I-V CURVES FOR THE DETERMINATION OF THE IONIZATION VOLTAGE IN SOIL SAMPLES

F. E. Asimakopoulou, I. F. Gonos and I. A. Stathopulos
High Voltage Laboratory, School of Electrical and Computer Engineering
National Technical University of Athens, Greece
*Email: <igonos@ieee.org>

Abstract: The behavior of a grounding system under fault currents differs from its steady state behavior. When the density of the injected current exceeds a critical value, then soil ionization phenomena occur, which decrease the soil resistivity and, consequently, the grounding impedance. The critical parameter for the ionization phenomenon is the soil ionization gradient. Aim of this paper is to investigate the effectiveness of the method based on I-V curves in determining the starting ionization voltage and in estimating the associated critical electric field. On that purpose, series of measurements have been conducted by imposing impulse voltages on soil samples with different moisture contents. The voltage and the current are recorded, the I-V characteristics are plotted, the starting ionization voltage is being determined and the soil ionization gradient is calculated. For the computation of the soil ionization gradient different approaches are adopted with a view to examine their effectiveness.

1 INTRODUCTION

The transient behavior of the grounding system has been subjected to investigation for many decades, since the impulse behaviour differs from the steady state behaviour. In late 20's Towne [1] observed that under high discharge currents the rods exhibit impulse impedance lower than expected. Bellaschi [2],[3] and Petropoulos [4] attributed this behavior to the development of arcs in the soil around the rod, which short-circuit the grounding systems' impedance and reduce the transient impedance. Since then a lot of effort has been made to study and analyze this phenomenon and new parameters have been introduced, in order for the phenomenon to be described. One of the most crucial parameters is the soil ionization gradient (E_o). In Table 1 the experimental results obtained by various researchers for the determination of E_o are presented.

It is important to notice that the researchers follow different approaches in order to determine the voltage level above which ionization takes place and to estimate the critical ionization gradient. Nor et al [17] and Lee et al. [16] define as critical the voltage level at which two peaks are presented in the current waveform.

Another approach is proposed by Loboda and Scuka [11], who define the onset of the ionization at the voltage level at which delay between the peaks of the current and voltage is observed.

Table 1: Summary of soil ionization experiments

Researcher	Experiments*	Configuration	Soil type	ρ (Ωm)	E_o (kV/m)
Towne [1]	F	Rods	Gravel	130-686	29-104
Norinder [4]	L	Cylindrical	Vegetal clay, red clay	-	327-360
Berger [4]	L	Hemispheres	-	1000	497-537
Petropoulos[4]	L	Hemispheres	Calcinary	290	800-860
Armstrong [7]	L	Rods	Sand, clay	52-495	330-480
Liew et al [8]	F	Rods	Sand, clay, gravel	50-540	110-300
Korsuntcev [9]	L	Cylindrical		100-470	800-1200
Loboda et al [10]	L	Cylindrical	Sand, clay, humus	30-750	150-500
Loboda et al[11]	L	Cylindrical	Sand, clay, organic soil	40-2150	560-900
Geri [12]	F	Rods, Horizontal wire	Agricultural soil	40.5-43.5	30-800
Liu et al [13]	L	Hemispherical	Sand mixed with salt	174-827	328-516
Asaoka et al[14]	F	Rods	Sand, mud, gravel	228-2056	1040-1430
Lima et al[15]	L	Parallel discs	4 different soil types with different moisture	80-10000	370-1440
		Cylindrical			312-882
Lee et al[16]	L	Hemispherical	Sand	134.3-336.5	1020-1650
Nor et al[17], [18]	L	Hemispherical	Sand	2.3-5.5	550-660
		Parallel discs			790-900
Manna et al [22]	L	Parallel discs	4 different soil types with different moisture	23-30200	560-1433
Asimakopoulou et al [19]	L	Parallel discs	Clay	-	767-984

*L= LABORATORY EXPERIMENT, F=FIELD EXPERIMENT

According to Nor et al [17] in the case of uniform field, the starting ionization voltage and the breakdown voltage coincide. Finally, in [16] and [21], the I-V characteristics are used in order for the starting ionization voltage to be determined. Having determined the critical voltage (V_{th}), the corresponding E_o is calculated. The determination of its value has proved to be a difficult and multivariable problem. Until today there hasn't been established a universal agreement on the procedure for determining the ionization voltage and the algorithm for the estimation of the critical ionization gradient.

