EXPERIMENTAL APPLICATION OF THE SIMILARITY THEORY ON SCALED STRIP ELECTRODE CONFIGURATIONS FOR THE CALCULATION OF THE GROUNDING IMPEDANCE

E. P. Nicolopoulou[1], V.T. Kontargyri[1], I. F. Gonos[1]
G. J. Tsekouras[2], E. C. Pyrgioti[3], I. A. Stathopulos[1]
[1] School of Electrical and Computer Engineering,
National Technical University of Athens,
9 Iroon Polytechneiou GR-15780, Zografou Campus, Athens
[2] Department of Electrical Engineering and Computer Science,
Hellenic Naval Academy,
Terma Hatzikiriakou, GR-18539, Piraeus – Athens
[3] University of Patras
Department of Electrical and Computer Engineering, High Voltage Laboratory
GR-26500, Patras
*Email: <hveleni@mail.ntua.gr>

Abstract: Aim of the present work is the rigorous application of the dimensional analysis for the calculation of the impulse impedance of grounding stripes. First, the dimensionless parameters are defined according to the Buckingham Πi-Theorem and the necessary scaling factors for the physical quantities of the problem arise. Stripes embedded in a metal tank filled with saline water are subjected to a lightning impulse produced by an impulse current generator. The waveforms of the injected current and the electrode voltage are recorded for different geometrical scaling factors and conductivities and the impulse impedance is calculated from the oscillogramms. The experimental ratios of the impedance values for the various scaling scenarios are compared to the theoretically expected ratios resulting from the present dimensional analysis. Finally, conclusions are drawn about the accuracy of the proposed method and about factors that influence the experimental results and should be incorporated in the dimensional analysis.

1 INTRODUCTION

Experiments on scaled down structures have been adopted in various fields of the engineering science as a way to achieve effective analysis and design of engineering systems. The Similarity Theory is a method applicable on scaled-model experiments, which allows the derivation of scale laws for the physical quantities of a problem, so that the actual values on the full size model can be predicted from measurements on the scaled model. Basis of the theory is the principle of physical similarity between model and prototype, which entails the condition that the equations for original and model differ only by a constant and demands geometrical similarity as a prerequisite [1], [2].

Dimensional analysis is a valuable tool to acquire physical similarity without necessarily having to specify and solve the governing equations of the physical process. By this method we must first identify the physical quantities involved in the problem and then seek dimensionless products formed from them. According to the Buckingham Πi-Theorem [1], [2] all these dimensionless Πi parameters must be identical between physical and scaled model.

In high voltage engineering, the Similarity Theory has been introduced in various areas, such as lightning protection and grounding system analysis [3], [4], [5]. The first attempt came from Korsuncev for the calculation of surge characteristics of earth electrodes [6]. He described the impulse impedance in terms of two dimensionless arguments and published a collection of relevant data points with an experimentally determined curve. Oettle [7] and Chisholm and Janischewskyj [8] further extended Korsuncev's model by proposing new definitions for the characteristic dimension of the electrode.

2 APPLICATION OF THE DIMENSIONAL ANALYSIS

In order to examine the validity of the dimensional analysis, measurements of the grounding impedance of grounding strip electrodes are conducted. For the purposes of the present analysis the following formula proposed by Grcev [9] has been adopted for the calculation of the grounding impedance:

$$A_i = Z/R \quad (1)$$

where: Z = impulse impedance (Ω)
R = steady state resistance (Ω)
A_i = impulse coefficient

This formula takes into consideration the two major physical processes that dominate the dynamic response of a grounding electrode subjected to a lightning current pulse: 1) the soil ionization, observed as a reduction of the grounding resistance due to the high value of the electric field in the vicinity of the electrode depending on the peak value of the injected current. 2) the limited speed of the lightning pulse propagation along the electrode related to the current pulse front time, thus resulting to an effective discharge of the lightning current to the earth only by a small part of the electrode and a deterioration of the grounding performance. The impulse coefficient taking into consideration both the effective length and ionization phenomena is:

$$A_i = \frac{1}{\sqrt{1+I_m/I_g}} + A - 1\,, \quad I_g = \frac{E_0 \rho}{2\pi R^2} \tag{2}$$

where: E_0 = the critical ionization field (V/m)
I_m = the peak value of the current (A),
I_g = the critical ionization current (A),
A = the impulse coefficient without the influence of the ionization, defined as:

$$A = 1 \quad \text{for} \ (l \leq l_{eff})$$
$$A = al + \beta \quad \text{for} \ (l > l_{eff}) \tag{3}$$
$$l_{eff} = \frac{1-\beta}{\alpha} \ \text{is the effective length (m)} \tag{4}$$

