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EXPERIMENTAL INVESTIGATION ON SOIL IONIZATION

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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 critical electric field, which corresponds to the electric field threshold above which the soil ionization occurs. The aim of this work is the experimental investigation of the soil ionization phenomenon on soil samples subjected to impulse voltages. The voltage and the current are recorded, and the soil critical electric field is calculated by using proposed in the bibliography methods. The influence of the soil parameters on the soil critical electric field is investigated, the results are compared to those drawn by the bibliography and useful conclusions derive.

1. INTRODUCTION

The grounding system comprises an essential part of the protection system of any power system, building, etc. Moreover, an efficient grounding system dissipates the stroke current into the soil and reduces the damages to electrical and electronic equipment and to personnel.

However, the impulse behavior of the grounding system greatly differs from the behaviour at industrial frequency. It has been observed that when a high impulse current is injected in the grounding system, its impulse impedance drops. This fact was attributed to soil ionization phenomena developed in the soil around the grounding system and was first introduced by Towne in 1929 [1].

This phenomenon develops when the electric field in the soil vicinity around the grounding system overcomes the soil critical electric field (E_c). In that case the soil breakdown occurs and the soil resistivity of the affected section of soil decreases, resulting in decrease of impulse impedance. Thus, the soil critical electric field is a fundamental parameter for the investigation of the impulse behaviour of grounding systems.

During the last decades a lot of effort has been made in order for the value of the soil critical electric field (E_c) to be determined. Various values for E_c have been suggested by numerous researchers. In the experiments conducted by Towne E_c ranges between 160-520kV/m. E_c was calculated by Bellaschi et al [2] in the range of 120-420kV/m. In 1974 Liew and Darveniza [4] used a value of 300kV/m for E_c. Loboda el al [5] investigated the electrical properties of different soils injected with current pulses and calculated E_c between 560-900kV/m. In impulse tests of several types of soil, which were conducted by Oettle [7], E_c varied in the range of 600-1850kV/m and 600-800kV/m for soils with higher moisture contents. The inhomogeneity of the soil also affects the value of E_c (in a homogenous soil E_c falls approximately 50%). Therefore, a value of 1MV/m was suggested. The value of 400kV/m is used by CIGRE [8]. Mousa [9] suggested that 300kV/m should be used for E_c. Gonos et al. [10] studied the variation of E_c against the soil resistivity and E_c was found to be approximately 200kV/cm. Nor et al. [11] conducted laboratory impulse tests on electrode systems embedded in sand and clay medium. In these tests a parallel plate test cell (providing a uniform field) and a hemispherical test cell (providing non-uniform field) were used. The E_c obtained by the parallel plate arrangement was 790kV/m, higher than that of 550kV/m by the hemispherical test cell. The influence of the field uniformity on the value of E_c has also been investigated by Lima et al. [14]. It was concluded that E_c in uniform fields was 3 to 4 times higher than in non-uniform fields.

Since the electrical characteristics of soil vary among different soil types and the adoption of one value for E_c is not suggested, Manna and Chowdhury [15] studied the influence of significant soil parameters to the value of E_c, and they proposed the following equation:

$$E_c = 8.6083 \cdot k_g^{-0.0103} \cdot \sigma_g^{-0.1526} \quad (1)$$

Where: E_c = the soil critical electric field (kV/cm)
k_g = the soil dielectric constant
σ_g = the soil conductivity (millimho/m).

This paper focuses on the methods for the determination of E_c and presents a critical comparison among them.

2. TEST ARRANGEMENT

2.1. Experimental set-up

The set-up presented in Figure 1 has been used in order for experimental data to be acquired. These data has been used for the estimation of E_c.

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The 1.2/50μs impulse voltage was generated by a high impulse voltage generator with charging capacity of up to 200kV, and energy of up to 3kJ. A low pass filter and an isolating transformer shield the power supply from noise and disturbances. The main supply is regulated to a constant value of 230±0.1V AC, 50Hz by means of a voltage stabilizer. The output voltage was measured by a differential probe with attenuation ratio 1/100. Current measurement was obtained by using a current transformer with 0.002A/V sensitivity. The signals were recorded by a two-channel digital oscilloscope.