In this paper, the I-V characteristics approach has been implemented for the determination of the ionization voltage, different approaches for the estimation of the soil critical gradient are summarized and a critical review is presented.

2 EXPERIMENTAL SET UP

The impulse voltage generator, presented in Figure 1, is designed in order to produce 1.2/50 μsec negative impulse voltages. The main supply is regulated to a constant value of 230 V ±0.1% AC, 50 Hz by means of a voltage stabilizer. The output voltage is measured by a voltage divider (with ratio 421:1) and a differential probe with attenuation ratio 100:1. Current measurement is obtained by using a Pearson current monitor with a 0.002 A/V sensitivity. The signals are recorded with a two-channel 500 MHz digital oscilloscope, which is placed in a Faraday cage with 50 dB signal attenuation up to 1 GHz. A low pass filter and an insulating transformer shield the power supply from noise and disturbances.

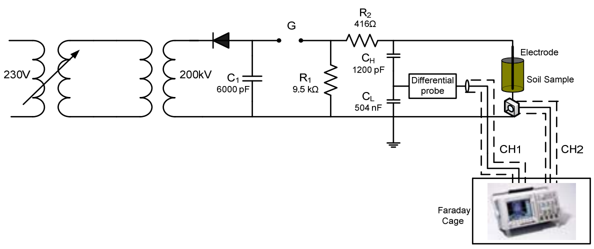

Figure 1: Experimental setup

A metallic cylinder 25 cm in diameter and 20 cm in depth with wooden bases is filled with the soil sample and a copper electrode is inserted in the soil, on which the impulse voltage is applied. Three different types of soil are used. The resistivity of the samples was calculated after measuring the resistance at low impulse voltage (Z_o). The resistivity of the soil samples in low-level impulse voltage are presented in Table 2.

The preparation of the soil comprised the following: sieving of the soil in order to release it from clods, drying of the soil in an oven (at 105°C) for 2 days and addition of de-ionized water in order to achieve the specified moisture content (5%, 10%, 20% by weight).

Table 2: Resistivity of the soil samples.

Soil Sample	Per weight water content (%)	Resistivity (Ωm)
A	5	950
A	10	400
B	10	880
C	20	514

3 EXPERIMENTAL RESULTS

3.1 Oscillogramms

Figures 2 and 3 show voltage and current waveforms obtained from tests on sample A with 0% and 10% per weight water content, respectively, for an applied charging voltage of the impulse generator of 36 kV. As it can be seen in Figure 2, the high resistivity of the dry soil does not allow the measurement of low currents, where the recorded current (captured in Ch2) is very low. However, as water is added to the soil sample, conduction currents are recorded. It is worth mentioning that, as the water content of the soil increases, the resistance decreases and the voltage waveform (Ch1) diverges from the standard 1,2/50 μsec waveform (Figure 3), because of the dependence of the impulse voltage waveform on the impedance of the soil sample.

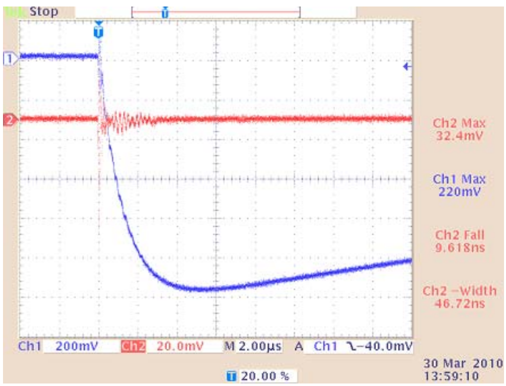

Figure 2: Typical voltage (Ch1) and current (Ch2) traces for soil sample A with 0% water content

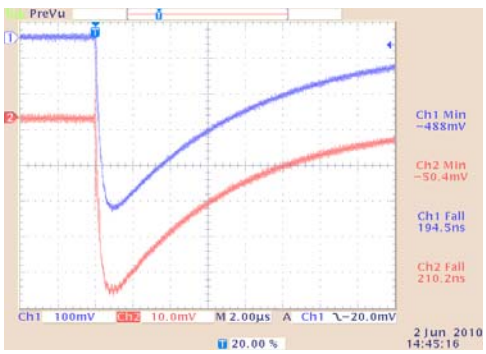

Figure 3: Typical voltage (Ch1) and current (Ch2) traces for soil sample A with 10% water content