The coefficients α and β are functions of the resistivity ρ and the current waveform rise time T_1 (sec). The steady state resistance R (Ω) of a grounding strip embedded in soil at a depth $h = 0{,}5 \div 1{,}0\ m$ is given by the formula:

$$R = \frac{\rho}{\pi l} ln\left(\frac{2l}{d}\right) \tag{5}$$

Where: ρ = the soil resistivity (Ω·m),
l = the length of the grounding strip (m)
d = the width of the strip (m)

According to the abovementioned analysis the impulse impedance is a function of the following parameters:

$$Z = f(d, l, \rho, I_m, E_0, T_1) \tag{6}$$

The physical quantities $\boldsymbol{d, l, \rho, I_m, E_0, T_1}$ are the independent variables of the problem, whereas the impulse impedance Z is the dependent variable (a total of $r = 7$ variables that form the problem). Their dimensions on the basis of the unit system $[\boldsymbol{M\ L\ T\ I}]$, which consists of the fundamental quantities $\boldsymbol{M}$ mass, $\boldsymbol{L}$ length, $\boldsymbol{T}$ time and $\boldsymbol{I}$ current are:

$$[Z] = [R] = \Omega = V/_A = kg \cdot m^2 \cdot s^{-3} \cdot A^{-2} \Rightarrow$$
$$[Z] = [M^1 L^2 T^{-3} A^{-2}] = (1, 2, -3, -2) \tag{7}$$
$$[d] = [l] = m \quad \Rightarrow$$
$$[d] = [l] = [M^0 L^1 T^0 A^0] = (0, 1, 0, 0) \tag{8}$$
$$[\rho] = \Omega \cdot m = kg \cdot m^3 \cdot s^{-3} \cdot A^{-2} \Rightarrow$$
$$[\rho] = [M^1 L^3 T^{-3} A^{-2}] = (1, 3, -3, -2) \tag{9}$$
$$[I_m] = A \quad \Rightarrow [I_m] = [M^0 L^0 T^0 A^1] = (0, 0, 0, 1) \tag{10}$$
$$[E_0] = V/_m = kg \cdot m \cdot s^{-3} \cdot A^{-1} \Rightarrow$$
$$[E_0] = [M^1 L^1 T^{-3} A^{-1}] = (1, 1, -3, -1) \tag{11}$$
$$[T_1] = s \quad \Rightarrow [T_1] = [M^0 L^0 T^1 A^0] = (0, 0, 1, 0) \tag{12}$$

Thus the matrix of the dimensions is

$$\begin{bmatrix} 1 & 2 & -3 & -2 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 3 & -3 & -2 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & -3 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{13}$$

The number of Πi-Parameters to be determined is $k = r - n = 7 - 4 = 3$, where $n = 4$ are the dimensionally independent variables, equal to the rank of the above dimension matrix. Choosing as complete, dimensionally independent subset of variables $[\boldsymbol{\rho, I_m, l, T_1}]$ the Πi-Parameters for the remaining variables arise [1], [2]:

$$\boldsymbol{\Pi_1 = Z \cdot \rho^{-1} \cdot l^1 = \frac{Z \cdot l}{\rho}} \tag{14}$$
$$\boldsymbol{\Pi_2 = d \cdot l^{-1} = \frac{d}{l}} \tag{15}$$
$$\boldsymbol{\Pi_3 = E_0 \cdot \rho^{-1} \cdot I_m{}^{-1} \cdot l^2 = \frac{E_0 \cdot l^2}{\rho \cdot I_m}} \tag{16}$$