The soil was dried in an oven (at 105°C). Deionized water was added and carefully mixed with the soil in order to achieve specified moisture contents (0%, 5%, 10%). The soil sample was placed in a cylindrical container of 14.6cm in diameter, while the impulse voltage was imposed by a rod of 0.5cm in diameter, positioned vertically.

2.2. Soil resistivity

The resistivity (ρ in Ωm) of each soil sample was calculated by measuring the resistance (R) of coaxial cylinder electrodes filled with soil at low AC current by the formula:

$$\rho = \frac{2\pi l R}{\ln \frac{r_{out}}{r_{in}}} \qquad (2)$$

Where: R = resistance (Ω)
r_{out} = inner radius of the outer electrode (m)
r_{in} = radius of the inner electrode (m)
l= 0.60m, length of the cylinder

In Table 1 the parameters of the tested soil samples are given.

2.3. Breakdown voltage

The voltage was increased stepwise until the breakdown of the gap. The breakdown in the sample occurs when the current increases rapidly while the voltage decreases. Whenever ionization phenomena didn't occur the gap spacing was gradually increased, until the oscillograms indicated the presence of soil ionization.

Figures 2-4 show typical voltage and current waveforms during the breakdown of the sample. The breakdown level is determined as the $U_{50\%}$ according to IEC 60-1 [16]. In Table 1 the breakdown voltages for the three soil samples are presented.

Table 1: Soil resistivity and Breakdown voltage of the soil samples.

Soil Sample	Moisture (%)	Resistivity (Ωm)	$U_{50\%}$ (kV)
I	0	2100	58,4 ± 0.95
II	5	1250	36.3 ± 0.50
III	10	400	29.0 ± 0.83

It can be easily observed that as the resistivity of the soil sample decreases the breakdown voltage also decreases.

