Calculation model for the earth potential of HVDC ground electrode based on image recognition of surface-layer soil moisture

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Abstract

Changes in soil electrical parameters can affect the distribution of earth potential in high-voltage direct-current (HVDC) ground electrodes when climatic conditions change. This paper proposes a model to describe the relationship between surface-layer soil moisture and surface-layer soil resistivity under short-term climatic influence, by using image recognition technology. Based on the relatively stable resistivity of lower soil layers, a soil model more reflective of the actual operating conditions is established for soils near the ground electrode, and a finite element method is adopted to calculate the earth-surface potential (ESP). The experimental results indicate the following: (1) Compared with other measurement methods, image recognition of surface soil resistivity is a low-cost, real-time, online, and accurate method; and (2) changes in surface-layer soil moisture affect both ESP and step voltage. These effects are large in the case of high resistivity for the soil layer where the ground electrode is buried. This large fluctuation in step voltage particularly results in a potential safety hazard during ground electrode operation. Therefore, in order to ensure personal safety and obtain more accurate electrical parameters, it is necessary to consider the effect of natural climate on the soil surface resistivity. Finally, the value of the step voltage can be observed using image recognition, this also provides a new method for the safety monitoring of the DC ground electrode.

Keywords

Ground electrode, finite element, image recognition, soil moisture, monitoring

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Introduction

The ground electrode in an HVDC transmission system plays an extremely important role in maintaining safe and stable operation of the entire system. Because the ground current can have a negative impact on nearby power and communication equipment,1–2 and the abnormal increase in step and touch voltages can cause personal injury and death,3–5 it is necessary to establish a surface-potential calculation and monitoring model for HVDC transmission systems. The existing models are mainly classified into ground grid and soil structure models. Given that the electrical structure of soil varies greatly with a large spatial scale, it is difficult to establish a unified soil structure model that is completely reflective of the real conditions. The extent to which the calculated and actual electrical parameters of ground electrodes are close to each other is directly affected by the soil structure model. Therefore, to provide more accurate data for the safe operation and fault maintenance of HVDC transmission systems, it is important to establish a more realistic soil structure model. At present, the Werner method6–7 and the magnetotelluric method (MT)8 are widely used in the inversion of soil electrical structure. The MT method cannot accurately measure the earth resistivity of the shallow layer (in the range of 0–100 m), so the measurement of the earth resistivity of the shallow layer still needs to use the Werner method.

Liu et al.9 established a three-dimensional soil structure model for soils near the ground electrode by partitioning the study region. In addition, Liu et al.10

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obtained earth potential distribution in a horizontal, vertical, and composite soil-structure models by using an equivalent complex image method, respectively. Ruan et al.\textsuperscript{11} established a multi-layered soil-structure model by using measurement data, and showed that the on-site measured soil resistivity of the region where the ground electrode was buried could be used for more accurate calculation of the electrical parameters of the ground electrode. Li et al.\textsuperscript{12} analyzed the effects of different soil-structure models on the earth-surface potential distribution, and proposed a criteria for soil model selection. Yang et al.\textsuperscript{13} calculated the nearby earth potential of the ground electrode in different soil-structure models to analyze the effects of upper-layer and lower-layer soil resistivity on the earth potential. Sima et al.\textsuperscript{14} modified the traditional soil models by considering vertical surface relief, hence establishing a more realistic soil model. Further, Ruan et al.\textsuperscript{15} studied the effects of horizontal layered, vertical layered, and finite-volume soils on ground resistance, current distribution, earth-surface potential, and touch voltage. Eduardo et al.\textsuperscript{16} proposed a method for calculating the electric field and current density generated by HVDC ground electrodes in homogeneous and heterogeneous soil structures. Mehrdad et al.\textsuperscript{17} proposed a method that combines the electromagnetic and circuit approaches is proposed to determine the transient resistance of the grounding electrode system by incorporating the soil ionization effect of non-homogeneous soils.

In HVDC transmission systems, the most important electrical parameters are step voltage and earth-surface potential. Changes in surface-layer soil moisture (characterized by the water content) lead to changes in resistivity, which in turn have a certain degree of effect on the step voltage and earth potential, resulting in potential safety hazards in severe conditions. As shown in the existing literature, the soil models that are used to calculate the electrical parameters of a grounding system are based on fixed resistivity values; therefore, they fail to consider the fact that the surface-layer soil resistivity is prone to soil moisture changes. Moreover, the existing soil-moisture measurement methods are subject to some drawbacks when applied in the region near the ground electrode. The current methods for measuring soil moisture mainly include satellite remote sensing,\textsuperscript{18} drying-weighing,\textsuperscript{19} and time-domain reflectometry (TDR),\textsuperscript{20} etc. Satellite remote sensing is suitable for a wide range of moisture surveys, but it is barely able to obtain remote sensing data in the region near the ground electrode. Drying-weighing has a high accuracy, but it is inapplicable to on-line monitoring. Further, while TDR can be used for on-line monitoring, it is expensive in terms of instrumentation and difficult in terms of maintenance. Therefore, it is highly desirable to use a low-cost, high-precision, online soil-moisture identification technology.

