Experimental Investigation of the Electrical Parameters of the Soil for the Purpose of the Grounding System Design

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Abstract – **The aim of the paper is to propose a mathematical equation, describing the influence of the electromagnetic field' frequency on the specific volume resistivity and the dielectric permittivity of multilayer soil. To obtain the dependence experimental studies have been done in the electrical power substation construction area.**

Keywords – **Specific volume resistivity, Relative dielectric permittivity, Multilayer soil**

I. Introduction

There are not many data for the specific volume resistivity ρ_v and the relative dielectric permittivity ε_r of the soil at different frequencies f of the electromagnetic field, arising due to a lightning current. Data for frequency of 50 *Hz* can be found more frequently. Since the specific volume resistance directly affects the grounding resistance, it is necessary to determine ρ_v depending on the frequency of the flowing through the grounding rod current. Such research has been done and published by the authors [1], but for the significantly narrower frequency range from 12 *Hz* to 100 *kHz*. A direct lightning stroke over an object leads an impulse current to flow through the grounding elements and high frequency processes develop in the soil area around them. The specific volume resistivity and the relative dielectric permittivity of the soil depend on those processes. The precise determination of the electrical characteristics of the soil ρ_v and ε_r is necessary to establish a correct model of the grounding system for the study of the wave processes.

In Section II the experiment equipment is described and the mathematical equations for data processing are given. In Section III, the experimental results and the analyses are presented. The concluding remarks are given in Section IV.

II. Experiment Description

Samples of the soil from the area where an electrical power substation will be constructed have been taken. The samples were taken from depths 0.4 *m* and 0.8 *m*, as well as from the soil surface. The values of the specific volume resistivity and the dielectric permittivity have been measured for wet and dry soils, as well as for the loose and the pressed soils.

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The measurements of the electrical characteristics R, C, C_0 for each of the samples, having different moisture contents, are made with the device Precision Impedance Analyzers 6500B Series, shown in Fig.1. The analyzer can measure directly the values of the resistance and the capacitance of the samples and after that the specific volume resistivity ρ_v and the relative dielectric permittivity ε_r can be calculated using formulas.

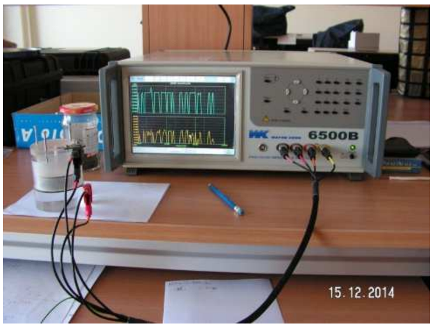

Fig. 1. Precision Impedance Analyzers 6500B Series

The device can measure the following parameters: capacitance C; inductance L; resistance R; reactance X; conductance G; dissipation factor D; quality factor Q, impedance Z; admittance Y; phase angle θ. The total frequency range is from 20*Hz* up to 5*MHz*. The speed of measurement for the used frequency from 1 *kHz* to 1000 *kHz* is from 60 *ms* to 250 *ms* (in the Meter Mode) and from 60 *ms* to 190 *ms* (in the Analysis Mode). The measurement accuracy is up to 0, 05%, and the dissipation coefficient has accuracy up to 0, 0005%.

For each sample the analyzer allows rapid and accurate measurements of a certain number of values of R, C, C_0, Z and D at different frequencies.

The samples are placed in a suitable sensor (Fig. 2), which is a flat capacitor with circular copper plates with a diameter of 37,78 *mm* and distance between them 49,2 *mm* (other sensors with different dimensions can be used). The surrounding surface is made from plexiglass, because of its great resistance. On the top of the sensor there is a spring so that the sample is under a constant mechanical pressure. This provides a minimum presence of air in the test soil.

Fig. 2. General view of the measuring sensor

The analyzer measures the resistance R_v of the soil sample. Using the measured value of R_v the specific volume resistivity can be calculated:

$$\rho_v = \frac{R_v S}{h}, \Omega.m \tag{1}$$

where R_v – volume resistance of the soil sample, Ω; S – surface of the electrode, m^2; h – thickness of the soil sample.

The specific volume resistivity can be calculated after measurement of the parameters C and D and using following formula [2, 5]:

$$D = \omega C R_v \tag{2}$$

where $\omega = 2.\pi.f$

$$R_v = \frac{D}{2\pi f C} \tag{3}$$

The dielectric permittivity of the soil can be determined using the dielectric measurement method [3], which is the most appropriate for granulated materials. This method measures the capacity C of the capacitor with a dielectric between the plates (the soil sample) and the capacity of the air capacitor C_0 (without soil between the plates). The alteration of values of the dielectric (the soil sample) parameters at different frequencies of the electric field is observed. Under the influence of the electric field the dielectric polarizes itself and its dielectric permittivity can be measured by measuring the capacitance at different frequencies of the alternating current.