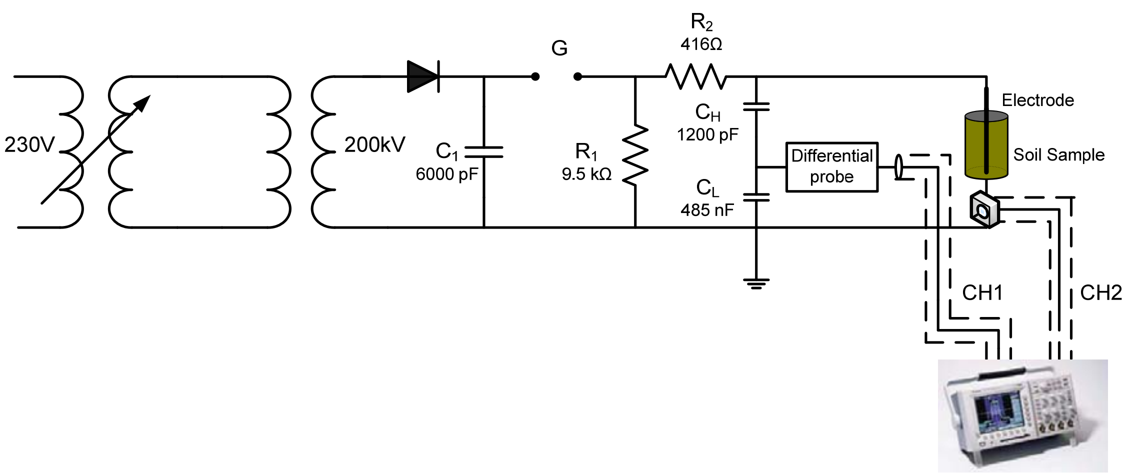

Figure 1: Test arrangement

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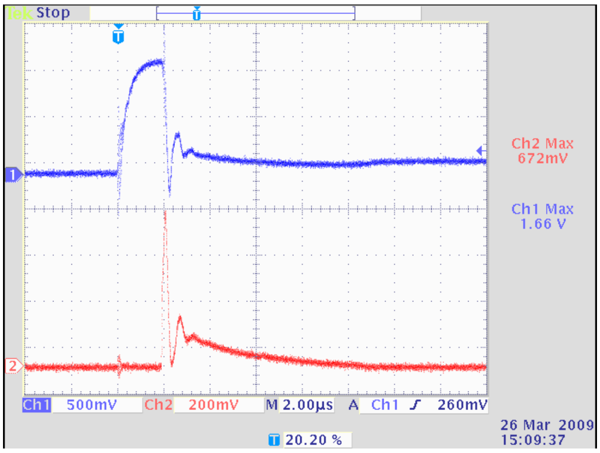

Figure 2: Voltage and Current traces of soil sample with 0% moisture.

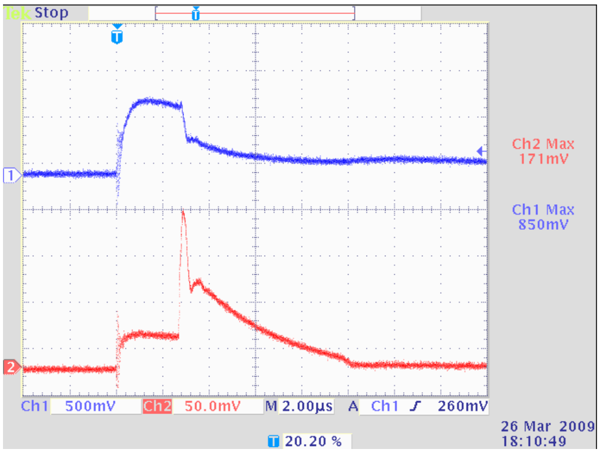

Figure 3: Voltage and Current traces of soil sample with 5% moisture.

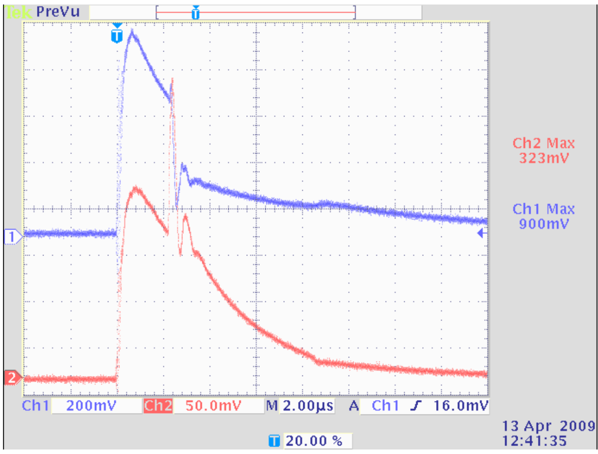

Figure 4: Voltage and Current traces of soil sample with 10% moisture.

3. SOIL CRITICAL ELECTRIC FIELD

The estimation of the soil critical electric field (E_c) is of paramount importance for the determination of the impulse impedance of a grounding system. The decrease in the impedance resulting by the ionization process can be proved beneficial for the grounding system's performance. The key for the initiation of the ionization process is the soil critical electric field.

Several researchers have determined the soil critical electric field for different soil types. Some of them have determined E_c experimentally [6], [9], [10], [13] while others have adopted an E_c value in order for the theoretically conclusions to fit the experimental results [2].

Oettle suggested the following formula [7], based on experimental results:

$$E_c = 241 \cdot \rho^{0.215} \qquad (3)$$

Where: E_c = soil critical electric field (kV/m)
ρ = soil resistivity (Ωm)

Manna conducted extensive experiments by using three different soil types with four different humidity contents [17]. Finally, he correlated soil resistivity with E_c in the following formula:

$$E_c = 843.2 \cdot \rho^{0.124} \qquad (4)$$

Where: E_c = critical electric field (kV/m)
ρ = soil resistivity (kΩm)