In view of the aforementioned context, when establishing a soil model, the effects of short-term climate (short-term rainfall and high temperature) on surface-layer soil resistivity were considered for the first time, this study also proposes an identification model for surface-layer soil resistivity based on soil image. In addition, the depth range where in the soil resistivity is susceptible to climate is determined. Based on the relatively stable resistivity values of lower-layer soils, a complete soil-structure model is established for the soil near the HVDC ground electrode, considering the effects of soil moisture changes. In addition, a finite element method is employed to calculate the earth-surface potential and step voltage of the region near the ground electrode, and the effect pattern of surface-layer soil moisture changes on the earth-surface potential and step voltage is analyzed. The experimental results show that climatic conditions have a greater impact on the step voltage and potential distribution when the shallow-layer resistivity is larger, which cannot be taken into account by traditional soil models. At the same time, the method used in this paper to identify resistivity, it can provide accurate parameters for establishing a soil model, and identify the step voltage through the soil image.

**Basic theory**

**Ground electric field and boundary conditions**

Figure 1 presents a schematic of HVDC transmission in a monopolar ground return mode. Here, a large DC current overflows through the ground electrode to a wide range of soil areas, resulting in the aberration of earth potential.

The electric field formed by the current distributed in the ground can be described as a constant current field wherein the potential satisfies the following basic equations:

\[ \nabla \cdot E = 0 \]  
\[ \nabla \cdot J = - \frac{\partial \rho}{\partial t} \]  
\[ E = - \nabla \varphi \]

In these equations, \( J \) and \( E \) represent the current density and electric field strength, respectively; \( \rho \) and \( \varphi \) represent the volume charge density and scalar potential, respectively. The region wherein the ground

![Figure 1. Schematic of HVDC transmission in a monopolar ground return mode.](image)
electrode is buried is a field with sources, where the potential satisfies the Poisson equation. In the areas outside the ground electrode region, the potential satisfies the Laplace equation:

\[ \nabla^2 \varphi = 0 \]  

(4)

In the three-dimensional Cartesian coordinate system, equation (4) can be written as:

\[
\frac{\partial}{\partial x} \left( \frac{1}{\rho} \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\rho} \frac{\partial \varphi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\rho} \frac{\partial \varphi}{\partial z} \right) = 0
\]  

(5)

In equation (5), \( \rho \) is a function of soil resistivity. To obtain a unique solution for the differential equation, it is necessary to introduce an electrostatic field boundary condition. Given that the ground electrode is installed in a coke bed, the entire ground electrode can be regarded as an equipotential body, and accordingly the following boundary condition can be defined:

\[
\varphi|_{s_1} = 0, \quad \frac{\partial \varphi}{\partial n}|_{s_2} = 0, \quad \varphi|_{s_3} = \varphi_0
\]  

(6)

In equation (6), \( s_1 \) is a site at the infinity of the ground plane, \( s_2 \) is the interface between the ground surface and air, and \( s_3 \) is the equipotential surface of the ground electrode. As shown in equation (5), the earth potential distribution is directly affected by the soil resistivity. The electric structure and parameters of the soil, as well as the factors such as lakes, fault layers, mountains, rivers and so on, determine the size of the grounding resistance of the grounding electrode, and the grounding resistance directly affects the distribution of the overflow current, and finally affects the distribution of the earth potential, when the grounding resistance is small, the current distribution is uniform, so the potential gradient is small; on the contrary, the potential gradient is large. From the Bessel function method\(^6\) and the Green function method\(^21\) show that the potential distribution mainly depends on the resistivity of the shallow-layer soil, when the shallow resistivity is smaller, the earth potential is higher, on the contrary, the potential is lower. In addition, lateral abrupt changes in surface soil resistivity cause changes in earth potential distribution.\(^22\) Therefore, it is necessary to consider the effects of varying values of soil resistivity on the earth potential.

**Relationship between soil color and moisture**

The measurement results of soil color reveal that the soil color can be considered as a function of climatic factors, and is significantly affected by soil moisture.\(^23\) The image characteristics of soil are jointly affected by several complicated factors, such as soil organic matter, water content, and soil roughness. Provided other characteristics of the soil remain unchanged, the image characteristics are mainly affected by water content. Before soil moisture is fully saturated, the soil spectral reflectivity decreases with increasing water content, exhibiting a linear relationship\(^23\) as described in equation (7):

\[
y = -kx + c
\]  

(7)

where \( y \) denotes the soil reflectivity, \( x \) denotes the soil water content, \( k \) and \( c \) are the fitting parameters. The visible light-based measurement of soil moisture is mostly conducted by using the relationship between the soil moisture and soil spectral reflectivity. The soil water content can be determined by using the spectral reflection information of the solar spectrum (380–2500 nm). The soil spectral reflectivity affects the brightness of the image. Because the brightness values coincide with the gray-scale values in a one-to-one relationship, it is possible to use the gray-scale values of soil images to estimate the soil moisture. The gray-scale values are divided into 256 levels from 0 to 255, with 0 representing completely black and 255 representing completely white. The higher the gray-scale value of the soil image, the lower the soil water content, and the reverse is also true. Based on this relationship, the gray-scale values of soil images can be used to predict soil moisture.

