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COMPARATIVE MEASUREMENTS OF GROUND RESISTIVITY

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Abstract: In all calculations and constructions of grounding systems, ground resistivity is very important data. Exploring the accuracy of ground resistivity determination, two different measuring methods were applied at the same place and at the same time. The first method is performed applying the resistive bridge, supplied by the time constant source, for different distances between two measuring points. The second method was based on simultaneous measurements of voltage and current, applying the time-varying voltage source. In the second method, the measurements were carried out for three different frequencies, 50 Hz, 60 Hz and 128 Hz and again for several different distances between two measuring points. Actually, the second method enables also the determination of the ground permittivity and the ground permeability if it is important for the grounding systems' parameters determinations. The results of both applied methods are presented in tables and graphically and compared, in order to explore the measurements' accuracy. For the second method the measurement uncertainty was calculated and presented as well. The analyze of the two methods comparison show that the results vary slightly, depending on the distances between two measuring points, which is normal, taking into account the non-homogeneity of the ground. Nevertheless, very important conclusion from the two methods comparison is that the dependence of the determined ground resistivity on the distances between two measuring points has the same shape and almost the same values in both measuring methods. The percentual difference in the two methods average resistivity values is only 2.25 %.
Keywords: grounding systems, measuring methods, applied methods, comparison

1. INTRODUCTION

In all systems for the production, transmission, distribution and consumption of electrical energy, the grounding systems are the very significant parts of the system. For that reason, the grounding systems must be developed and calculated for each grounding system very carefully, taking into consideration all necessary data of the system's location.

One of the most important data for every grounding system is the ground resistivity at the system position. For this reason, prior to the system's construction, the ground resistivity must be determined and after the construction it must be controlled from time to time, in previously defined time periods. Knowing the ground resistivity, every relay protection can be successfully calculated and constructed and any possibility of wrong assessment calculation of short circuit and incorrect settings of relay protection could be avoided.

The ground resistivity can be determined only by measurements, applying several different measuring methods. The most applied measuring methods for ground resistivity determinations are the method of resistive bridge [1] and the standard voltage – current measuring method (U-I method) [1]. Usually one of the methods is applied during the ground resistivity measurements, considering that the results are accurate enough. In order to estimate how accurate the results of each method are, in this paper the procedure of the simultaneous measurements applying both methods at the same location, at the same time, i.e. under the same conditions, is described.

First of all, the results of each method are observed, investigated and presented separately, together with the measurement uncertainty for the second method. Finally all obtained results are discussed, compared and presented in tables and graphics.

Moreover, since the equipment for the standard U-I method application enables the determination of the ground impedance, at different frequencies, in the paper the ground resistivity is measured and calculated for three different frequencies and all those results are mutually compared.

2. THEORETICAL APPROACH

In order to determine the ground resistance the resistance between two points on the ground surface should be measured first. For the resistance measurements two methods are usually applied and both methods will be described in details in the next subsections.

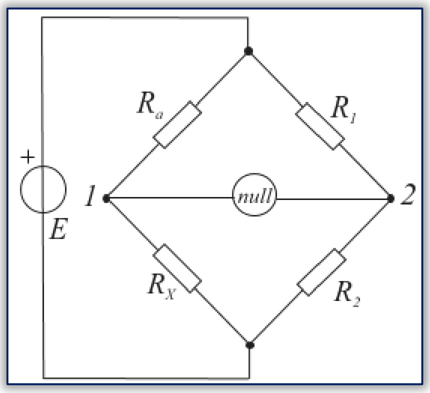

Figure 1. Resistive bridge scheme

— Resistive bridge measuring method

The principle of the resistive bridge measuring method is well known and the circuitry of a resistive bridge is presented in Figure 1. The resistive bridge is supplied by a time constant voltage source and the bridge is in balance when the resistor values satisfy the ratio,

$$\frac{R_a}{R_x} = \frac{R_1}{R_2}. \tag{1}$$

The resistor R_a is with variable resistance; so the resistance changing produces the balance of the bridge, which is presented by zero value on null indicator. The resistance between two points defined by measuring probe sticks driven into the ground, R_x, can now easily be calculated from (1).

