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Prototype of a measurement device for frequency dependent soil electrical properties

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Prototype of a measurement device for frequency dependent soil electrical properties

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Abstract. Studies show that grounding potential rise and lightning performance of transmission lines are significantly influenced by frequency dependent soil properties (resistivity and permittivity). In order to perform calculations of the transient grounding characteristics more accurately, additional experimental data for different soils is needed. Currently, field measurements of the frequency dependent soil properties can take a significant amount of time. This limits the amount of available experimental data. Thus, for conducting a large number of measurements, a convenient measurement device is needed. Several parameters of the measurement device for the frequency dependent soil electrical properties are discussed in the article (such as preferable generated waveform, the amplitude of the signal, input impedance of the voltage measurement probe, isolation between measurement circuits), and a prototype of the device is presented. A critically important factor for this kind of measurements is high impedance between the current and voltage measurement circuits. In order to achieve proper isolation between the circuits, the optically-isolated probe was made for the voltage measurements. An example of measurements with the dipole-dipole electrode array for high-resistivity soil is presented. Further improvements for the measurement device are also suggested in the article. With these improvements, the measurements can be almost as fast and simple as those made with a conventional soil resistivity meter.

1. Introduction

In order to choose grounding configurations [1], frequency dependent soil electrical parameters (for the frequency range of lightning currents) should be known [2-4]. Current measurement methods for these parameters, however, can be time-consuming. Usage of different electrode arrays needs a significantly lesser amount of time. However, calculations have shown that in this case, electromagnetic coupling effects between the measurement circuits can be significant [5]. Therefore, only particular arrays can be used for accurate measurements. The similar problem exists in induced polarization (IP) surveys [6-8].

Apart from the array configuration, special care must be taken for isolation between the measurement circuits. There are also other parameters of the measurement device that should be taken into account. These parameters are discussed below. Based on the parameters, a measurement device for soil electrical properties was created.

2. Parameters of the measurement device

Before the development of the measurement device, there are some parameters that should be considered, such as generated waveform, the amplitude of the signal, probe impedance, isolation between measurement circuits.

2.1. Waveform

It is possible to use either the sine waveform or some other waveform that covers a particular frequency spectrum.

The strength of the second option is that this needs a smaller amount of voltage and current measurements to cover the needed frequency range. But it is more susceptible to the noise (and may need higher currents/voltages).

The sine waveform, on the other hand, allows measuring the needed parameters for a particular frequency even if there is some noise in the measured currents and voltages. To get measurement results for a particular frequency range, an interpolation can be used, and if the measurement results are expressed as complex permittivity, Debye function expansion is preferable [9]. Also, direct digital synthesis (DDS) devices allow to generate and control a sine waveform easily (supposing that the needed generated voltage is relatively low, and the signal should not be amplified significantly). Thus, for the measurement device presented here, a sine waveform was chosen.

2.2. Amplitude

Another parameter of the generator is the sufficient voltage amplitude. A rough estimation of the voltage is made below.

The measured current and voltage are related to the resistivity and permittivity via the equation:

$$\hat{Y}(\omega) = \frac{\hat{I}(\omega)}{\hat{V}(\omega)} = k\left(\frac{1}{\rho} + j\omega\varepsilon'\right),\tag{1}$$

where k is the geometric factor, $\rho(\omega)$ is the soil resistivity and $\varepsilon'(\omega)$ is the soil permittivity. The bigger the geometric factor, the smaller the measured voltage V for the same current I.

For the sake of simplicity, one can consider only the low-frequency case and neglect the frequency dependence and the capacitive effect of the soil. In this case equation (1) becomes:

$$Y = \frac{I}{V} = \frac{k}{\rho}.\tag{2}$$

For the estimation, an electrode array (Figure 1) with relatively big geometric factor was considered (in this case, the measured voltage is relatively low). The geometric factor for this array is 19.431π [5].
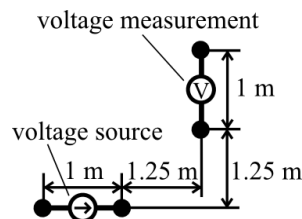
Figure 1. Dipole-dipole array. Top view.