**Figure 2.** Soil structure.
air; therefore, the conductivity of surface soils is dominated by soil moisture.

According to their texture, soils can be classified into sand, silt, clay, and other types; however, these soil types exhibit a similar trend in terms of the relationship between their resistivity and moisture. This means the resistivity decreases gradually with increasing soil moisture.\(^{26}\) Many researchers have researched the relationship between soil resistivity and soil moisture. The results show that soil resistivity and moisture are inversely proportional, and the fitting models for the relationship are mainly linear model\(^ {27}\) and exponential model\(^ {28}\) and power function model,\(^ {29}\) etc. In addition, a relevant study\(^ {30}\) showed that a highly significant functional relationship exists between the soil moisture and resistivity:

\[ x = \lambda \rho^{-\beta} \quad \text{(8)} \]

In equation (8), \( x \) is the soil water content, \( \rho \) is the soil resistivity, and \( \lambda, \beta \) are the fitting parameters.

**Modeling methods**

**Soil-resistivity identification model based on image gray-scale values**

The two ground electrodes of the HVDC transmission system are far apart, because of which the ground current causes a wide range of potential distribution. If a soil model that describes the effects of surface-layer soil moisture on soil resistivity is to be established, then the traditional measurement method cannot be used because it is expensive and involves complicated engineering processes. Therefore, an alternative is to install high-resolution cameras in selected sites of the ground electrode region to acquire surface soil images. Image gray-scale values are calculated by using an image processing technology. The calculated gray-scale values are then compared with the sensor-measured soil moisture and resistivity data to establish a functional image gray-scale values and resistivity values of the surface soil in the ground electrode region. Figure 3 shows the process of establishing the relationship between soil color and resistivity. Thus, the image gray-scale values can be used to achieve real-time estimation of surface-layer soil resistivity changes caused by the climatic factors such as rainfall.

**Image preprocessing and color space conversion.** Because a varying degree of interference effects may arise during the image acquisition process, the soil images are subjected to a preprocessing step called smoothing that is based on median filtering with a window size of 3×3. This process effectively removes the noise and preserves the original information of the images. In addition, because RGB images are subjected to illumination intensity, it is necessary to convert the RGB mode into the \( L^*a^*b^* \) image mode, and then extract the feature parameters. In the \( L^*a^*b^* \) image mode, \( L^* \) denotes the brightness, and \( a^* \) and \( b^* \) denote the range of color changes. The brightness channel is separated from the color channel. The parameter \( L \) is significantly affected by the illumination intensity, whereas the gray-scale values of \( a^* \) and \( b^* \) channels are basically independent of illumination intensity when it lies in a certain range. The RGB color space cannot be transformed directly into the \( L^*a^*b^* \) space. Therefore, \( R, G, \) and \( B \) in the RGB mode are first transformed into the \( XYZ \) mode, and then the chromatic values \( X, Y, \) and \( Z \) are transformed into the \( \Delta L\Delta a\Delta b \) spatial mode, with the transformation modes, as expressed in Eqs. (9) and (10). Under standard white light illumination, the values of \( X_0, Y_0, \) and \( Z_0 \) are 0.983, 1, and 1.183, respectively.

\[
\begin{align*}
X &= 0.607R + 0.174G + 0.201B \\
Y &= 0.299R + 0.587G + 0.114B \\
Z &= 0.066G + 1.117B \\
L &= 116(Y/Y_0)^{1/3} - 16 \\
a^* &= 500((X/X_0)^{1/3} - (Y/Y_0)^{1/3}) \\
b^* &= 200((Y/Y_0)^{1/3} - (Z/Z_0)^{1/3})
\end{align*}
\]  

**Filtering of image interference area.** In soil image data, the pixel brightness is affected by the soil-reflected light, vegetation-reflected light, and light reflected by the other non-soil materials. Cracks may form in surface soils and be covered with seed vegetation under natural conditions. In these areas, the reflected light will have a large interference with the image features; therefore, these areas should be identified and filtered out of the images. The gray-scale values of the non-interference areas are set to be distributed in the range \([a, b]\), and the areas outside this range are defined as interference...
areas. Owing to the frequent changes in surface water content and consequent changes in soil color, the filtering of the interference areas should be based on a varying threshold value (rather than a fixed threshold value) to avoid misclassification. To this end, the constant false-alarm rate (CFAR) technique is employed to determine the corresponding threshold values according to the moisture of the surface. As shown in Figure 4, the gray-scale values of surface-layer soil images are normally distributed, with the probability density function expressed in equation (11):

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-u)^2}{2\sigma^2}}$$  \hspace{1cm} (11)

where $u$ and $\sigma$ are the mean and standard deviation of the image, respectively. The threshold $a$ is then determined, and the pixels with gray-scale values higher than $a$ are regarded as background pixels, whereas the pixels with gray-scale values lower than $a$ are regarded as interference pixels forming interference areas. The false alarm probability of misclassifying the background as interference pixels is obtained, and the pixels with gray-scale values higher than $a$ are then filtered out using a reasonable functional mapping relation.