The ground resistivity has to be calculated from the resistance R_x for the each pair of the measuring probe sticks, driven into the ground. For the pair denoted bi "*i*", the ground resistivity is,

$$\rho_i = 2\pi R_{xi} \ell_i. \tag{2}$$

The distances, ℓ , between two measuring probe sticks vary along the measuring path and for each pair of the measuring probe sticks, according to (1) and (2), the resistance and the ground resistivity are calculated. The final value of the ground resistivity is determined as the average of resistivity values along the entire measuring path.

$$\rho = \rho_{av} = \frac{1}{N}\sum_{i=1}^{N} \rho_i. \tag{3}$$

In above equation N is the number of the measuring probe sticks pairs.

— Standard U-I measuring method

The standard U-I measuring method is also a well-known method for the resistance or the unknown complex impedance determination.

The circuitry for the standard U-I measuring method is shown in Figure 2.

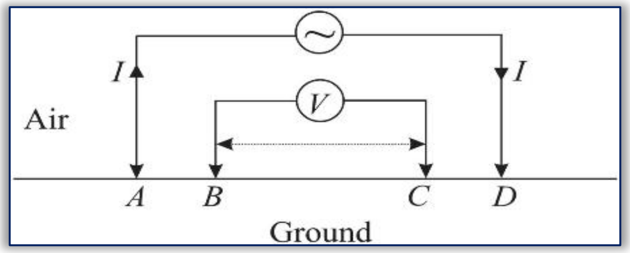

Figure 2. Standard U-I method scheme

As it can be seen in Figure 2, the circuit is supplied by an alternating current source, which extends the measuring possibilities; instead of only resistance measurements, in this case it is possible to measure the impedance between two measuring probe sticks driven into the ground. In the case when only the resistance measuring probe sticks driven into the ground has to be determined, this resistance can be determined from the known (measured) current, I, and the measured voltage between the points B and C, U_{BC}. According to the circuit in Figure 2, the potential of the points B and C are,

$$V_B = \frac{I}{2\pi\ell} - \frac{I}{4\pi\ell} = \frac{I}{4\pi\ell} \qquad V_C = -\frac{I}{4\pi\ell}. \tag{4}$$

As in (2), ℓ is the distance between two measuring probe sticks. The measured voltage between points B and C is,

$$U_{BC} = V_B - V_C = \frac{I}{4\pi\ell} - \left(-\frac{I}{4\pi\ell}\right) = \frac{I}{2\pi\ell}. \tag{5}$$

The ground resistance between the points B and C is,

$$R_{BC} = \frac{U_{BC}}{I}. \tag{6}$$

The ground resistivity values can now be determined following the procedure described earlier, according to (2) and (3).

In the case when the ground impedance is to be measured, the procedure is the same but the complex values of the potentials, voltage and current must be involved,

$$\underline{V}_B = \frac{\underline{I}}{2\pi\ell} - \frac{\underline{I}}{4\pi\ell} = \frac{\underline{I}}{4\pi\ell} \qquad \underline{V}_C = -\frac{\underline{I}}{4\pi\ell}, \tag{7}$$

$$\underline{U}_{BC} = \underline{V}_B - \underline{V}_C = \frac{\underline{I}}{4\pi\ell} - \left(-\frac{\underline{I}}{4\pi\ell}\right) = \frac{\underline{I}}{2\pi\ell}, \tag{8}$$

$$\underline{Z}_{BC} = \frac{\underline{U}_{BC}}{\underline{I}} = R_{BC} + j\cdot X_{BC}. \tag{9}$$

In this case the ground resistivity values are again determined from the ground resistance between the points B and C, R_{BC}, but the ground reactance between the same two points can be determined as well, together with the ground inductance and the ground permittivity or permeability.

Another advantage of this method is the possibility that the measuring process can be performed at different frequencies.

3. MEASURING EQUIPMENTS

Prior to all measuring procedures, the measuring path, with the previously defined distances, was prepared, as shown in Figure 3. Each measuring method should be applied for the distances defined by the measuring equipment. The first method requires the total distance between the external measuring probe sticks of $\ell = \pm 50$ m from the central measuring point, while the standard U-I methods is working with the maximal distances of $\ell = \pm 6$ m. At each distance from the central measuring point the appropriate label was positioned, i.e. driven into the ground, like shown at the left hand side of Figure 3. The positions and the connections of the measuring probe sticks are presented at the right hand side of Figure 3.