The capacitance of the flat vacuum capacitor is:

$$C_0 = \varepsilon_0 \varepsilon_r \frac{S}{h} \tag{4}$$

where $\varepsilon_r = 1$.

The capacitance of the same capacitor when there is a dielectric (the soil sample) with relative dielectric permittivity ε_r between the electrodes is:

$$C = \varepsilon_r \varepsilon_0 \frac{S}{h} \tag{5}$$

where $\varepsilon_0 = 8,85 .10^{-12}$ F/m; $S=2374,6.10^{-6}$ m^2.

Then the relative dielectric permittivity of the soil sample is:

$$\varepsilon_r = \frac{C}{C_0} \tag{6}$$

The formula (6) allows, after measurement of the two capacitances, to determine the relative dielectric permittivity of the soil sample between the electrodes of the sensor. The relative dielectric permittivity is determined at different soil humidity.

The humidity of the samples ψ is evaluated by the relative content of the water into them [2, 3]:

$$\psi = \frac{m_1 - m_2}{m_2}.100\% \tag{7}$$

where m_1 is the mass of the wet sample, m_2 is the mass of the same dry sample.

The difference m_1- m_2 is exactly the mass of the water into the sample.

The drying at the samples is carried out by a special methodology - Gravimetric method [3]. The mass m of the wet material is measured. Then the sample is placed in an oven at about 120^0C to dry for an hour or two. After that they are placed into a desiccator for about an hour to reach the thermal equilibrium. The mass m_0 of the dried sample is measured. By formula (7) is calculated the humidity. For greater accuracy should be used electronic scales for measuring of the mass.

The measurements are carried out at different densities of the soil, which are calculated using the following formulae:

$$\gamma_n = \frac{m[kg]}{V[m^3]} \tag{8}$$

$$V = Sh \tag{9}$$

$$S = \frac{\pi d^2}{4} \tag{10}$$

where m – mass of the soil sample; V – volume of the soil in the sensor; S – surface of the electrode; d – diameter of the electrode; h – thickness of the sample.

The obtained from measurements results are processed by the computer program Grafer [4]. This is a mathematical program for processing of the experimental results. The program has an option to draw a theoretical curve by the experimental results and to give the best mathematical function describing the experimental curve as well as the coefficient of determination, which shows how the approximated (theoretical) curve is close to the experimental.

The resultant mathematical expression of the dependencies of the specific volume resistivity and the relative permittivity from the frequency (from 1 *kHz* to 1000 *kHz*) of the electric field can be used for different humidity and density of the samples. This equation can be used in the calculation of the specific volume resistance of the soil and the grounding resistance value at a specific frequency.

III. Experimental results

Measurements for investigation of the dependence of the specific volume resistivity and the dielectric permittivity from the frequency in the range 1 *kHz* to 1000 *kHz* at different humidity and density of the samples were made.

A. *Dependence of the specific volume resistivity of wet pressed (γ_p = 1239,8 kg / m^3) soil samples from the frequency of the electric field at a depth of 0.4 m.*

Figure 3 presents the results from the fulfilled test measurements of wet pressed soil samples.

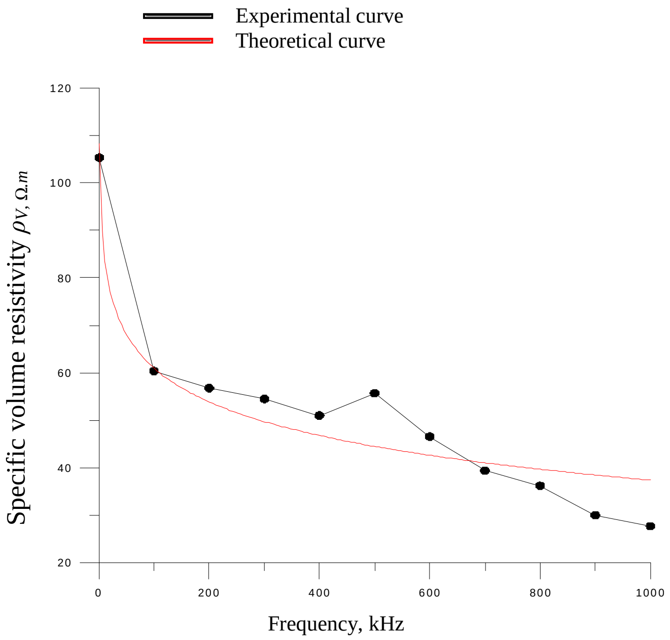

Fig.3. Specific volume resistivity ρ_V of wet pressed soil from point №1 at a depth of 0.4 m versus the frequency

For the results the following equation is processed by Grafer:

Y = -10,25159429 ln(X) + 108,2316067

The coefficient of determination, R-squared = 0,914924.