Calculation of the average gray-scale value of surface-layer soil image. Based on the determined threshold, the original image areas with gray-scale values outside the range $[a, b]$ are regarded as interference areas, and are filtered out using a reasonable functional mapping relationship. By defining $f(x, y)$ as the gray-scale value of an original image pixel $(x, y)$, a functional mapping relationship can be obtained, as expressed in equation (17). After the aforementioned image processing, an image that is more reflective of the changes of surface-layer soil moisture is obtained, and then the average gray-scale value of the original image is calculated. Thus, the relationship of the average gray-scale value with the surface-layer soil moisture and resistivity can be established, respectively.

### Table 1. Sensor parameters.

| Parameter type | Moisture (%) | Temperature (°C) | Conductivity (ms/cm) |
|----------------|-------------|-----------------|---------------------|
| Measurement range | 0%–100% | -30–70 | 0–10 |
| Accuracy | ±3% | Absolute error | < 0.4 |
| | | | 2% of the full measurement range |

$$p_f = \int_{-\infty}^{\infty} p(x)dx = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-u)^2}{2\sigma^2}} dx$$  \hspace{1cm} (12)

By normalizing equation (12) and using a new variable $k$, a new probability density function can be obtained as shown in the following:

$$p(k) = \frac{1}{\sqrt{2\pi}} e^{-\frac{k^2}{2}}$$  \hspace{1cm} (13)

In equation (13), $k = \frac{u-a}{\sigma} > 0$, and the false alarm probability for the same can be expressed as shown in the following:

$$p_f = \int_{a}^{b} p(k)dk = \int_{a}^{b} \frac{1}{\sqrt{2\pi}} e^{-\frac{k^2}{2}} dk$$  \hspace{1cm} (14)

When $p_f$ is constant, the false alarm probability will also be constant, that is, the value of $k$ will be constant; thus, the threshold $a$ can be determined. Similarly, the threshold $b$ can be determined. The values of $k$ vary between 3 and 4.

$$a = u - k\delta$$  \hspace{1cm} (15)

$$b = u + k\delta$$  \hspace{1cm} (16)

Relationship between the gray-scale values of soil images and the soil resistivity values. In this experiment, a loam layer (15 cm thick) was used as the sample. DC ground electrode are often located in uncovered, relatively flat soil areas. The change in soil moisture is mainly affected by rainfall and evaporation, therefore, in order to better simulate the effect of rainfall on moisture, tap water
was used as experimental water. A certain amount of tap water was added to the sample surface and was allowed to diffuse through the soil pores until an even soil color was obtained; consequently, the soil water content was measured to be approximately 30%. Next, the soil sample was placed in a dry and ventilated environment to evaporate the water naturally, and the soil images were acquired at equal time intervals. As the soil water evaporation proceeded, soil images at different levels of soil moisture were obtained. Meanwhile, a multifunctional sensor was employed to measure the soil temperature, moisture, and conductivity; here, the sensor probe was placed at the center of the experimental soil. The relationship of the gray-scale values with the soil moisture and conductivity values was determined by using computer-aided image processing. The major measurement parameters of the sensor (model SMET-3-V3) are shown in Table 1:

| Image No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Gray-scale value | 167.76 | 163.98 | 157.71 | 155.43 | 153.46 | 149.30 | 146.57 | 145.12 | 140.93 | 138.55 | 133.48 | 130.10 |
| Temperature | 24.01 | 23.91 | 23.90 | 23.60 | 23.51 | 23.33 | 23.02 | 22.78 | 21.35 | 21.15 | 19.93 | 19.14 |
| Moisture | 4.92 | 6.25 | 7.42 | 9.69 | 10.90 | 13.13 | 15.27 | 17.06 | 20.01 | 22.12 | 24.78 | 26.09 |
| Conductivity | 2040 | 1075 | 345 | 222 | 139 | 92 | 71 | 59 | 53 | 47 | 41 | 36 |

The conductivity is in us/cm, and the resistivity is in Ω·m.

A total of 12 images were selected for analysis. Their gray-scale values were first calculated in the order of image acquisition, and then the corresponding values of temperature, moisture, and conductivity were measured; here, the measured conductivity was converted into resistivity. The experimental results are presented in Table 2, and the soil images in the order of increasing soil moisture are shown in Figure 5.