According to the principles of physical similarity, which require that these parameters are equal between model system (M) and full scale system (F), the scale factors for the variables of the problem are defined:

$$\Pi_{1_F} = \Pi_{1_M} \ \Rightarrow \ \frac{Z_F \cdot l_F}{\rho_F} = \frac{Z_M \cdot l_M}{\rho_M} \ \Rightarrow \ \frac{Z_F}{Z_M} = \frac{\rho_F}{\rho_M} \cdot \frac{l_M}{l_F}$$
$$\Rightarrow \ \boldsymbol{K_Z = K_\rho \cdot K_l{}^{-1}} \Rightarrow \ \boldsymbol{K_Z = 1/(K_\sigma \cdot K_l)} \tag{17}$$

$$\Pi_{2_F} = \Pi_{2_M} \ \Rightarrow \ \frac{d_F}{l_F} = \frac{d_M}{l_M} \ \Rightarrow \ \frac{d_F}{d} = \frac{l_F}{l_M}$$
$$\Rightarrow \boldsymbol{K_d = K_l} \tag{18}$$

$$\Pi_{3_F} = \Pi_{3_M} \Rightarrow \frac{E_{0_F} \cdot l_F{}^2}{\rho_F \cdot I_{m_F}} = \frac{E_{0_M} \cdot l_M{}^2}{\rho_M \cdot I_{m_M}}$$
$$\Rightarrow \frac{E_{0_F}}{E_{0_M}} \cdot \left(\frac{l_F}{l_M}\right)^2 = \frac{\rho_F}{\rho_M} \cdot \frac{I_{m_F}}{I_{m_M}} \Rightarrow \boldsymbol{K_{E_0} K_l{}^2 = K_\rho K_{I_m}}$$
$$\Rightarrow \boldsymbol{K_{I_m} = K_{E_0} K_l{}^2 K_\sigma} \tag{19}$$

3 EXPERIMENTAL PROCEDURE

The test arrangement is shown in Figure 1. The lightning impulse is produced by a high impulse current generator with maximum stored energy 1.5 kWs which generates 8/20μs current waveforms with a peak value up to 25 kA. The output of the generator is connected to electrode models placed in a rectangular electrolytic tank with dimensions 2m x 1m x 0.5m. The metal walls of the tank are grounded providing a return path for the discharge current.

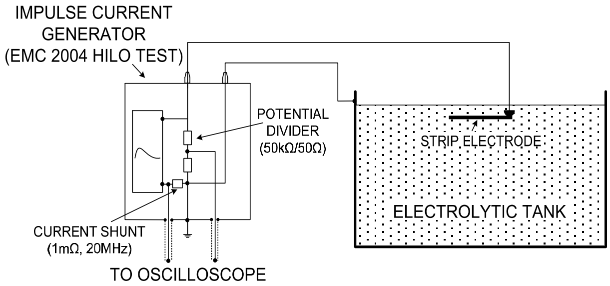

Figure 1: Experimental setup

The strip electrodes are hung with very thin ropes from insulating plastic rods placed across the tank. The hanging is properly adjusted during the measurements in order to achieve a horizontal configuration with the minimum deformation and bend. Three copper stripes, each with dimensions 20cm x 2cm, 30cm x 3cm and 40cm x 4cm are tested. Each electrode under test is located at the centre of the tank at a depth of 2 cm, 3cm and 4cm respectively below the surface of the electrolyte. These depths are chosen to be in accordance with the length and the width of the stripes to maintain geometrical similarity.

The shape and the size of the tank are of great importance because they can distort the field in the vicinity of the model and alter the measurements. Investigations on this matter carried out by previous researchers have shown that a hemispherical tank should have a diameter at least three times the width -or approximately twice the diagonal- of a square grid model [5].

According to this concept, our 2m-long tank can accommodate a strip with up to 60cm length. The rectangular shape of the tank may not exactly simulate a semi-infinite hemispherical earth but it is ideal for the specific strip models which are also rectangular.