The depth of investigation [10] for this array equals 0.67 m [5].

The current I is related to the voltage of the generator V_g and resistance of two rods $2R_r$ (where R_r is the resistance of one rod) via:

$$I = \frac{V_g}{2R_r}.\tag{3}$$

As long as this is only a rough estimation, it was assumed that total resistance of two rods equals to the sum of two values R_r.

Using the known formula for the resistance of a vertical rod with length l and radius a [11]:

$$R_r = \frac{\rho}{2\pi l} \ln\left(\frac{4l}{a} - 1\right). \tag{4}$$

and combining this formula with the equations (2) and (3), one can find voltage V_g:

$$V_g = \frac{kV \ln\left(\frac{4l}{a} - 1\right)}{\pi l}. \tag{5}$$

For the array in Figure 1:

$$V_g = \frac{19.431 \cdot V \ln\left(\frac{4l}{a} - 1\right)}{l}. \tag{6}$$

Assuming that several tens of mV are sufficient for the amplitude of V, for the rod with length 0.2 m and diameter 0.01 m, and choosing, for example, $V = 30$ mV, the value of V_g then equals to 14.8 V.

Most of the arrays have a higher (or comparable) geometric factor (and, therefore, higher voltage V) for the depth of investigation about 0.7 m [5]. Thus, for this depth of investigation, the voltage around some tens of volts appears to be sufficient. In the present device, the maximum value of the amplitude is 15 V (also, a lower amplitude can be set).

2.3. Internal probe impedance

One of the important parameters of the measurement device is the internal impedance of the voltage measurement probe. Therefore, an estimation of this parameter should be made as well. Here only very approximate estimation is made, therefore only active resistance of rods is taken into account.

In a soil with resistivity 10^4 Ω·m, the rod with length 0.2 m and diameter 0.01 m has earth resistance about 40 kΩ, according to the formula (4). The resistance of two electrodes equals to 80 kΩ. If we assume that this resistance should not exceed approximately 1% of the internal probe resistance, then the probe resistance should be higher than 8 MΩ.

The estimation of preferable internal capacitance is made for the high frequency, as long as reactance is small in this case. At the same time, soil resistivity at high frequency is relatively small (as well as earth resistance of rods). As an example, we will use resistivity 1000 Ω·m and frequency 4 MHz. In this case, the earth resistance of two rods equals approximately 8 kΩ. Assuming that the resistor (earth resistance of rods) and capacitor (internal probe capacitance) are connected in series, the capacitor will influence the measured voltage approximately to the same extent as in the previous case (with the internal probe resistance) if its value equals roughly 0.7 pF. I.e. internal probe capacitance should not exceed this value significantly.

2.4. Isolation between measurement circuits

One of the most important factors for this kind of measurements is isolation between the current and voltage measurement circuits.

One can assume that a regular oscilloscope with isolated channels can be used for this purpose. However, this kind of oscilloscopes cannot provide a sufficiently high impedance between the measurement channels (due to parasitic capacitance), which can lead to inaccurate measurement results at high frequencies. Moreover, regular passive measurement probes also cannot be used, as they have a "ground" which should be connected to one of the rods during measurements. This additional wire can lead to the electromagnetic coupling which, in turn, causes errors in measurement results too.

To achieve proper isolation between the current and voltage measurement circuits, the impedance between them should be very high. One can mark out two possible approaches for the measurements: using the differential probes or using the optically-isolated probes.

In the case of differential probes, two probes should be used (so that both of them have a high impedance between the "ground" and each of the rods). These probes are connected as it is shown in Figure 2.
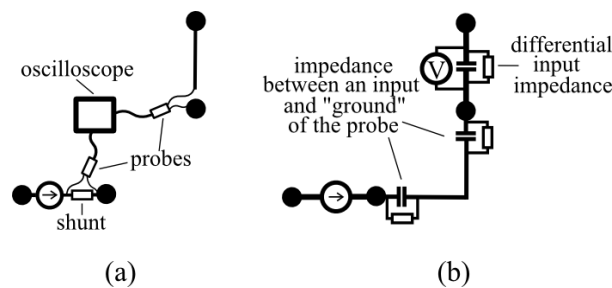
Figure 2. The connection of differential probes and their impedance.