As shown in Figure 6, the soil reflectivity of natural light decreases gradually with increasing soil water content; this in turn decreases the image gray-scale values linearly. This observation is consistent with the aforementioned mathematical model. As shown in Figure 7, there is an exponential relationship between the soil image gray-scale values and soil resistivity values, meaning the resistivity values increase with increasing gray-scale values. Moreover, the increase rate is high at the beginning, but flattens out after a certain point. The functional relationship between the soil image gray-scale values $G$ and soil resistivity values $\rho$ can be fit into equation (19):

$$G = 445.4\rho^{-0.7042} + 167.5$$

where the coefficient of determination $R^2 = 0.98$, and $RMSE = 1.88$, indicating that it is reliable to use...
image gray-scale values to estimate the surface soil resistivity. Therefore, the resistivity can be better identified by the soil gray value, which is a new method with high reliability. In addition, this provides the data for the subsequent simulation calculation.

**Calculation model for earth potential**

As shown in Figure 8, the ground can be divided into a number of uniform horizontal structures based on the geophysical properties; here, $h_i (i = 1, 2, 3 \cdots)$ and $\rho_i (i = 1, 2, 3 \cdots)$ represent the thickness and resistivity of each horizontal soil layer, respectively. The resistivity of the upper-layer soil (surface soil) is susceptible to a variety of natural factors, whereas the resistivity of the lower-layer soil is relatively stable.\(^{32}\) The surface-layer soil moisture is affected by several factors such as rainfall, evaporation, and soil hydraulic properties. Therefore, it is necessary to determine the depth range wherein the soil moisture is susceptible to short-term climatic conditions. In this regard, several researches have been reported as mentioned in the following:

1. Yuan et al.\(^{33}\) measured the soil moisture at depths of 20, 40, and 60 cm. Under low-intensity rainfall, the soil moisture increased rapidly at a depth of 20 cm, and increased slightly at a depth of 40 cm; however, it did not change at a depth of 60 cm. Moreover, when the weather was clear, large changes in moisture were observed at the depth of 20 cm;

2. Guo et al.\(^{34}\) monitored the resistivity of different soil layers, and observed that under high-temperature conditions without rainfall, the soil resistivity at the depth of 20 cm increased by 1.76 times the original value. Further, the soil resistivity at depths of 40 and 60 cm increased to 1.14 and 1.12 times the original values, respectively; however, deeper soil layers did not exhibit any changes in resistivity. Under rainfall, the resistivity changed greatly at the depth of 20 cm and slightly at the depth of 40 cm; however, it did not change at increased depths.

Based on the aforementioned reports, to consider the position of the probe and the downward infiltration of water during the measurement comprehensively, the maximum soil depth above which the soil moisture changes greatly with the climatic conditions is considered 0.3 m. When measuring the resistivity with the Winner method, it is necessary to change the electrode distance for multiple measurements, and to process the data to obtain the apparent soil resistivity. Therefore, for this shallow layer affected by the environment, the resistivity changes greatly in a short time, using the image method, the resistivity can be quickly and accurately identified, this measurement method can measure and transmit the current soil resistivity in real time, which is more convenient than the Winner method in obtaining data. This is consistent with the soil depth range that soil images can identify. Moreover, because a large geographical range is under the influence of rainfall and temperature increases, the studied areas near the ground electrode can be considered to be under uniform influence of climatic conditions.

Although soil texture varies from region to region and accordingly, and soil resistivity changes with soil moisture to a varying extent, it is possible to conduct an online calibration of the functional relationship between the soil resistivity values and soil image gray-scale values in the soil region to be measured in engineering practice. Thus, the first-layer soil resistivity in the soil structure model can be estimated online using the aforementioned image method. For the lower-layer soil, moisture is less likely to be lost under non-extreme weather conditions; however, there may be a slight variation. The resistivity of lower-layer soil can be obtained by using the following two methods: (1) Field measurement by engineering equipment, such as the commonly used Werner four-electrode method or magnetotelluric method; (2) Soil structure stratification and soil resistivity allocation according to the local geological and historical field survey data. A lower-layer soil structure model established by using the aforementioned two methods will be consistent with the actual
soil structure in the local environment, and this soil structure will not change in a short period of time. Although the Werner four-electrode method and the magnetotelluric method can accurately invert the soil structure, the surface soil resistivity is time-varying due to the influence of short-term climate, it is complicated, and the cost of equipment and maintenance is relatively expensive. Therefore, this paper uses soil images to identify the surface resistivity. Therefore, by combining the surface soil of labile resistivity with the underlying soil of relatively stable resistivity, a complete soil-structure model is established considering the changes in surface-layer soil moisture. By using a finite method and ANSYS simulation, the potential equation mentioned in Section 1.1 can be solved numerically to obtain the potential at any point in the field under the boundary conditions as specified in Section 1.1.

**Case analysis**

To explore the influence of surface soil-moisture changes on the earth potential distribution, a four-layer soil model was established for experimentation. The distribution of earth-surface potential is most affected by the soil parameters of the soil layer where the ground electrode is buried, and very slightly affected by the other low-resistivity layers. Therefore, this study addresses the effects of surface-layer soil moisture on earth potential distribution in two cases considering the impact of ground-electrode soil-layer resistivity on earth potential, as elaborated below.