Figure 3. Prepared measuring path with the measuring probe sticks driven into the ground, at the predefined distances

All measurements and calculations results are shown by tables and graphics in this section. The results obtained by two measuring methods will be presented separately and will be compared in the next section. Unfortunately, it was impossible to find the data for the resistive bridge instrument; hence only for the second method the measurement uncertainty could be calculated and presented.

— Instrument for the resistive bridge measuring method

The instrument for resistance measurement, based on resistive bridge, at the measurements site, is presented in Figure 4.

Figure 4. Instrument for the resistive bridge measuring method

The instrument is equipped with a manual generator (dynamo machine) and need no other supply source, i.e. it is independent on AC source or batteries. It is constructed for the outdoor application.

— Instrument for the standard U-I measuring method

The instrument for resistance measurement, based on U-I measuring method, Omicron CPC 100, is shown in Figure 5 at the measurements location.

Figure 5. Instrument for the standard U-I measuring method

Figure 6. 230 V, AC source, positioned in the specialized van

The instruments need a 230 V AC source and it was supplied from the diesel aggregate, positioned in one of the vans, shown in Figure 6. The instrument Omicron CPC 100 is a multi-purpose primary test set for commissioning and maintaining substation equipment [2]. It performs current transformer (CT), voltage transformer (VT) and power transformer (TR) tests. Furthermore it can be applied for contact and winding resistance testing, polarity checks as well as primary and secondary protection relay testing. In this case the instrument measures the resistance between two measuring probe sticks, applying the circuitry presented in Figure 2. The first set of electrodes, with the connections denoted as A and D is applied to measure the current, while the other set, B – C, measures the voltage. All characteristics of applied instrument could be retrieved in [2], while the procedure for the measurement uncertainty determination is described in details in [3].

As mentioned earlier, the instrument enables all testing at several different frequencies. The guaranteed AC specifications are defined for the frequency range of 45 Hz < f < 65 Hz. The frequencies above 400 Hz are eliminated by filtration and the measurements at the frequencies less than 15 Hz are not stable [2].

4. RESULTS OF THE MEASUREMENTS AND THE CALCULATIONS

The measuring results will be presented by appropriate tables and graphically as the diagrams, separately for each measuring method and after that presentation, the comparison of two methods will be also presented by tables and graphics.

– Measuring results obtained with the instrument for the resistive bridge measuring method

The results obtained by the standard resistive bridge method are shown in Table 1. For different, previously defined distances between two measuring points, in the range of $\ell = \pm$ 50 m from the central measuring point, the measured values of resistance and ground resistivity are presented.

Table 1. The results obtained by the standard bridge resistive method

N° of meas.	ℓ [m]	$2\pi\ell$ [m]	R_x [Ω]	ρ [Ωm]
1	50.00	314.159	0.04	12.566
2	40.00	251.327	0.05	12.566
3	30.00	188.496	0.07	13.195
4	20.00	125.664	0.11	13.823
5	15.00	94.2478	0.15	14.137
6	10.00	62.832	0.25	15.708
7	8.00	50.265	0.33	16.588
8	6.00	37.699	0.48	18.096
9	5.00	31.416	0.60	18.850
10	4.00	25.133	0.80	20.106
11	3.00	18.850	1.10	20.735
12	2.00	12.566	1.70	21.363
13	1.50	9.425	2.30	21.677
14	1.00	6.283	3.30	20.735
15	0.50	3.142	5.80	18.221
16	0.25	1.571	6.50	10.210
ρ_{av}				16.786
ρ_{av} (excluding last result)				17.2244

Graphical presentation of all these results is given in Figure 7.

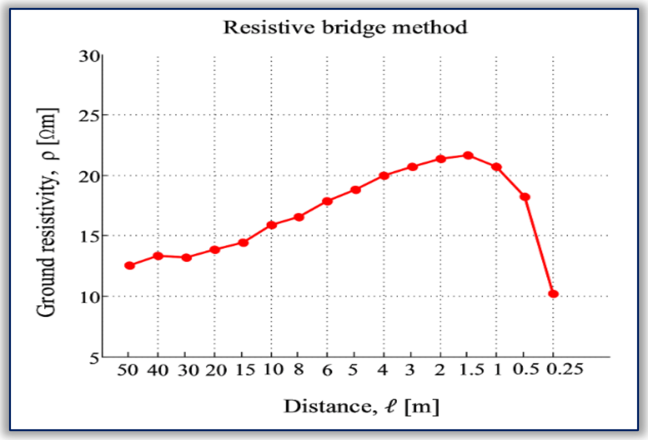

Figure 7. Ground resistivity as a function of distance ℓ

As it can be noticed in Table 1 and Figure 7, the biggest deviation from ground resistivity average value is achieved at the smallest distance between measuring points, due to the ground non-homogeneity. For that reason the ground resistivity average value is calculated with and without this result in order to make a better comparison between two measuring methods.