The results present that the alteration of the specific volume resistivity ρ_v is according to a power decreasing function which is confirmed and by other authors [1, 2, 3, 6, 7] for granulated materials for different frequency ranges. The high coefficient of determination 0,914924 shows that the experimental curve can be described very precisely by the function as:

$$\rho = \rho_0 \left(\frac{f}{f_0} \right)^{-n}$$

B. Dependence of the relative permittivity of wet pressed (γ_p = 1207,9 kg/m^3) soil samples from the frequency of the electric field at a depth of 0.4 m.

The results are shown in Fig. 4

For the results the following equation is processed by Grafer:

Y = -20,17964574 ln(X) + 145,8162477

Coef of determination, R-squared = 0,855494.

In most cases, experimental curves, describing the permittivity dependence on the frequency, get a complex character and the Grapher program processes them with less accuracy.

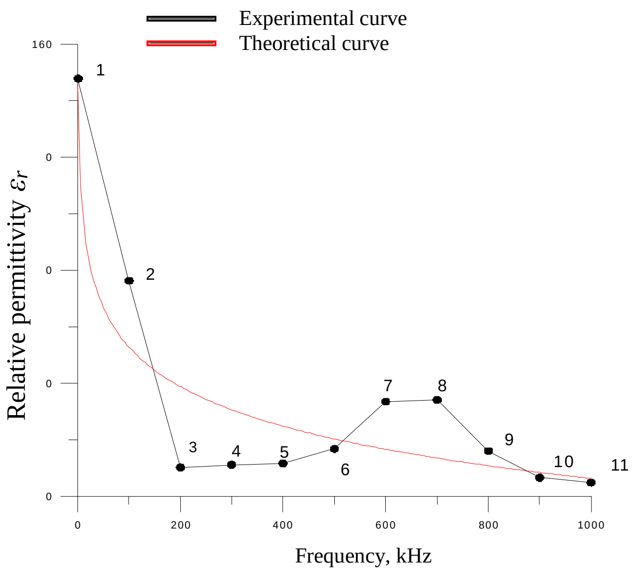

Fig.4. Relative permittivity ε_r of wet pressed soil from point №2 at a depth of 0.4 m versus the frequency

In this case the curve is examined in several sections – Fig.5÷7.

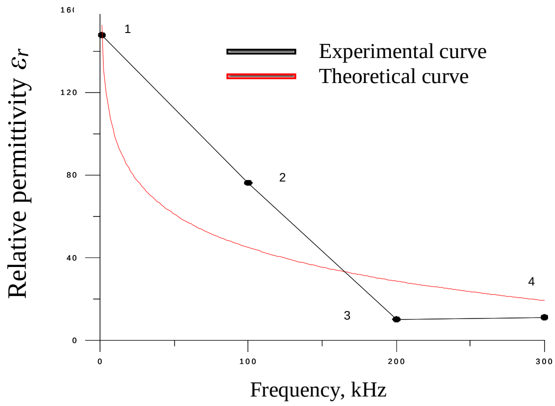

Fig.5. Relative permittivity ε_r of wet pressed soil from point №2 at a depth of 0.4 m for the sector №1 versus the frequency

Equation: *Y = -23,32579912 ln(X) + 152,4130114*

Coef of determination, R-squared = 0,88972

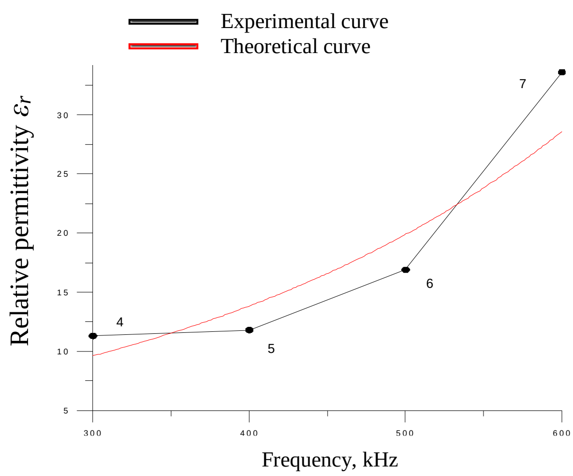

Fig.6. Relative permittivity ε_r of wet pressed soil from point №2 at a depth of 0.4 m for the sector №2 versus the frequency