Given the cylindrical configuration of the experimental et-up, Nor [13] used the following equation in order to estimate E_c on the surface of the electrode:

$$E_c = \frac{U_{50\%}}{r_i \cdot \ln \frac{r_e}{r_i}} \qquad (5)$$

Where: $U_{50\%}$ = breakdown voltage determined by the up and down method according to IEC 60-1 [16]
r_{out} = inner radius of the outer electrode (m)
r_i = radius of the inner electrode (m)

However (5) does not take into account the ionization radius. Therefore Nor in [18] uses the formula:

$$E_c = \frac{U_{50\%}}{r_{ion} \cdot \ln \frac{r_e}{r_{ion}}} \qquad (6)$$

Where: $U_{50\%}$ = breakdown voltage determined by the up and down method according to IEC 60-1[16]
r_{out} = inner radius of the outer electrode (m)
r_{ion} = radius of the ionization area (m)

Loboda [6] calculated the soil critical electric field based on current and voltage oscillograms and the variation of the impulse resistance. After determining the minimum impulse resistance, the ionization radius is calculated. Given the dimensions of the electrode

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and its arrangement, the current flow (J) at the surface of the ionized zone can be estimated assuming an electrode with expanded dimension. Finally the soil critical electric field is calculated from:

$$E_c = \rho \cdot J \tag{7}$$

Where: ρ = soil resistivity (Ωm)
J = current flow (A/m^2)

4. RESULTS

The estimation of the ionization radius (r_{ion}) is required for the calculation of E_c using equations (6) and (7). Therefore, the following equation [14] is being used:

$$r_{ion_i} = r_{out}^{(1-Z_o/Z_{ion_i})} \cdot r_{in}^{(Z_o/Z_{ion_i})} \tag{8}$$

Where: r_{out} = the inner radius of the outer electrode (m)
r_i = the radius of the inner electrode (m)
r_{ion} = the radius of the ionization area (m)
Z_o = the impedance when no ionization occurs (Ω)
Z_{ion_i} = the impedance when ionization occurs (Ω), which is calculated by (9)-(12).

The determination of the ionization radius greatly depends on the determination of the impedances. Z_o can be easily calculated. However for the estimation of Z_{ion_i} the following formulas can be used.

$$Z_{ion1} = \frac{U_{50\%}}{I_{max}} \tag{9}$$

$$Z_{ion2} = \frac{U_{I_{max}}}{I_{max}} \tag{10}$$

$$Z_{ion3} = \frac{U_{50\%}}{I_{U_{50\%}}} \tag{11}$$

$$Z_{ion4} = \min(Z(t)) \tag{12}$$

Where: $U_{50\%}$ = the breakdown voltage (kV)
I_{max} = the maximum value of the current (A)
U_{Imax} = the voltage at maximum current (kV)
$I_{U50\%}$ = the current value at $U_{50\%}$ (A)
$Z(t) = \frac{U(t)}{I(t)}$, the impedance at time t (Ω)

The values for $U_{50\%}$, I_{max}, U_{Imax} and $I_{U50\%}$ are drawn by the recorded oscillograms of the experiments.

Therefore, the ionization radius (r_{ion_i} where i=1, … ,4 corresponds to the four determinations of Z_{ion}) is calculated by applying equations (9)-(12) to (8). These r_{ion_i} values have been used for the estimation of E_c according to the methods proposed by Nor and Loboda and different E_c values have emerged. In order to come up with one characteristic value of E_c for each soil sample, the average value of E_c is considered. $E_c(r_{ion4})$ is not to be used for the calculation of the average value of E_c, as it does not occur at the same moment with neither $U_{50\%}$ nor I_{max}. Hereafter the names Aver(6) and Aver(7) are assigned to the average values, depending on which method (Nor's or Loboda's) is being used. In Tables 2 and 3 E_c calculated by (6) and (7) is presented for all r_{ion_i} as well as the Aver(6) and Aver(7) values. Table 4 tabulates the results drawn by the implementation of (3), (4), (5), Aver(6) and Aver(7) on the experimental data.

Table 2: E_c (kV/m) calculated for different ionization radii by (6) and Aver(6).