Case 1: The ground-electrode soil-layer resistivity is small, and the second-layer soil resistivity is set to 20 $\Omega \cdot m$.

Case 2: The ground-electrode soil-layer resistivity is large, and the second-layer soil resistivity is set to 400 $\Omega \cdot m$. The detailed parameters are listed in Table 3.

The first-layer soil resistivity ($\rho$ in the table) changes with the surface-layer soil moisture, and can be calculated by using the functional relationship between the soil image gray-scale values and soil resistivity values as shown in equation (19). The first-layer soil resistivity is set to vary in the order of 350, 160, and 40 $\Omega \cdot m$ to reflect the increase in soil moisture. As shown in the table, the ground-electrode soil layer is called as a shallow soil layer, and will not be elaborated hereinafter.

**Earth-surface potential calculation**

The ground electrode is set to have a shape of single circular ring with a radius of 600 m, and is buried at a depth of 3 m. The cross section of coke is set to 0.7 $\times$ 0.7 m. When only the influence of the soil structure on the earth potential is to be considered, a voltage (1015 V in this study) is applied to the equipotential surface of the ground electrode. Because of the symmetry of the model, the finite element analysis is performed on two-dimensional axisymmetric elements to reduce the calculation time. Figure 9 shows the potential distribution in the soil profile for a shallow-layer resistivity of 400 $\Omega \cdot m$, and Figure 10 shows the earth-surface potential distribution for the two cases of shallow-layer resistivity (20 vs 400$\Omega \cdot m$).

As shown in Figure 10, the calculated earth-surface potential in the case of large shallow-layer resistivity differs significantly, that is by nearly 200V, from that in the case of small shallow-layer resistivity. In

| Soil layer    | Thickness (m) | Resistivity ($\Omega \cdot m$) |
|---------------|---------------|-------------------------------|
| Surface layer | 0.3           | $\rho$                         |
| Shallow layer | 4             | 20                            |
|               |               | 400                           |
| Middle layer  | 50            | 200                           |
| Bottom layer  | infinity      | 350                           |

**Figure 9.** Earth potential distribution of the HVDC ground electrode.

**Figure 10.** ESP distribution of the HVDC ground electrode.
addition, the earth potential drops quickly within the 2 km region of the ground electrode and slowly outside this region.

The earth potential distribution is calculated for a variety of surface layer resistivity changes with moisture under the two conditions of shallow-layer resistivity, respectively. To address the effects of moisture-dependent surface soil resistivity on the earth potential under the two conditions of shallow-layer resistivity, the earth potential is selected within a certain geographical range for comparison, as shown in Figure 11.

As shown in the figure, in both cases of shallow-layer resistivity, the earth-surface potential is affected by the surface-layer soil moisture; it increases with the increase in moisture. When the shallow-layer resistivity is high (400 $\Omega \cdot m$), the earth-surface potential changes by 20 V because of the varying surface layer soil resistivity, and changes only by approximately 3 V when the shallow-layer resistivity is low (20 $\Omega \cdot m$). This indicates that the potential distribution is more susceptible to surface-layer soil moisture when the shallow-layer resistivity is large.

**Step voltage calculation**

The changes in surface-layer soil moisture have a certain degree of impact on the step voltage. Given that the maximum step voltage is distributed near the inner and outer sides of the circular ring, only the step voltage within a small distance of the inner and outer sides of the circular ring is calculated, as shown in Figure 13. The maximum step voltage for each soil parameter is shown in Table 4.

As shown in Figure 12, the peak step voltage is higher at the outer side of the circular ring than at the inner side. Considering only the shallow-layer resistivity, the maximum step voltage at the resistivity of 400 $\Omega \cdot m$ is significantly higher than at the resistivity of 20 $\Omega \cdot m$, with a difference of approximately 18 V near the circular ground ring. As shown in Table 4, when the surface-layer soil resistivity drops from 350 to 40 $\Omega \cdot m$, the maximum step voltage reduces by 8.99 V. However, when the shallow-layer resistivity is 20 $\Omega \cdot m$, the surface-layer soil moisture leads to small changes in maximum step voltage, that is, approximately 0.2 V. Therefore, when the shallow-layer resistivity is 400 $\Omega \cdot m$, the step voltage is greatly affected by the surface-layer resistivity, which will cause the step voltage to exceed the limit and cause hidden dangers. Therefore, in such cases, it is necessary to consider the short-term climate effect on the surface-layer moisture.

To use the gray-scale values of soil images better and to reflect the moisture-induced changes in soil...
surface-layer soil resistivity and in turn step voltage, calculation is performed on step voltage by using surface-layer soil resistivity in the range (40, 2000) for the two cases of shallow-layer resistivity. Moreover, according to the aforementioned functional relationship between the soil resistivity values and soil image gray-scale values, the change pattern of the step voltage with respect to the gray-scale values of surface-layer soil images is obtained, as shown in Figure 13.

