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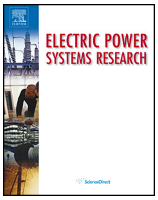

Experimental study on frequency-dependent properties of soil electrical parameters

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ABSTRACT

In the value calculation of the impulse characteristics of a grounding device, the suitability of the key parameters of the control equation, namely, soil resistivity and dielectric constant, has a considerable effect on the accuracy of the calculation results. The values of these two soil electrical parameters differ at various current frequencies. Thus, rules on the changes of soil electrical parameters with the current frequency into the ground have to be studied. Limited research has been conducted on the change in the rules of the soil electrical parameters in the lightning current band. This paper reports on the use of the broadband dielectric impedance spectrometer to conduct frequency sweep measurement of soil samples at various moisture content levels, discusses the change rules of soil resistivity and relative dielectric constant with current frequency from 50 Hz to 106 Hz, and details the conduct of rational analysis and value fitting. Results show that change is rapid when the soil resistivity and relative dielectric constant are at low frequency (below 100 kHz), and the change slows down when the frequency increases. In the low-frequency band (below 100 kHz), the soil moisture content has a significant effect on the frequency-dependent properties of the resistivity and relative dielectric constant, and the effect is minimal in the high-frequency band. The soil resistivity and relative dielectric constant as well as the current frequency meet the power function relation.

1. Foreword

When the impulse current is dispersed into the ground via the grounding device, the control equation that uses scalar potential as a variable can be expressed through the following equation [1]:

$$D(\varphi(x,y,z)) = \varepsilon \frac{\partial}{\partial t}\left(\nabla^2\varphi\right) + \nabla \cdot \left(\frac{1}{\rho}\nabla\varphi\right) = 0 \qquad (1)$$

where ε is the dielectric constant of the medium, ρ is the resistivity of the medium, and φ is the scalar potential function.

The value selection of soil resistivity and dielectric constant has a considerable effect on the accuracy of the calculation results of the impulse characteristics of the grounding device.

Existing studies show that the soil in the burying area of the grounding grid has significant frequency-dependent properties, i.e., soil electrical parameters (resistivity and dielectric constant) that change along with injection current frequency [2,3]. Domestic and foreign scholars have conducted further research on the frequency-dependent properties of soil parameters and have achieved significant results in the fields of logging technology, soil pollution monitoring, and mineral exploration, among others. Monitoring the differences between soil and rock under currents at various frequencies can reflect geological anomalies, mainly in two aspects. The complex resistivity method (also known as "spectral induced polarization method") is adopted at the low-frequency band to measure the complex resistivity of soil, and the status of the contaminated soil is analyzed on the basis of changes in amplitude and phase [4–12]. The electromagnetic survey based on the dielectric differences of soil and rock at the high-frequency band (above MHz) is mainly adopted to measure changes in the real and imaginary sections of its complex dielectric constant and is mainly used in the fields of mineral exploration, soil moisture detection, and so on [13–17].

Fourier transformation showed that lightning current frequencies were mainly centralized within the range from dozens of Hz to hundreds of kHz. At this band, however, research on the change of soil electrical parameters with frequency is limited. Qining, Xiaoming et al. adopted the plate capacitance method to measure the rules of dispersion characteristics of multiple rock samples within

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the frequency range from 1 kHz to 1.5 MHz [18]. Mi, Jianguo et al. measured the effect of AC frequency on the measurement of soil resistivity from 50 kHz to 200 kHz by experiments. The measurement results show that when the injection current frequency is less than 1000 Hz, the measurement error is less than 6% compared with the results at 50 Hz; therefore, minimal effect is observed on the measurement results [19].

In the current numerical calculation, however, the effect of frequency-dependent properties of soil electrical parameters on the impulse properties of the grounding device is often ignored, and simplification using predefined parameters is usually adopted in the simulation model [20]. Visacro et al. adopted the indirect measurement method to measure changes in soil resistivity and dielectric constant as current frequency changes from 10^2 Hz to 10^6 Hz and measured the transient voltage $v(t)$ and transient current $i(t)$ by injecting the impulse current to the ground and measuring ground potential rise (gpr); they obtained $V(\omega)$ and $I(\omega)$ by FFT. The ratio of the obtained $V(\omega)$ and $I(\omega)$determines the frequency characteristics of grounding impedance $Z(\omega)$, soil resistivity $\rho(\omega)$ corresponding to the real section of $z(\omega)$, and dielectric constant $\varepsilon(\omega)$ corresponding to the imaginary section of $z(\omega)$, consequently obtaining the frequency-dependent properties of soil electrical parameters [20,21]. Visacro et al. also introduced the measured frequency-dependent properties into the shock transient model for calculation. The results showed a significant difference in the calculation results of shock transient characteristics of the grounding electrode when the frequency-dependent properties of the soil are considered; these characteristics conform to the practically measured results [22,23]. However, this method is an indirect measurement, and the accuracy of Fourier transformation has a greater effect on the measurement results.