The impulse voltage is measured by means of a resistive voltage divider (50kΩ/50Ω) and the injected impulse current by an impulse current shunt (1.0 mΩ) both built in the impulse generator cover. The voltage and current waveforms are recorded with a digital oscilloscope [10].

The salinity of the water is varied in order to achieve the desired conductivity. Taking into consideration that a typical conductivity value for seawater is 5S/m, the tests are conducted for two conductivity levels, 1S/m and 2S/m (the corresponding resistivity values are 1Ωm and 0,5Ωm). The desired injected current is acquired by properly adjusting the generator charging voltage. At each current level five impulses are carried out -to assure the repeatability of the measurements- the voltage and current waveforms are recorded and from the mean value of the electrode peak voltage V_m and peak current I_m the impulse impedance is calculated:

$$Z = \frac{V_m}{I_m} \tag{20}$$

The levels of the injected current are defined according to equation (19) so as to allow specific comparisons for each combination of conductivity and electrode dimensions. Thus, the following measurement scenarios are implemented:

1) For the same conductivity $(\boldsymbol{K_\sigma = K_{E_0} = 1})$ comparison of the measurements recorded under injected current conditions between electrodes: $\boldsymbol{K_{I_m} = K_l{}^2}$. The scaling law to be verified in this case is: $\boldsymbol{K_Z = 1/K_l}$

2) For the same electrode dimensions $(\boldsymbol{K_l = 1})$ comparison between conductivity cases of the measurements recorded under injected current conditions: $\boldsymbol{K_{I_m} = K_{E_0} K_\sigma}$. If we adopt the assumption that the critical ionization field has a constant value $(\boldsymbol{K_{E_0} = 1})$ the above condition is simplified: $\boldsymbol{K_{I_m} = K_\sigma}$. The scaling law to be verified in this case is: $\boldsymbol{K_Z = 1/K_\sigma}$

4 MEASUREMENT RESULTS

In the following tables the recorded current and impedance values are presented along with the deviations $\boldsymbol{K_{I_m}}$ and $\boldsymbol{K_Z}$ which are calculated as a percentage of the corresponding theoretically expected scale factors. Especially in the case of the impedance, the theoretical $\boldsymbol{K_Z}$ is calculated in two ways, either directly as $\boldsymbol{K_{Z(\alpha)}}$ considering $\boldsymbol{K_\sigma = 2}$ or from the exact values of the measured conductivities as $\boldsymbol{K_{Z(b)}}$. Thus the deviation of the experimental ratio is defined with respect to both theoretical scaling factors i.e. deviation (α) and deviation (b).

Table 1: Comparison between the 40x4 and the 30x3 electrodes for σ=1S/m

	Theoretical			experimental			K_{I_m} deviation %	theoretical	experimental			K_Z deviation %
	40x4 I_m (A)	30x3 I_m (A)	K_{I_m}	40x4 I_m (A)	30x3 I_m (A)	K_{I_m}		K_Z	40x4 Z (Ω)	30x3 Z (Ω)	K_Z	
40x4 - 30x3	177,8	100	1,778	171,2	102,8	1,665	-6,323	0,750	2,9813	4,0000	0,745	-0,623
	355,6	200		352	198,8	1,771	-0,402		3,0114	4,0563	0,742	-1,015
	533,3	300		535,2	300,8	1,779	0,083		3,0007	4,0293	0,745	-0,701
	711,1	400		710,4	399,2	1,780	0,100		2,9842	3,9980	0,746	-0,476
	888,9	500		880	500	1,760	-1,000		2,9864	4,0000	0,747	-0,455
	1067	600		1062	600	1,770	-0,437		3,0019	3,9667	0,757	0,904
	1244	700		1240	699,2	1,773	-0,243		2,9806	4,0160	0,742	-1,041
	1422	800		1420	800	1,775	-0,156		3,0056	4,0150	0,749	-0,187
	1600	900		1600	897,6	1,783	0,267		2,965	4,0018	0,741	-1,211
	1778	1000		1784	1010	1,766	-0,644		2,9955	3,9762	0,753	0,447
$K_l = \frac{4}{3} = 1,333$				**average values**		**1,762**	**-0,876**		**average values**		**0,747**	**-0,436**

