interface (m) | Depth of bottom interface (m) | Thickness (m) | Resistivity (Ω·m) |
|-----------------------------|-----------------------------|---------------|------------------|
| 0                           | 5                           | 5             | 63.4             |
| 5                           | 10                          | 5             | 62.7             |
| 10                          | 20                          | 10            | 60.7             |
| 20                          | 50                          | 30            | 52.7             |
| 50                          | 100                         | 50            | 36.9             |
| 100                         | 200                         | 100           | 25.4             |
| 200                         | 400                         | 200           | 63.6             |
| 400                         | 1000                        | 600           | 1292.0           |
| 1000                        | 5000                        | 4000          | 783.0            |
| 5000                        | 10000                       | 5000          | 62.2             |
| 10000                       | 15000                       | 5000          | 33.8             |
| 15000                       | 20000                       | 5000          | 27.1             |
| 20000                       | 30000                       | 10000         | 30.3             |

Resistivity of shallow soil of Yanmenguan converter station measured by Wenner method is shown in table 2. GS1, GS2, GS3 and GS4 denote the measuring point in the east, south, west and north of Yanmenguan converter station, respectively. It can be seen that the soil is approximately uniform in the four direction. Resistivity at GS2 is larger than at GS1, GS3 and GS4. The reason for this is that the soil at GS2 has much coarse sand.

Based on the experimental data, the soil structure of Yanmenguan converter station can be inverted. Solving the minimum of (14), the number of soil layer of Yanmenguan converter station is 3. The first layer is from the surface to the depth of 400m, the thickness is \( h_1 = 400 \) m, the soil resistivity is \( \rho_1 = \)
101.72 $\Omega\cdot m$. The second layer is from 400m to 5000m with thickness $h_2 = 4600m$, and the soil resistivity $\rho_2 = 1037.5 \Omega \cdot m$. The third layer is from 5000m to infinity, with the soil resistivity $\rho_3 = 76.4 \Omega \cdot m$.

Table 2. Resistivity of shallow soil measured by Wenner method.

| Pole Spacing (m) | GS1 (Ω·m) | GS2 (Ω·m) | GS3 (Ω·m) | GS4 (Ω·m) |
|------------------|------------|------------|------------|------------|
| 1                | 94.8       | 112.8      | 119.8      | 78.9       |
| 2                | 103.3      | 124.9      | 112.1      | 82.0       |
| 3                | 106.2      | 136.0      | 110.9      | 87.1       |
| 4                | 106.7      | 148.4      | 105.3      | 90.4       |
| 6                | 107.5      | 176.04     | 106.0      | 93.1       |
| 10               | 106.8      | 201.59     | 108.4      | 98.4       |
| 20               | 96.2       | 170.05     | 103.0      | 99.0       |
| 30               | 104.1      | 142.37     | 92.8       | 92.3       |

4. Conclusions

(1) The resistivity of shallow soil can be measured by Wenner method. The resistivity of deep soil can be measured by magnetotelluric method.

(2) The soil structure can be inversed by solving the minimum of square difference of the experimental and calculated value.

(3) Three-layer horizontal layered soil resistivity model of Yanmenguan converter station is established by using optimization method, which lays a foundation for the later electromagnetic interference analysis.

Acknowledgments

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