– Measuring results obtained with the instrument for the standard U-I measuring method

The results obtained with the instrument for standard U-I measuring method could be treated and presented on several different ways, taking into account the applied frequency and calculating the complex impedance as well. All necessary data and the measuring results are given in Table 2.

The graphical presentation of ground resistivity, determined with standard U-I measuring method, as the function of the distance ℓ, for three different frequencies, is shown in Figure 8.

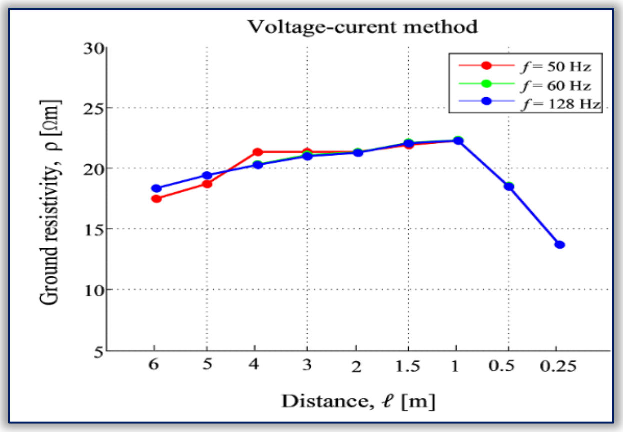

Figure 8. Ground resistivity as a function of distance ℓ, at three different frequencies

From the Table 2 and the Figure 8 it is obvious that the values of the ground resistivity, measured at 60 Hz and at 128 Hz, are practically the same. Only the ground resistivity measured at 50 Hz differs from the other two frequencies, due to the electromagnetic fields, produced by the neighbouring electrical transmission and distribution systems.

The measuring results, collected in Table 2, could be presented in another way. In Figure 9 the ground resistivity is presented as the function of frequency. From Figure 9 it is obvious that the ground resistivity is almost constant, except at the basic industrial frequency, f = 50 Hz. The reason of this sudden ground resistivity drop is again the influence of external electromagnetic fields, produced by nearby electrical power transmission and distribution systems.