Equation: $\ln(Y) = 0{,}003628384114\, X + 1{,}175912635$

Coef of determination, R-squared = 0,863944

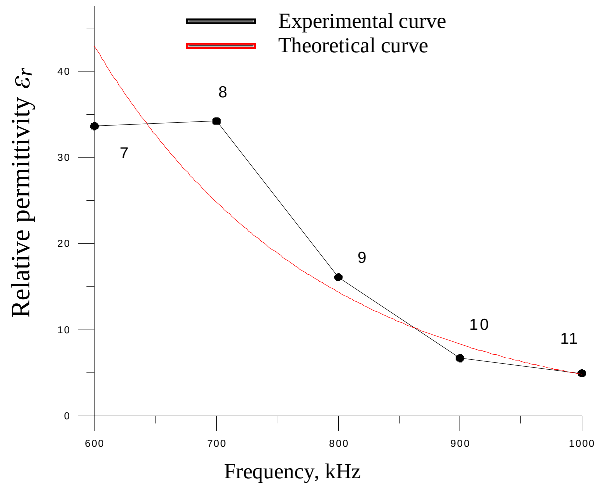

Fig.7. Relative permittivity ε_r of wet pressed soil from point №2 at a depth of 0.4 m for the sector №3 versus the

Equation: $\ln(Y) = -0{,}005454867346\, X + 7{,}030009011$

Coef of determination, R-squared = 0,930534

For the three section:

$$Y = \begin{cases} -23{,}32579912 \ln(X) + 152{,}4130114; & 0 \prec X \prec 300kHz \\ \ln(Y) = 0{,}003628384114\, X + 1{,}175912635; & 300kHz \prec X \prec 600kHz \\ -0{,}005454867346\, X + 7{,}030009011; & 600kHz \prec X \prec 1000kHz \end{cases}$$

C. Dependence of the specific volume resistivity and the relative permittivity of the soil samples from the depth at which the sample was taken.

The results are shown in Fig. 8 and Fig. 9.

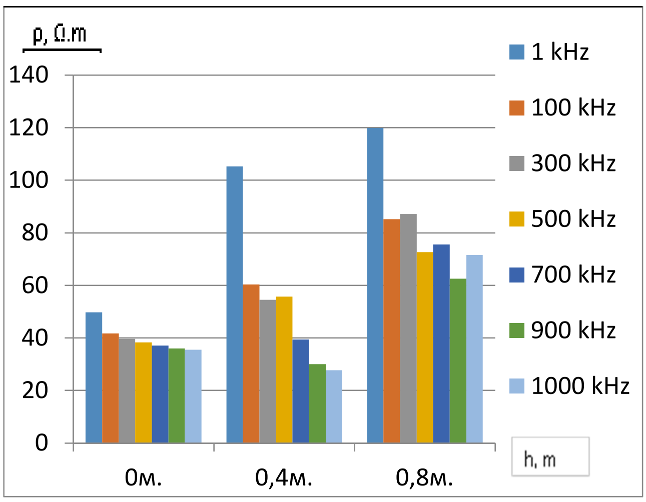

Fig. 8. Specific volume resistivity of the wet pressed soil versus the depth at which the sample was taken.

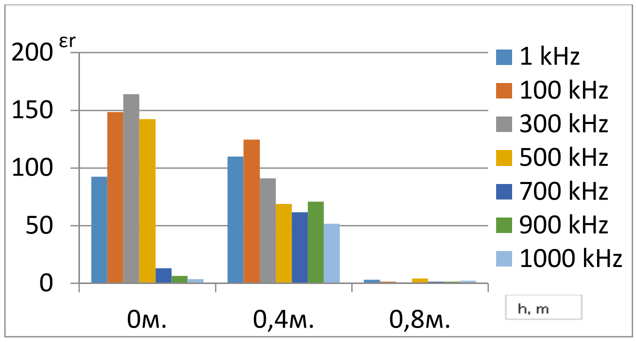

Fig. 9. Dielectric permittivity versus the depth at which the sample was taken.

IV. Conclusion

The dielectric method for measuring the electrical characteristics of the soil and the received experimental results, which are confirmed in other studies, give reason to continue the investigation for other samples - multilayer soils.

The resultant mathematical expression of the dependence of the specific volume resistivity from the frequency can be used in the calculation of the resistance of the grounding system for a specific frequency value.

The resulting mathematical expressions of the dependence of the dielectric permittivity from the frequency can be used in calculating the capacitance of the grounding system, which is necessary to create a model scheme of the installation for the study of the wave processes in it.

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