However, in some cases, even differential probes can lead to erroneous results (caused by insufficient isolation between channels, or induced voltage due to the small distance between the generator and the current measurement probe etc.).

Therefore, to achieve satisfactory accuracy, the use of optical fiber probes is preferable. For the optical isolation, either two probes can be used or only one (Figure 3).
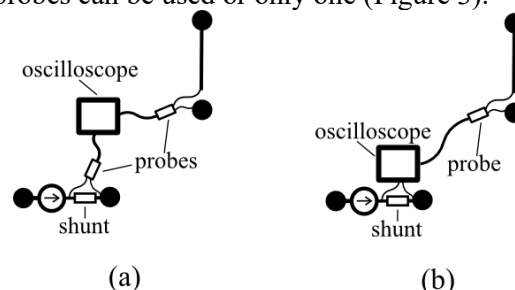

Figure 3. Possible connections of optically-isolated probes.

Most optically-isolated probes are very expensive which narrows their application for the kind of measurements described in the article. The high price is caused partly because these probes provide very wide frequency range and have excellent measurement characteristics in general.

For the measurements related to lightning currents, however, frequency range about 10 MHz is sufficient. Also, as long as measurements are performed for particular frequencies, it is possible to make corrections (for measured amplitude and phase values) caused by imperfections of the measurement device. Therefore, the measurement device does not need some special tools and can be created with relatively cheap and accessible electronic components.

3. The measurement device

For the measurement device described in the article, the connection (b) in Figure 3 is used. The functional diagram of the measurement device is depicted in Figure 4. The measurement setup contains three main parts:

1. A block that contains a control board with a microcontroller, wave generator, current measurement circuit ant receiver.

2. A block that contains a voltage measurement probe and transmitter.

3. Oscilloscope.

The sine wave generator contains a DDS microchip and an amplifier. A needed frequency is set by the microcontroller from the control board. There is also a possibility to control the amplitude of the signal using the voltage controlled amplifier.

Current measurement circuit contains a shunt (connected between the sine wave generator and a rod) and an operational amplifier.

"Voltage measurement probe" in Figure 4 is a differential probe with high input impedance. The output voltage from the probe is converted to current in order to feed the light-emitting diode (LED) in the transmitter.

As an oscilloscope, the portable 100 MS/s SmartScope (from LabNation) is used. It connects to a regular smartphone, which then controls the SmartScope and where the measurement results are stored.
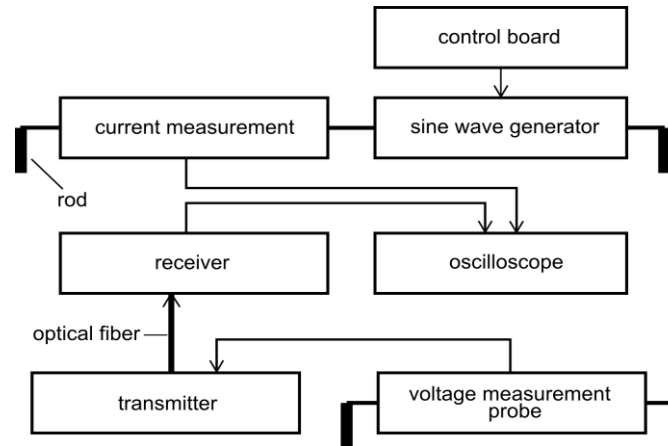

Figure 4. The functional diagram of the measurement device.

The measurement device is shown in Figure 5.

Figure 5. The prototype of the measurement device.

As long as the phase difference between current and voltage should be measured accurately, phase responses of the current and voltage measurement circuits should be taken into account. To achieve this, the same signal is used as an input for both circuits, and the angle between the output signals is measured for each frequency. Then, after the current $I(t)$ and voltage $V(t)$ are measured and Fourier transform is applied to the current and voltage, this angle is taken into account by rotating one of the values (current or voltage), after which the resistivity and permittivity are calculated.