As shown in Figure 13(a), when the shallow-layer resistivity is low (20 Ω · m), the step voltage gradually increases and then stabilizes with the increase in surface-layer soil resistivity. This means the surface layer soil resistivity has a limited impact on the step voltage in this case. In addition, when the soil image gray-scale value is 160 (resistivity is approximately 900 Ω · m), the maximum step voltage changes greatly. When the gray value is about 163, the maximum step voltage reaches a maximum value of 5.12 V, and reaches a stable value. Moreover, the simulation and calculation results of maximum step voltage are all below the safety control value. As shown in the figure, the safety value gradually increases with the decrease in surface-layer soil moisture. However, when the surface-layer soil resistivity is lower than 600 Ω · m, the step voltage is higher than the safety control value, posing a potential safety hazard to nearby persons.

Step voltage estimation based on the soil images reveals that if the shallow-layer has large resistivity, the gray-scale values of surface-layer soil images should be higher than 162.56 to ensure personal safety. As aforementioned, the changes in surface-layer soil moisture affect the earth-surface potential and step voltage. A decrease in shallow-layer soil resistivity leads to a higher earth-surface potential and lower potential gradient, with the latter more preferred to the former in engineering practice with respect to personal safety.

![Figure 13. Relationship between soil image gray-scale values and step voltage values. (a) Shallow-layer resistivity of 20 Ω · m. (b) Shallow-layer resistivity of 400 Ω · m.](image)

![Figure 14. Changes in step voltage with surface-layer soil resistivity.](image)

### Table 4. Maximum step voltage.

| Shallow-layer resistivity (Ω · m) | Surface-layer soil resistivity (Ω · m) | Maximum step voltage (V) |
|----------------------------------|---------------------------------------|--------------------------|
| 400                              | 350                                   | 23.00                    |
|                                  | 160                                   | 20.32                    |
|                                  | 40                                    | 14.01                    |
| 20                               | 350                                   | 4.73                     |
|                                  | 160                                   | 4.70                     |
|                                  | 40                                    | 4.55                     |

14 presents the change pattern of the step voltage with respect to the surface-layer soil resistivity. As shown in the figure, the safety value gradually increases with the decrease in surface-layer soil moisture. However, when the surface-layer soil resistivity is lower than 600 Ω · m, the step voltage is higher than the safety control value, posing a potential safety hazard to nearby persons. Step voltage estimation based on the soil images reveals that if the shallow-layer has large resistivity, the gray-scale values of surface-layer soil images should be higher than 162.56 to ensure personal safety.

As aforementioned, the changes in surface-layer soil moisture affect the earth-surface potential and step voltage. A decrease in shallow-layer soil resistivity leads to a higher earth-surface potential and lower potential gradient, with the latter more preferred to the former in engineering practice with respect to personal safety.
However, the earth-surface potential and step voltage are slightly affected by the surface-layer soil moisture. In the case of high shallow-layer soil resistivity, the step voltage and earth-surface potential are significantly affected by the surface-layer soil resistivity. The large changes in earth potential affect (to some extent) the solution-seeking process for the problems of other electrical parameters. The large fluctuation in step voltage poses a certain degree of potential safety hazard to nearby people. The comparison between the soil model and the traditional model in this paper shows that the traditional model cannot reflect the impact of short-term climate on the step voltage and ground potential. Therefore, in order to obtain more practical electrical parameters of the ground electrode, ensure personal safety and maintain the ground electrode operates safely, it is essential to establish a dynamic soil model that is affected by short-term climate.

Conclusion

1. (1) Compared with the widely used Winner method, the method proposed in this paper has certain advantages in identifying the surface resistivity under the influence of climate. The image measurement method can not only measure the resistivity in real time and easily, but also overcome the influence of the harsh environment, and reduce the investment of resources. Finally, this non-contact measurement method has better protection for the measurement equipment, and reduces equipment damage.

2. (2) According to the specific working conditions of the ground electrode, the image collected on the site is processed, the step voltage of the site is identified by the soil image gray value, and the extreme value of safe gray value is determined, which is the safety monitoring of the ground electrode determines an accurate data reference. High-definition probes are arranged at the ground monitoring site of the ground electrode, and the on-site environment is observed by images. The area with the lower gray value represents the greater the moisture, so the greater the potential danger. By grading these areas, different warning levels are obtained, the smaller the gray value, the higher the danger level. In this way, it is possible to intuitively monitor and identify dangerous areas by means of images, provide reliable troubleshooting solutions for workers, and reduce waste of time and human resources.