Table 2. All data and the results obtained by the standard U-I method

Nº of meas.	ℓ [m]	f[Hz]	I[mA]	U[V]	φ [º]	R_x [Ω]	X_x [mΩ]	Z_x [Ω]	ρ [Ωm]
1	0.25	50	546.5	4.7798	179.54	8.7498	69.61	8.7462	13.7442
2	0.25	60	595.9	5.2111	179.71	8.7469	44.74	8.74492	13.7396
3	0.25	128	490.9	4.2848	179.54	8.7287	70.55	8.72846	13.7110
4	0.50	50	584.6	3.4498	179.36	5.8991	66.28	5.90113	18.5326
5	0.50	60	645.0	3.8114	179.64	5.9111	37.51	5.90915	18.5703
6	0.50	128	519.4	3.0628	179.48	5.8963	53.88	5.8968	18.5238
7	1.00	50	558.0	1.9789	179.74	3.5479	16.48	3.54642	22.2921
8	1,00	60	610.8	2.1721	179.62	3.5574	23.74	3.55616	22.3518
9	1.00	128	497.3	1.7643	179.54	3.5465	28.36	3.54776	22.2833
10	1.50	50	608.8	1.4208	179.66	2.3278	13.66	2.33377	21.9390
11	1.50	60	680.9	1.5999	179.6	2.3509	16.23	2.34968	22.1567
12	1.50	128	540.9	1.2678	179.54	2.3434	18.97	2.34387	22.0860
13	2.00	50	542.6	0.9224	178.22	1.7013	52.81	1.69996	21.3792
14	2.00	60	606.1	1.0281	179.67	1.6987	9.837	1.69625	21.3465
15	2.00	128	495.9	0.839	179.66	1.6916	10.03	1.69187	21.2573
16	3.00	50	585.8	0.6622	177.92	1.13368	41.23	1.13042	21.3694
17	3.00	60	643.9	0.7182	179.70	1.1199	5.918	1.11539	21.1096
18	3.00	128	519.0	0.5783	179.40	1.1135	11.68	1.11426	20.9890
19	4.00	50	607.7	0.5098	179.95	0.8487	0.685	0.8389	21.3302
20	4.00	60	676.8	0.5479	179.54	0.8103	6.494	0.80954	20.3651
21	4.00	128	540.6	0.4366	179.35	0.8065	9.151	0.80762	20.2696
22	5.00	50	583.5	0.3504	177.86	0.5952	22.21	0.60051	18.6988
23	5.00	60	647.9	0.4019	179.64	0.6183	3.901	0.62031	19.4245
24	5.00	128	519.6	0.3218	179.87	0.6179	1.433	0.61932	19.4119
25	6.00	50	549.6	0.2596	175.99	0.4649	32.56	0.47234	17.5263
26	6.00	60	620.0	0.3022	179.98	0.4866	0.166	0.48742	18.3444
27	6.00	128	500.4	0.2441	179.81	0.4862	1.615	0.48781	18.3293
28	6.00	15	245.3	0.1224	179.56	0.4902	3.73	16353.3	18.4801
29	6.00	30	417.9	0.2048	179.75	0.4884	2.108	13930	18.4122
30	6.00	50	549.6	0.2596	175.99	0.4649	32.56	10992	17.5263
31	6.00	60	620.0	0.3022	179.98	0.4866	0.166	10333.3	18.3444
32	6.00	70	699.6	0.3413	179.76	0.4872	2.022	9994.29	18.3670
33	6.00	100	605.7	0.2947	179.28	0.4855	6.128	6057	18.3029
34	6.00	128	500.4	0.2441	179.81	0.4862	1.615	3909.38	18.3293
35	6.00	150	424.6	0.2085	179.41	0.489	5.031	2830.67	18.4349
36	6.00	250	243.3	0.1155	179.84	0.4854	1.344	973.2	18.2991
37	6.00	350	161.1	0.08021	179.35	0.4842	5.509	460.286	18.2539
39	6.00	400	140.7	0.07039	179.74	0.4819	2.169	351.75	18.1672
ρ_{av} at 50 Hz									19.3485
ρ_{av} at 60 Hz									19.5752
ρ_{av} at 128 Hz									19.5141
ρ_{av} at 50 Hz, 60 Hz and 128 Hz									19.4793
ρ_{av} at other frequencies									18.3334

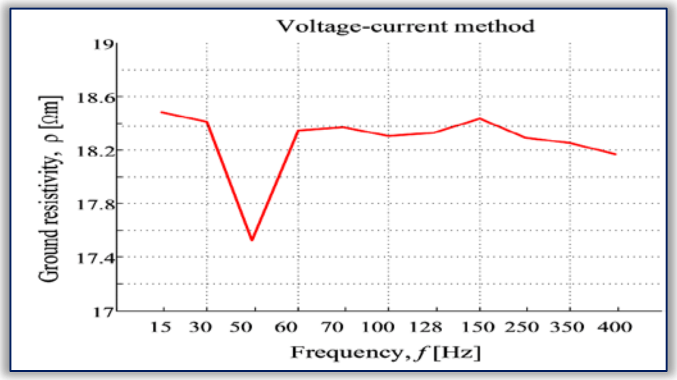

Figure 9. Ground resistivity as a function of frequency

The data in Table 2 enables also the graphical presentation of the ground resistance, reactance and impedance module, as a function of frequency. This presentation is shown in Figure 10. Like in Figure 9, the significant influence of external electromagnetic field at 50 Hz is evident in these figures as well.