Table 2: Comparison between the 40x4 and the 20x2 electrodes for σ=1S/m

	Theoretical			experimental			K_{I_m} deviation %	theoretical	Experimental			K_Z deviation %
	40x4 I_m (A)	20x2 I_m (A)	K_{I_m}	40x4 I_m (A)	20x2 I_m (A)	K_{I_m}		K_Z	40x4 Z (Ω)	20x2 Z (Ω)	K_Z	
40x4 - 20x2	200	50	4	198,4	50,3	3,944	-1,392	0,500	2,9839	5,9141	0,505	0,906
	400	100		400	98,9	4,044	1,112		3,0000	5,8900	0,509	1,868
	600	150		600,8	148,2	4,054	1,350		2,9960	5,8731	0,510	2,024
	800	200		798,4	198	4,032	0,808		3,0110	5,8990	0,510	2,086
	1000	250		1000,4	248,8	4,021	0,523		2,9988	5,8682	0,511	2,206
	1200	300		1200	300	4,000	0,000		2,9867	5,9333	0,503	0,674
	1400	350		1400	349,6	4,005	0,114		3,0000	5,9382	0,505	1,040
	1600	400		1600	400,8	3,992	-0,200		2,9650	5,9581	0,498	-0,471
	2000	500		2004	501,6	3,995	-0,120		2,9940	5,9729	0,501	0,253
	2400	600		2404	601,6	3,996	-0,100		2,9784	5,9840	0,498	-0,456
	2800	700		2800	699,2	4,005	0,114		2,9771	5,9382	0,501	0,271
$K_l = \frac{4}{2} = 2$				**average values**		**1,762**	**-0,876**		**average values**		**0,505**	**0,946**

Table 3: Comparison between the 30x3 and the 20x2 electrodes for σ=1S/m

	Theoretical			experimental			K_{I_m} deviation %	theoretical	experimental			K_Z deviation %
	30x3 I_m (A)	20x2 I_m (A)	K_{I_m}	30x3 I_m (A)	20x2 I_m (A)	K_{I_m}		K_Z	30x3 Z (Ω)	20x2 Z (Ω)	K_Z	
30x3 - 20x2	225	100	2,25	224,8	98,9	2,273	1,022	0,667	4,0641	5,8900	0,690	3,499
	450	200		448	198	2,263	0,561		4,0000	5,8990	0,678	1,712
	675	300		675,2	300	2,251	0,030		3,9751	5,9333	0,670	0,495
	900	400		897,6	400,8	2,240	-0,466		4,0018	5,9581	0,672	0,748
	1125	500		1130	501,6	2,253	0,124		4,0000	5,9729	0,670	0,454
	1350	600		1350	601,6	2,244	-0,266		4,0000	5,9840	0,668	0,267
	1575	700		1576	699,2	2,254	0,178		3,9645	5,9382	0,668	0,143
$K_l = \frac{3}{2} = 1,5$				**average values**		**2,254**	**0,169**		**average values**		**0,674**	**1,046**

Table 4: Comparison between conductivities σ=2S/m and σ=1S/m for the 20x2 electrode