3.2 I-V Characteristics

In order to determine the voltage level above which the ionization process commences, the voltage and current traces for impulse generator's charging voltages (V_{char}) from -18 kV down to -100 kV are recorded and the I-V characteristic for each voltage level is plotted. The inability to record current measurement for dry soil samples has as a result the inability to produce I-V characteristics for dry soil samples. In the case of wet soil samples, the shape of the I-V characteristics is used for the determination of V_{th}. For low current densities, the I-V curve forms a loop characteristic of a parallel RC circuit at high frequencies, and ionization does not occur. This behavior is illustrated by the solid lines in Figures 4 -7 for negative charging voltages of 42 kV, 51 kV, 60 kV, 25 kV, respectively. For higher charging voltage level, the ionization process starts to develop. Dashed dotted lines in Figures 4 through 7 show this behavior for negative charging voltages of the impulse generator of 48 kV, 54 kV, 63 kV and 27 kV. The ionization process develops and the I-V characteristic forms an inclined eight '8', as it can be seen by the dash lines. In Table 3 the charging voltages (V_{char}) of the impulse generator corresponding to the critical ionization level and the critical ionization voltages (V_{th}) on the soil samples as determined by the procedure described above are tabulated. Moreover, in the same table the impedance of the soil samples (Z_o) corresponding to a charging level of 15 kV, as well as, the minimum impedance (Z_{min}) at the critical ionization voltage level are recorded.

4 CALCULATION OF SOIL IONIZATION GRADIENT

Following the methods for calculating the soil ionization gradient are presented. The first two methods are based on formulas, which correlate the critical ionization gradient (E_o) with soil resistivity and are proposed by Oettle [9] and Manna [23], while the rest of the methods are based on the estimation of the radius of the ionization region.

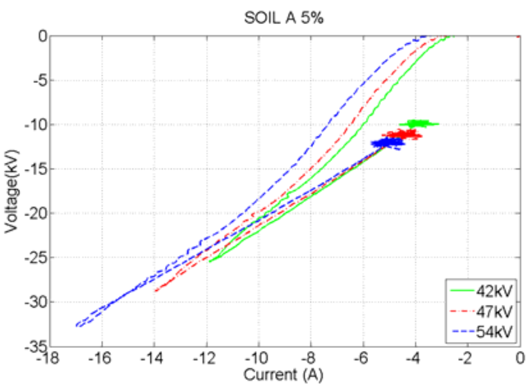

Figure 4: I-V curves for soil A with 5% moisture content and different charging voltages.

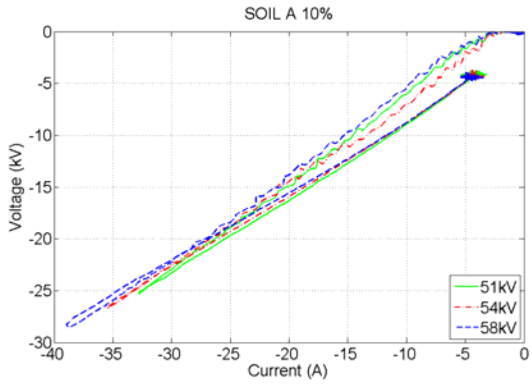

Figure 5: I-V curves for soil A with 10% moisture content and different charging voltages

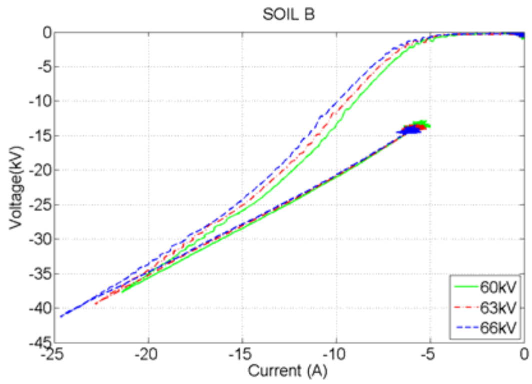

Figure 6: I-V curves for soil sample B with 10% water content for different charging voltages.