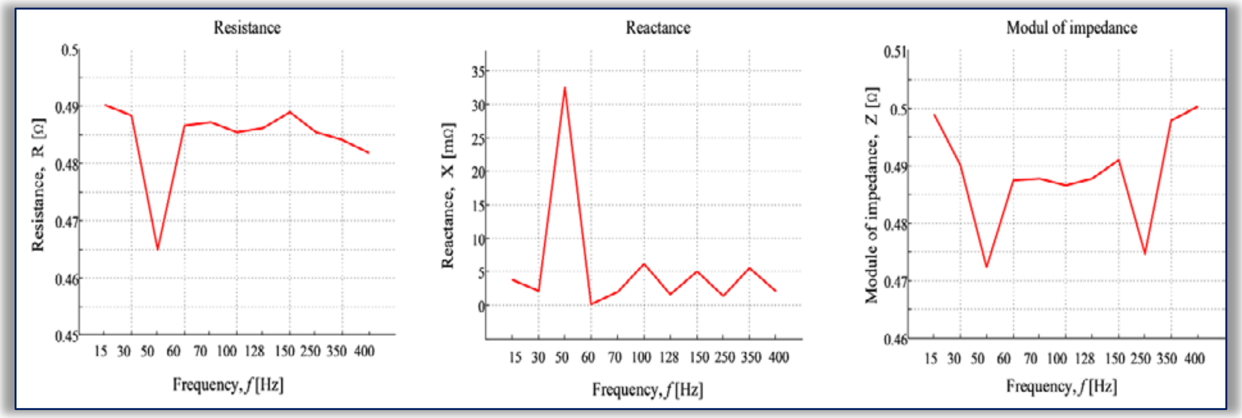

Figure 10. Resistance, reactance and impedance module of the ground

— Measurement uncertainty

For the measurement uncertainty assessment the guaranteed accuracy data is used, where the absolute error of any measurement with this device can be calculated as,

$$\Delta X = \pm(\text{value read x reading error} + \text{full scale of the range x full scale error}). \tag{9}$$

After identifying the quantities contributing to the measurement uncertainty and calculating the individual standard uncertainties, for the range of 1 A, the following results are obtained:

Table 3. Uncertainty budget for ground resistivity measurement, using U-I method

Influence factor	Reference	Probability distribution	Division factor	Sensitivity factor	Standard uncertainty $u(x_i)$ [%]
Current absolute error	Omicron CPC 100 User Manual	Rectangular	$\sqrt{3}$	1	0.115
Current phase error	Omicron CPC 100 User Manual	Rectangular	$\sqrt{3}$	1	0.048
Voltage absolute error	Omicron CPC 100 User Manual	Rectangular	$\sqrt{3}$	1	1.150
Voltage phase error	Omicron CPC 100 User Manual	Rectangular	$\sqrt{3}$	1	0.032
Digital display resolution	Omicron CPC 100 User Manual	Rectangular	$\sqrt{12}$	1	0.029
Distance measurement reading error	GUM	Rectangular	$\sqrt{12}$	1	1.160
		Combined standard uncertainty u_C [%]			1.173
		Expansion factor k			2.000
		Expanded uncertainty U [%]			2.346

According to the data presented in Table 3, the measurement uncertainty is very small for applied instrument, meaning that the measured results are very accurate, probably more accurate that the results obtained with the resistive bridge measuring method.

5. COMPARISON OF OBTAINED RESULTS

The comparison between the results obtained by two measuring methods is presented graphically in Figure 11.

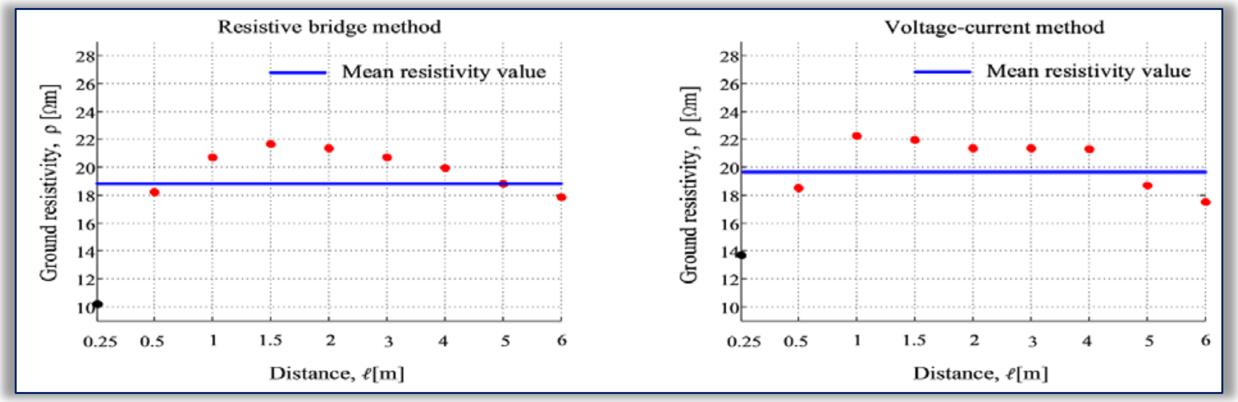

Figure 11. Mean resistivity values of both measuring methods

The average ground resistivity value is calculated according to (3), once with the first results and then without these results. From Figure 11 it can be concluded that the difference between two applied methods is small enough and the both obtained results could be defined as enough accurate.