	theoretical			experimental			K_{I_m} deviation %	theoretical	experimental			K_Z deviation (α) (%)	K_Z deviation (b) (%)
	σ=2 I_m (A)	σ=1 I_m (A)	K_{I_m}	σ=2 I_m (A)	σ=1 I_m (A)	K_{I_m}			σ=2 Z (Ω)	σ=1 Z (Ω)	K_Z		
20x2	100	50	2	99,4	50,32	1,975	-1,232	$K_{Z(a)}$ 0,500	2,8893	5,9141	0,489	-2,291	-1.834
	200	100		198,8	98,88	2,011	0,526		2,9537	5,8900	0,501	0,297	0.765
	300	150		302	148,2	2,038	1,889		2,9563	5,8731	0,503	0,672	1.142
	400	200		401,6	198	2,028	1,414		2,9681	5,8990	0,503	0,632	1.102
	500	250		500	248,8	2,010	0,482		2,9280	5,8682	0,499	-0,207	0.259
	600	300		599,2	300	1,997	-0,133		2,9306	5,9333	0,494	-1,217	-0.755
	700	350		700	349,6	2,002	0,114	$K_{Z(b)}$ 0,498	2,9200	5,9382	0,492	-1,654	-1.194
	800	400		800	400,8	1,996	-0,200		2,9300	5,9581	0,492	-1,646	-1.187
	900	450		899,2	451,2	1,993	-0,355		2,9493	5,9929	0,492	-1,574	-1.114
	1000	500		1000	501,6	1,994	-0,319		2,9480	5,9729	0,494	-1,287	-0.826
	1200	600		1200	601,6	1,995	-0,266		2,9400	5,9840	0,491	-1,739	-1.280
	1400	700		1400	699,2	2,002	0,114		2,9257	5,9382	0,493	-1,461	-1.001
measured $K_\sigma = 2,008$				**average values**		**2,003**	**0,170**		**average values**		**0,497**	**-0,956**	**-0,494**

Table 5: Comparison between conductivities σ=2S/m and σ=1S/m for the 30x3 electrode

	theoretical			experimental			K_{I_m} deviation %	theoretical	experimental			K_Z deviation (α) (%)	K_Z deviation (b) (%)
	σ=2 I_m (A)	σ=1 I_m (A)	K_{I_m}	σ=2 I_m (A)	σ=1 I_m (A)	K_{I_m}			σ=2 Z (Ω)	σ=1 Z (Ω)	K_Z		
30x3	200	100	2	200,8	102,8	1,953	-2,335	$K_{Z(a)}$ 0,500	2,0438	4,0000	0,511	2,191	3,146
	400	200		400,8	198,8	2,016	0,805		2,0200	4,0563	0,498	-0,405	0,526
	450	225		450,4	224,8	2,004	0,178		2,0142	4,0641	0,496	-0,877	0,049
	600	300		601,6	300,8	2,000	0,000		2,0246	4,0293	0,502	0,495	1,434
	800	400		800	399,2	2,004	0,200		2,0200	3,9980	0,505	1,051	1,995
	900	450		899,2	448	2,007	0,357	$K_{Z(b)}$ 0,495	1,9973	4,0000	0,499	-0,133	0,800
	1000	500		1000	500	2,000	0,000		2,0080	4,0000	0,502	0,400	1,338
	1200	600		1200	600	2,000	0,000		2,0033	3,9667	0,505	1,008	1,952
	1350	675		1350	675,2	1,999	-0,030		2,0089	3,9751	0,505	1,073	2,018
	1400	700		1400	699,2	2,002	0,114		2,0029	4,0160	0,499	-0,257	0,676
	1800	900		1800	897,6	2,005	0,267		2,0156	4,0018	0,504	0,733	1,674
measured $K_\sigma = 2,020$				**average values**		**2,000**	**0,007**		**average values**		**0,502**	**0,480**	**1,419**

5 CONCLUSIONS

A comparison of the results shows an overall satisfying performance of the theory. The first measurement scenario (same conductivity) has yielded very small impedance deviations, not exceeding 1%. The deviations at the second measurement scenario (same electrode) are slightly higher. For all the electrodes the deviations $K_{Z(b)}$ are smaller than the deviations $K_{Z(a)}$. This proves that the exact value of the conductivity must be taken into account.

These deviations can be justified by the limited accuracy of the instruments (generator and oscillograph). A differential voltage probe and a current monitor would increase the accuracy of the measurements.

The effect of the K_{I_m} deviation (not more than 1%) was proven to be negligible. Special attention must be given at the exact adjustment of the conductivity so that the comparison of the results can be done on the proper basis.