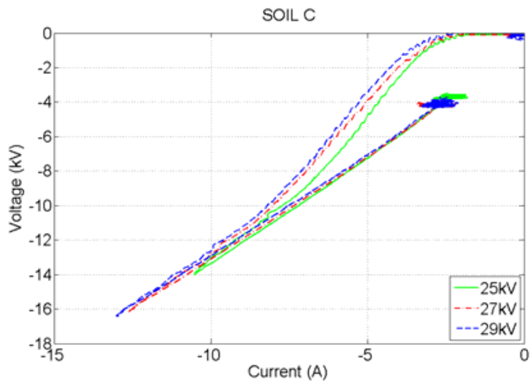

Figure 7: I-V curves for soil sample C with 20% water content for different charging voltages.

1st Method: Based on experimental results Oettle suggested the following formula [9]:

$$E_o = 241 \cdot \rho^{0.215} \quad (1)$$

where: E_o = soil ionization gradient (kV/m)
ρ = soil resistivity (Ωm)

2nd Method: Manna [23] correlated soil resistivity with E_o in the following formula:

$$E_o = 843.2 \cdot \rho^{0.124} \quad (2)$$

where: E_o = critical electric field (kV/m)
ρ = soil resistivity (kΩm)

3rd Method: Given the cylindrical configuration of the experimental set-up, and in order to take into account the development of the ionization area, (3) can be used:

$$E_o = \frac{V_{th}}{r_{ion} \cdot \ln \frac{r_{out}}{r_{ion}}} \quad (3)$$

where: V_{th} = the critical ionization voltage in kV
r_{out} = the inner radius of the outer electrode in meters (m)
r_{ion} = the radius of the ionization area (m)

The ionization radius defines the extent of the ionization area around the electrode under the hypothesis that the ionization area is developed uniformly around the electrode and that the resistivity of the ionized region is negligible. The ionization radius can be calculated by (4), as suggested in [15].

$$\frac{Z_d}{Z_o} = \frac{\ln\left(r_{out} / r_{in} \right)}{\ln\left(r_{ion} / r_{in} \right)} \Rightarrow r_{ion} = r_{out}^{\left(1 - \frac{Z_d}{Z_o}\right)} \cdot r_{in}^{\frac{Z_d}{Z_o}} \quad (4)$$

where: Z_d = the impedance at 9μsec at the critical voltage level in Ohm (Ω)
Z_o = the impedance at the lowest applied voltage level in Ohm (Ω)
r_{in}= the radius of the inner electrode in meters (0.0025 m)
r_{out} = the inner radius of the outer electrode in meters (0.125 m)
r_{ion} = the radius of the ionization area in meters (m)

4th Method: A variation of the above mentioned method is proposed by substituting Z_d with the minimum impedance at the voltage level when the loop is formed in Ohm (Ω). This variation is considered to be less arbitrary in comparison to the selection of the impulse impedance at the 9μ sec, since at the moment of the minimum impulse impedance the ionization area reaches its maximum extend.

5th Method: According to the model proposed by Liew and Darveniza [8] the resistivity in the ionization region varies with time. According to their model the area around the electrode can be divided into three regions, the region where soil ionization does not occur and the resistivity remains steady, the region where the ionization has started to evolve, the resistivity decreases, and the region where the soil de-ionises and the resistivity recovers. Each region comprises shells that have different current density; therefore, calculations for each shell should be performed in order to calculate the overall resistance. Moreover, experiments conducted by Loboda [10] verify that the resistivity in the ionized area is not equal to the resistivity of the electrode. This was studied by Liu et al. [13] who calculated the residual resistivity in the ionization region and concluded that the resistivity in the ionization region can reach 7% of the original soil resistivity. According to a study conducted by Nixon [24] the model proposed by Liew and Darveniza can be simplified by treating the ionization and the de-ionization regions as a complete unit using the current density at the outer border of these regions. Taking all the above into consideration the determination of the ionization radius can be made by defining the minimum grounding impedance at the voltage level at which ionization starts to develop. More analytically, the minimum resistance at the threshold ionization voltage comprises the resistance of the ionization region and the resistance of the non-ionized region as described by (5)

$$Z_{\min} = Z_{ion} + Z_{non-ion} = \frac{\rho_{ion}}{2 \cdot \pi \cdot l} \ln\left(\frac{r_{ion}}{r_{in}}\right) + \frac{\rho}{2 \cdot \pi \cdot l} \ln\left(\frac{r_{out}}{r_{ion}}\right) \quad (5)$$

where: ρ_{ion} = the resistivity of the ionization region in (Ωm)
ρ = the resistivity of the soil in (Ωm)
r_{in}= the radius of the inner electrode in meters (m)
r_{out} = the inner radius of the outer electrode in meters (m)
r_{ion} = the radius of the ionization area in meters (m)

In (5) not only the ionization radius has to be determined but also the resistivity in the ionized area. In order to determine these parameters a genetic algorithm (GA) has been applied. The same GA produces excellent results in several optimization problems [25]-[29].