3. The traditional soil model remains unchanged after engineering measurement and is used to calculate relevant electrical parameters. In fact, the surface resistivity of the earth electrode is greatly affected by the environmental climate, which changes the entire soil structure and ultimately affects the distribution of earth potential. In this paper, the soil model is established by combining traditional measurement methods with the methods in this paper. The resistivity of the lower layer resistivity is not easy to change through the Werner four-electrode method or the magnetotelluric method to invert the soil structure, and the surface resistivity of the soil with time-varying characteristics is identified by images, so that not only can ensure the accuracy of the soil electrical structure, at the same time, it can also reduce the personnel and economic invested by traditional methods for repeated measurements. Therefore, a dynamic soil model considering the impact of climate is established in this paper, so that the parameters calculated by this soil model are closer to the actual situation.

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References

1. Jardini JA, Vasquez-Arnez RL, Kovarsky D, et al. Interference of a line-commutated converter high-voltage direct current system upon pipelines located in its vicinity. Int Trans Electr Energ Syst 2014; 24: 1688–1699.
2. Zhang B, Zhao J, Zeng R, et al. Numerical analysis of DC curent distribution in AC power system near HVDC system. IEEE Trans Power Deliv 2008; 23(2): 960–965.
3. Zhiwei L. Measurement of grounding resistance of ground electrode in two-layer soil. Power Syst Technol 1998; 22(5): 56–58.
4. Yuhua C. Research on the measurement system of the electrical parameters of variable frequency power. Hunan: Hunan University, 2009.
5. Kostić V, Raščević N and Pavlović A. Enhanced grounding system impedance measurements for high-voltage
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14. Wenxia S, Donghui L and Tao Y. Influence of surface content and resistivity of earthen ruin walls. Chin J Rock Mech Eng 2009; 28(Suppl. 2): 4054–4058.

15. Ruan W, Ma J, Liu J, et al. Performance of HVDC system under single-maximal operation in composite soil model. Proc CSEE 2007; 36: 8–13.

16. Telles Villas JE and Portela CM. Soil heating around the ground electrode of an HVDC system by interaction of electrical, thermal, and electroosmotic phenomena. IEEE Trans Power Deliv 2003;18: 967–873.

17. Liu R, Zhang K and Chao L. Analysis of temporal and spatial characteristics of soil moisture in China based on multi-source satellite observation. Adv Water Sci 2017; 28(04): 479–487.

18. Ruan T, Luo L and Yang Q. Soil temperature characteristics test and analysis of its influence on heating of annular DC ground electrode. Proc CSEE 2013; 33(1): 188–195.

19. Haibo L, Yanlin Z and Chuangliang C. Experimental study on measuring water content of expansive soil by time domain reflection method. Chin J Rock Mech Eng 2008; 27(12): 2568–2574.

20. Yang Y, Liu X, Chen T, et al. Impact of soil structure adjacent to ground electrodes of UHVDC power transmission lines on DC bias of power transformers. Power Syst Technol 2012; 36(7): 26–32.

21. Chen D, Huang Z, Liu J, et al. Calculation of current field of current source in horizontal layered soil. High Voltage Eng 2008; 34(7): 1379–1382.

22. Shengli Y, Xiaomin F and Jijun L. Study on the relationship between table color and climate qualitative to semi-quantitative relationship. Science China (Series D) 2001; 31: 175–179.

23. Ruru D, Xiaoxiang C and Zhihe H. A remote sensing survey method for deep soil moisture content supported by GIS. J Sun University 1997; 5: 102–105.

24. Xiaobin C, Guangning W and Longhai F. Study on the influence of temperature on soil resistivity. Trans Chin Electr Soc 2007; 22(9): 1–6.

25. Mi Z, Jianguo W, Songbo H, et al. Experimental study on influencing factors of soil resistivity measurement. Rock Soil Mech 2011; 32(11): 3269–3275.

26. Hadzick ZZ, Guber AK, Pachepsky YA, et al. Pedotransfer functions in soil electrical resistivity estimation. Geoderma 2011; 164: 195–202.

27. Dong X, Wang Y, Cheng J, et al. Spatial variation and relationship of soil resistivity and water moisture on typical grass slopes of Yunwu Mountains. Trans Chin Soci Agricul Eng 2012; 28(7): 130–137.

28. Nijland W, Van der Meijde M, Addink EA, et al. Detection of soil moisture and vegetation water abstraction in a Mediterranean natural area using electrical resistivity tomography. Catena 2010; 81: 209–216.

29. Junliang G, Fengmin L and Yingbin M. Monitoring soil moisture of artificial Haloxylon ammodendron forest by resistivity imaging. Trans Chin Soci Agricul Eng 2018; 34(22): 92–101.

30. Jiaxiang H and Tao W. Study on on-line detection method of soil surface moisture content based on image processing. Trans Chin Soci Agricul Eng 2007; 10: 57–61.

31. Rongbiao Z, Jiaxiang H and Tao W. Development and performance of soil moisture measurement system for layered soil. Chin J Sci Instr 2014; 35(6): 1306–1314.

32. Lianguang L and Chenglian M. Calculation of earth potential distribution in multi-layer grounding of HVDC based on finite element method. Power Syst Prot & Control 2015; 43(18): 1–5.