The overall measurement process consists of the following steps for each frequency of interest:

1. Measurement of the phase difference between the output signals from the current and voltage measurement circuits (for the same input signal).

2. Measurement of current $I(t)$ and voltage $V(t)$ for a particular array and soil.

4. Applying the Fourier transform to the measured current and voltage.

3. Correcting the phase difference between $I(\omega)$ and $V(\omega)$ by the angle measured in step 1.

5. Calculation of resistivity and permittivity using the equation (1).

As long as an optical fiber (its length, bending etc.) can influence amplitude, a calibration of amplitude is also needed (and during the calibration, the optic fiber should not be bent significantly). The amplitude, however, is quite constant throughout the frequency range.

4. Measurement results

As an example, measurements of soil parameters were conducted with the array in Figure 1.

Measurement results are presented in Table 1. The measurements were conducted during winter, therefore resistivity of the top layer of soil is very high.

Table 1. Measured values of resistivity and permittivity.

Frequency	Resistivity, $\Omega \cdot m$	Relative permittivity
10 kHz	8647	45.4
14 kHz	8627	35.7
18 kHz	8402	35.0
24 kHz	8149	33.0
34 kHz	7664	28.4
44 kHz	7401	27.1
60 kHz	7122	24.6
82 kHz	6696	22.4
110 kHz	6276	20.9
148 kHz	5869	19.5
200 kHz	5310	18.3
270 kHz	4971	17.0
364 kHz	4541	15.9
492 kHz	4111	14.5
662 kHz	3453	13.3
894 kHz	3195	13.7
1.21 MHz	2859	13.1
1.63 MHz	2459	12.3
2.20 MHz	2014	12.4
2.96 MHz	1585	11.9
4.00 MHz	1168	11.7

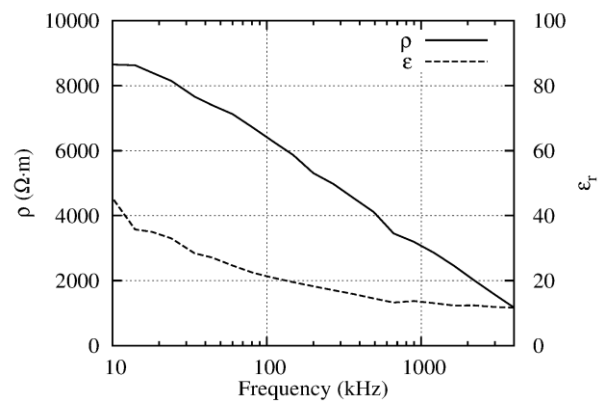The same measurement results are also shown in Figure 6.

Figure 6. Measurement results.

Examples of waveforms are presented in Figures 7-9 (10 kHz, 200 kHz, and 4 MHz). Note that the phase difference is corrected only approximately in Figures 7-9 (by shifting with a particular number of sampling data points); in the measurement results, the phase difference is corrected more accurately.
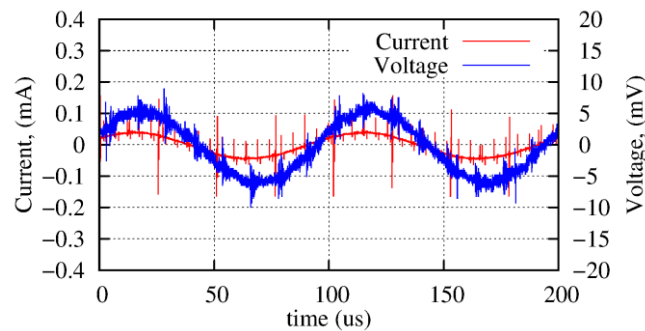
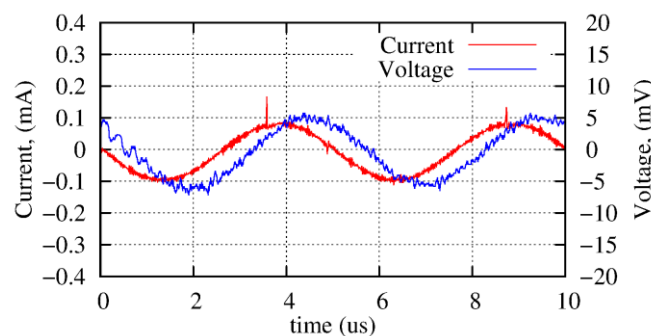Figure 7. The measured current and voltage, 10 kHz.