The results obtained by the application of the above mentioned methods are presented in Table 3 and in Figure 8.

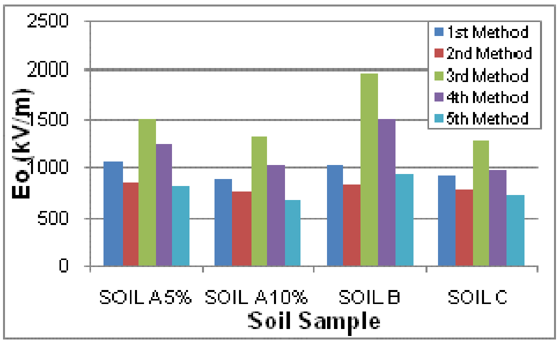

Figure 8: E_o as derives from Methods 1 through 5 for each soil sample.

Table 3: Ionization gradient for each soil sample.

Soil Sample	ρ (Ωm)	V_{char} (kV)	V_{th} (kV)	Z_o (Ω)	Z_d (Ω)	Z_{min} (Ω)	r_{ion} by GA (m)	E_o (kV/m)				
								Method				
								1st	*2nd*	*3rd*	*4th*	*5th*
A 5%	950	47	28.7	3000	2245	2020	0.08	1056	839	1507	1244	804
A 10%	400	54	26.8	1180	867	746	0.07	874	753	1321	1028	660
B	880	63	43	2750	1944	1620	0.05	1035	830	1976	1496	938
C	514	27	16.2	1560	1422	1320	0.10	922	776	1281	980	726

5 DISCUSSION AND CONCLUSION

For the determination of V_{th} of soil samples the I-V characteristics for various voltage levels have been produced. The results of this method show that in the case of soil samples with high resistivity the method cannot be applied. However, in the case of wet soil samples the method gives results. At this point it is worth mentioning that the soil always contains a certain amount of water, therefore the I-V characteristics method can be applied for the study of soil ionization. From the experimental results, another useful conclusion, which derives is that there has not been observed a second peak at the current waveform for voltage level above V_{th} as suggested by [16] and [17]. Consequently the I-V characteristic is an effective method for determining V_{th}.

Comparing the results of the methods for calculating E_o it can be concluded that, Method 3 gives the maximum values of E_o for all soil samples. On the other hand, with exception soil sample B, Method 5 provides with the lowest values of E_o.

It is also noteworthy that, soil sample A with 5% water content has resistivity slightly higher than that of soil sample B. That is also the case for soil sample A with 10% water content and soil sample C. According to expressions (1) and (2) as the resistivity decreases E_o also decreases, observation which is in agreement with our data. However, when applying the rest methods E_o of the soil sample A with 10% water content (400 Ωm) is higher than E_o of soil sample C (514 Ωm). These results support the statement of Mousa [7], according which E_o is not only influenced by the soil resistivity. As a conclusion, it can be said that (1) and (2) should be used only as an approximation of E_o.

As far as the calculation of E_o concerns by applying Methods 3 through 5, the knowledge of r_{ion} is of importance. However, experience has shown that the determination of the ionization radius greatly depends on the determination of the impedance Z_d. For the same soil sample as Z_d increases, r_{ion} decreases and E_o decreases.

Regarding the application of the GA it can be said that it offers a more realistic approach to the phenomenon since it takes into account the remaining resistivity of the ionized region and does not assume any electrode with extended dimensions.

To sum up, the analysis of the above mentioned methods reveals the advantages and the drawbacks of each one, highlights the difficulties regarding the calculation of E_o and underlines the necessity for further research on the subject and the establishment of a specific method for determining V_{th} and estimating E_o.

6 ACKNOWLEDGMENTS

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