Table 6: Comparison between conductivities σ=2S/m and σ=1S/m for the 40x4 electrode

	theoretical			experimental			K_{I_m} deviation %	theoretical	experimental			K_Z deviation (α) %	K_Z deviation (b) %
	σ=2 I_m (A)	σ=1 I_m (A)	K_{I_m}	σ=2 I_m (A)	σ=1 I_m (A)	K_{I_m}			σ=2 Z (Ω)	σ=1 Z (Ω)	K_Z		
40x4	200	100	2	202,4	98,2	2,061	3,055	$K_{Z(a)}$ **0,500**	1,5771	2,9369	0,537	7,399	3.083
	400	200		400,8	198,4	2,020	1,008		1,5888	2,9839	0,532	6,494	2.215
	600	300		600,8	298	2,016	0,805		1,5872	3,0121	0,527	5,390	1.156
	800	400		800	400	2,000	0,000		1,6000	3,0000	0,533	6,667	2.381
	1000	500		998,4	499,2	2,000	0,000	$K_{Z(b)}$ **0,521**	1,5960	3,0008	0,532	6,372	2.098
	1200	600		1200	600,8	1,997	-0,133		1,5867	2,9960	0,530	5,919	1.663
	1400	700		1400	700,8	1,998	-0,114		1,5714	2,9795	0,527	5,484	1.246
	1600	800		1600	798,4	2,004	0,200		1,5875	3,0110	0,527	5,446	1.209
	2000	1000		2000	1000,4	1,999	-0,040		1,5900	2,9988	0,530	6,042	1.782
measured $K_\sigma = 1,919$				**average values**		**2,011**	**0,531**		**average values**		**0,531**	**6,135**	**1,870**

An initial proposal for future improvement of this work would be the processing of the measurements with an alternative definition of the impulse impedance that takes ionization consideration by accounting for the instantaneous voltage value at the current peak.

In the present analysis the critical ionization field was considered to have a steady value. The influence of this parameter and its possible dependence from the conductivity highlighted by other researchers should be investigated through experiments at different salinity levels. Higher conductivity levels would make the effect of the ionization procedure more obvious. In the presented measurements the recordings stopped at specific charging voltage levels where sparks on the tank base were observed. Thus the injected current -which determines the ionization procedure- was limited by the depth of the tank.
Finally, other electrode configurations would enable the investigation of the alternative definitions given for the characteristic dimension of the electrode suggested by Korsuncev, Popolansky and Oettle.

6 REFERENCES

[1] Sonin A.A. 2001. "The Physical Basis of Dimensional Analysis", 2nd Edition, Department of Electrical Engineering, MIT

[2] Politis G.K., Lamprinidis G.N. 1993, "Hydrodynamics of ship propulsion", 1st Edition, Astir Publications.

[3] Frentzel R. 1997, "Use of Similarity Relations in the Analysis of Lightning-Induced Transient Phenomena", European Transactions on Electric Power Engineering (ETEP), Vol. 7, no 3, pp. 173-177.

[4] Metwally I.A., Heidler F.H., Zischank W.J. 2006, "Magnetic Fields and Loop Voltages Inside Reduced- and Full-Scale Structures Produced by Direct Lightning Strikes", IEEE Transactions on Electromagnetic Compatibility, Vol. 48, no 2, pp. 414-426.

[5] Caldecott R., Kasten D. G., "Scale model studies of station grounding grids", IEEE Transactions on Power Apparatus and Systems, 1983, PAS-102(3), pp.558-566.

[6] Korsuncev A.V. 1958, "Application of the Theory of Similitude to the Calculation of Concentrated Earth Electrodes", Elektrichestvo, no 5, pp. 31-35.

[7] Oettle E.E. 1988, "A New General Estimation Curve for Predicting the Impulse Impedance of Concentrated Earth Electrodes", IEEE Transactions on Power Delivery, Vol. 3, no 4, pp. 2020-2029.

[8] Chisholm W.A., Janischewskyj W. 1989, "Lightning Surge Response of Ground Electrodes", IEEE Transactions on Power Delivery, Vol. 4, no 2, pp. 1329-1337.

[9] Grcev L., "Modeling of Grounding Electrodes under Lightning Currents", IEEE Transactions on Electromagnetic Compatibility, Vol.51, No.3, pp. 559-571, August 2009.

[10]Gonos I.F.: "Experimental study of transient behaviour of grounding grids using scale models", Institute of Physics Publishing, Measurement, Science and Technology, Vol. 17, No. 7, pp. 2022-2226, July 2006.