In summary, research on the changes in soil resistivity and dielectric constant with current frequency into the ground should be conducted. In this study, the broadband dielectric impedance spectrometer is used to perform frequency sweep measurement. Subsequently, changes in rules of soil resistivity and relative dielectric constant with current frequency are determined, and mechanism analysis and numerical fitting are conducted on the frequency-dependent properties of soil electrical parameters.

2. Experiment principles

In the alternating electric field, soil samples have no pure resistance, and a certain phase difference is observed between the current through the soil and the generated voltage. At this time, the admittance of both ends of the sample can be expressed as follows:

$$Y = G + j\omega C \tag{2}$$

where Y is the admittance of the soil sample, G is the equivalent conductance of the sample, $\omega = 2\pi f$ is the angular frequency of the current injection, C is the equivalent capacitance of the sample, and j is the imaginary unit.

The conductivity G and capacitance C can be, respectively expressed as

$$G = \frac{\sigma A}{l} \tag{3}$$

$$C = \frac{\varepsilon A}{l} = \frac{\varepsilon_0 \varepsilon_r A}{l} \tag{4}$$

where σ is the conductivity of the conductive medium to the conduction current; ε is the dielectric constant of the polarization characteristics; and ε_0 and ε_r are, respectively, the vacuum dielectric constant and the relative dielectric constant of the sample.

The expression of the conductivity G and capacitance C can be introduced into Eq. (2) to achieve the following:

$$Y = \frac{\sigma A}{l} + j\omega\left(\frac{\varepsilon_0 \varepsilon_r A}{l}\right) = \frac{(\sigma + j\omega\varepsilon_0\varepsilon_r)A}{l} \tag{5}$$

Eqs. (5) and (2) have the same form. Thus, we obtain the equation $\sigma^* = (\sigma + j\omega\varepsilon_0\varepsilon_r) = \sigma' + j\sigma''$, where σ^* is complex conductivity, σ' is the real section of complex conductivity, and σ'' is the imaginary section of the complex conductivity.

The admittance of the soil sample is expressed in the form of real and imaginary sections, as follows:

$$Y = Y' + jY'' \tag{6}$$

From Eqs. (5) and (6), the real and the imaginary sections are regarded as equal to achieve

$$\sigma = Y' \times \frac{l}{A}, \quad \varepsilon_r = \frac{Y''}{\omega\varepsilon_0} \times \frac{l}{A} \tag{7}$$

With the frequency-dependent properties of the soil, conductivity and relative dielectric constant in Eq. (7) are the values associated with frequency, which can be expressed as

$$\sigma(\omega) = Y'(\omega) \times \frac{l}{A}, \quad \varepsilon_r(\omega) = \frac{Y''(\omega)}{\omega\varepsilon_0} \times \frac{l}{A} \tag{8}$$

Thus, as long as the re-admittance of the sample is measured, the conductivity and relative dielectric constant of the sample can be achieved using Eq. (8), and the reciprocal of conductivity is resistivity.

3. Experiment program

For the measurement of frequency-dependent properties of soil parameters, different stimulation frequencies are selected for the point-by-point or frequency sweep measurement that will determine the functional relation of the complex resistivity or complex dielectric constant to the measurement frequency. In this study, the Novocontrol broadband dielectric impedance spectrometer in the laboratory is used to measure the complex impedance of the soil sample between 50 Hz and 10^6 Hz. The frequency range (3 μHz to 3 GHz) and impedance analysis range (10 mΩ to 100 tΩ) are very broad and the measurement accuracy is high. The testing principle is shown in Fig. 1. The voltage of different frequencies is applied to the testing samples through the upper and lower electrodes of the experiment sample to measure the current flowing through the sample and initially obtain the impedance value of the sample.

The BDS 1200 sample holder, which has a PT100 temperature sensor, is used. The frequency range of this sample holder is from 3 μHz to 10 MHz. The sample holder is connected to the broadband dielectric spectrometer by a coaxial cable. The structure of the sample holder is shown in Fig. 2.

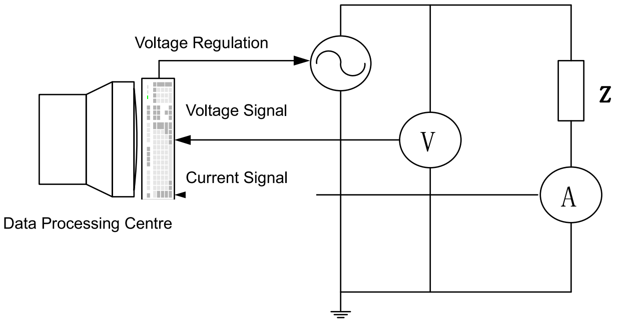

Fig. 1. Principle behind testing by soil sample frequency domain dielectric spectrum method.