Soil Sample	E_c (kV/m)				
	(6(r_{ion_1}))	(6(r_{ion_2}))	(6(r_{ion_3}))	(6(r_{ion_4}))	Aver(6)
I	3511	2418	4610	3417	3513
II	1424	2064	1404	1532	1631
III	1306	1777	1183	1236	1422

Table 3: E_c (kV/m) calculated for different ionization radii by (7) and Aver(7).

Soil Sample	E_c (kV/m)				
	(7(r_{ion_1}))	(7(r_{ion_2}))	(7(r_{ion_3}))	(7(r_{ion_4}))	Aver(7)
I	3511	5674	3204	3390	4130
II	1424	3381	1236	905	2014
III	1306	2397	1002	441	1568

Table 4: E_c (kV/m) calculated by (3), (4), (5), Aver(6) and Aver(7).

Equation	E_c (kV/m)		
	Soil I	Soil II	Soil III
(3)	1248	1117	874
(4)	2739	2529	2122
(5)	6920	4297	3443
Aver(6)	3513	1631	1422
Aver(7)	4130	2014	1568

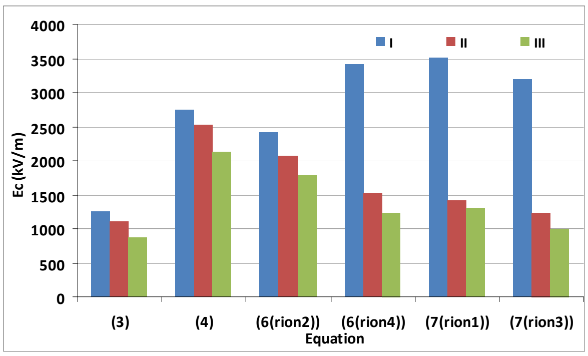

Figure 5: E_c derived by equations (3), (4), (6(r_{ion_2})), (6(r_{ion_4})), (7(r_{ion_1})) and (7(r_{ion_3})) for each soil type.

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As the moisture content increases, the E_c decreases, which is obvious in Figures 5 and 6. Comparing the results of the equations (3)-(7) it can be concluded that (5), which does not take into account the radius of the ionization area, gives the maximum values of E_c for all soil samples. On the other hand, (3) provides us with the lowest values of E_c. Also, it is noteworthy that as the moisture content increases, the values calculated by (3) and (4) do not present great variation between soil samples. In the cases, where the E_c is calculated by (5)-(7), the increase in the moisture causes E_c to decrease dramatically as it can be observed in Figures 5 and 6. Furthermore, when the ionization impedance (Z_{ion}) is estimated by (9), the soil critical electric field that derives from (6) is equal to E_c that derives from (7) (Tables 2 and 3 second column).

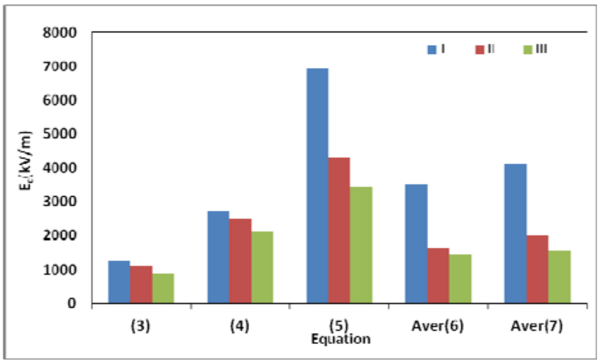

Figure 6: E_c derived by equations (3), (4), (5) Aver(6) and Aver (7) for each soil type.

5. CONCLUSION

Undoubtedly, the soil critical electric field (E_c) is of great importance for the performance of the grounding systems subjected to transient phenomena. However, the determination of its value has proved to be a difficult and multivariable problem. The results derived in this paper point out that the discrepancies in the definition of the ionization impedance influence the estimation of E_c. Therefore, further research and extensive experiments should be carried out using different soil types with various moisture levels so as for a standard method for the calculation of E_c to be determined.

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