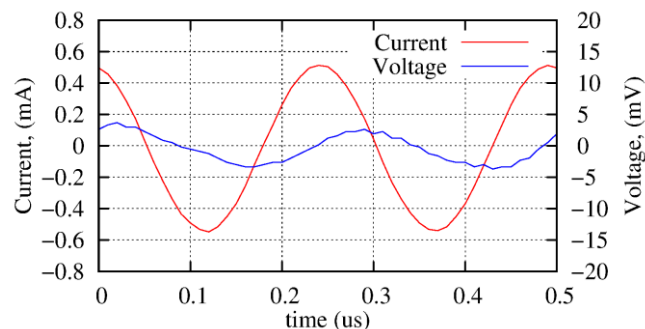Figure 8. The measured current and voltage, 200 kHz.

Figure 9. The measured current and voltage, 4 MHz.

It can be seen that there is a significant noise for the low currents. This is caused by the small voltage on the shunt resistor (its value is 270 Ω). This can be improved by changing the value of the shunt resistors for different currents.

The measurements are conducted for the voltage V_g that several times lower than the maximum value (15 V), therefore, the measured voltages and currents are several times lower than those for $V_g = 15$ V.

5. Conclusion

A measurement device for frequency dependent parameters was presented in the article. Currently, the measurement process takes a significant amount of time since current and voltage are measured by oscilloscope and processing of the measured current and voltage is performed on a computer. The same procedures can be done inside a microcontroller (and signals can be measured by an analog to digital converter). After the needed improvements, the measurements with this device can be almost as fast as those made with a conventional soil resistivity meter.

References

[1]   Kuklin D 2016 Choosing configurations of transmission line tower grounding by back flashover probability value *Front. Energy* **10** 213–26

[2]   Portela C 1999 Measurement and modeling of soil electromagnetic behavior *1999 IEEE International Symposium on Electromagnetic Compatability. Symposium Record (Cat. No.99CH36261)* **2** 1004–9

[3]   Visacro S and Alipio R 2012 Frequency dependence of soil parameters: experimental results, predicting formula and influence on the lightning response of grounding electrodes *IEEE Transactions on Power Delivery* **27** 927–35

[4]   Alipio R and Visacro S 2013 Frequency dependence of soil parameters: effect on the lightning response of grounding electrodes *IEEE Transactions on Electromagnetic Compatibility* **55** 132–9

[5]   Kuklin D 2019 Numerical analysis of electromagnetic coupling effects in measurements of frequency dependent soil electrical properties *Progress In Electromagnetics Research* **79** 101–11

[6]   Fullagar P K *et al* 2000 EM-coupling removal from time-domain IP data *Exploration Geophysics* **31** 134–9

[7]   Loke M H, Chambers J E, Rucker D F, Kuras O and Wilkinson P B 2013 Recent developments in the direct-current geoelectrical imaging method *Journal of Applied Geophysics* **95** 135–56

[8]   Mocitaiba L S R *et al* 2017 Effect of coupling noise on the interpretation of results of electromagnetic horizontal sounding and modeling *Stud Geophys Geod* **61** 801–25

[9]   Kelley D F *et al* 2007 Debye function expansions of complex permittivity using a hybrid particle swarm-least squares optimization approach *IEEE Transactions on Antennas and Propagation* **55** 1999–2005

[10]   Barker R 1989 Depth of investigation of collinear symmetrical four-electrode arrays *GEOPHYSICS* **54** 1031–7

[11]   1992 IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems IEEE Std 142-1991 1–240