Nevertheless, in order to investigate the measuring accuracy with more details, the relative percentual deviation is adopted as follows,

$$\delta[\%]=\left|\frac{\rho_{RBm}-\rho_{UIm}}{\rho_{RBm}}\right|\cdot 100. \quad (10)$$

In the equation above, ρ_{RBm} is the mean value of ground resistivity obtained by the resistive bridge measuring method, while ρ_{UIm} is the mean value of ground resistivity obtained by the standard U-I measuring method.

The relative percentual deviation, defined in (10) is shown in Figure 12, with the first results, at the left hand side of the figure and without these results at the right hand side of the figure.

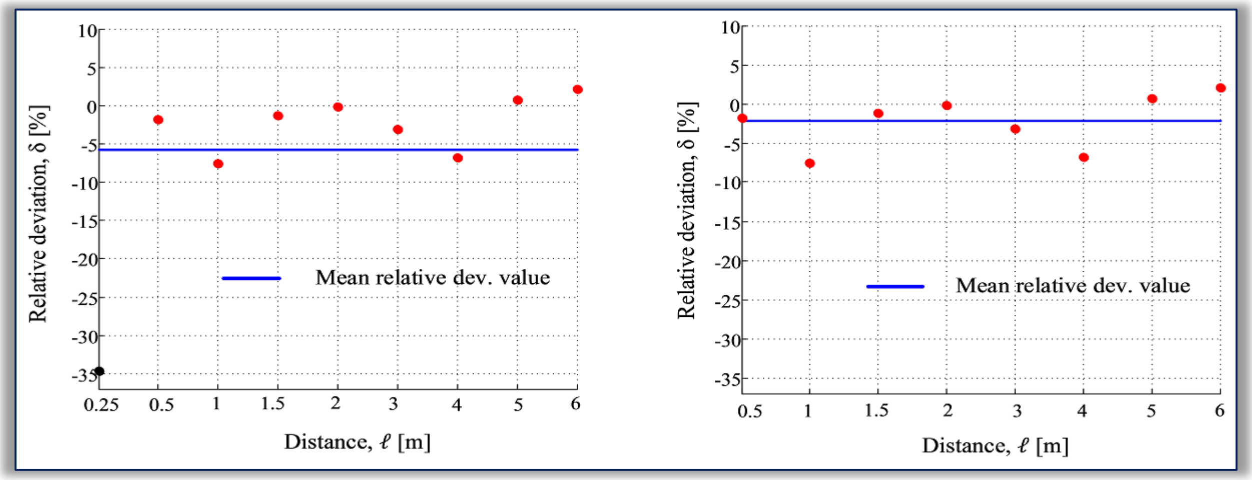

Figure 12. Relative percentual deviation of the mean resistivity values of both measuring methods

According to the presented results, the relative percentual deviation with the first results including is 16.045 % and without the first results it is 9.311 %.

6. CONCLUSION

This investigation was carried out in order to estimate the accuracy of two measuring methods for the ground resistivity determination. In practice only one of the methods applies to measure the ground resistivity and this paper should approve that both methods are accurate enough and that there is no need to verify the obtained results with the other method.

The results of the investigations approved the expectations that only one of explored method is enough to determine the ground resistivity. The results of both methods vary slightly, depending on the distance between two measuring points, which is the consequence of the ground non-homogeneity. In spite of the unknown ground non-homogeneity, the difference between the results of two observed method is quite small and it can be neglected in practice.

Moreover, the second method, due to the better applied instrument, enables the determination of complex ground impedance, from which the ground capacitance and the ground inductance can be determined as well. This also enables the determination of the ground permittivity and the ground permeability. For the second method the instrument's characteristics was available and the measurement uncertainty was calculated as well.

All the results in this paper were presented in Tables and graphically, by appropriate diagrams.

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