Uncertainty of Soil Breakdown Voltage

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***Abstract*—Aim of this work is the analysis of the components of uncertainty and the estimation of the uncertainty regarding the determination of the breakdown voltage associated with the soil critical electric field. For that reason, series of measurements have been conducted by inducing impulse voltages to soil samples with different moisture content in order to determine the impact of the moisture content on the uncertainty of the breakdown voltage.**

I. INTRODUCTION

The purpose of any grounding system is to provide a minimum resistance path to the fault and impulse currents, while minimizing the damages to human beings and equipment. It is well known that the impulse behavior of any grounding system under impulse waveforms greatly differs from its steady state behavior. Moreover, it is well established that non–linear ionization phenomena develop around the grounding rod [1] - [14]. The critical parameter is the soil critical electric field (E_c). Up to this point, numerous attempts are presented aiming at estimating E_c and different values have been proposed. In [10]-[14] the voltage, above which ionization phenomena are developed, is connected to the breakdown voltage of the soil.

Taking these observations into consideration, experiments aiming at the determination of the breakdown voltage (U_{50}) according to HD 588.1 S1 [15] for soil samples with different moisture contents were conducted.

However, not only the value of U_{50} is of importance but also the uncertainty regarding this value. The uncertainty of the measuring procedure contributes to the validity / credibility of the experimental results and the experimental procedure. Many difficulties lie in the determination of those components which contribute to the uncertainty. However, it can be said that, the uncertainty regards mainly, the credibility of the measuring equipment, the experimental procedure and the ability of the person who conducts the experiments.

The rest of the paper is organized as follows: in paragraph II the experimental setup is described. In paragraph III some representative experimental results are presented, by which the breakdown voltage is determined. The components of uncertainty which influence its value are analyzed in paragraph IV. In the same paragraph, the overall uncertainties regarding U_{50} and time to breakdown (t_B) are for the first time in literature estimated. Finally, in paragraph V useful conclusions are drawn.

II. EXPERIMENTAL SET UP

In Figure 1 the experimental set-up for the determination of U_{50} according to HD 588.1 S1 [15] of the soil sample is presented. A 1.2/50μs positive impulse voltage is generated by a high impulse voltage generator with a charging capacity of up to 200kV, and energy of up to 3kJ. The main supply is regulated to a constant value of 230V±0.1% AC, 50Hz by means of a voltage stabilizer. The output voltage is measured by means of a voltage divider (with ratio 421:1) and a differential probe with attenuation ratio 100:1. Current measurement is obtained by using a current transformer with a 0.002A/V sensitivity. The signals are recorded by a two-channel 500MHz digital oscilloscope, which is placed in a Faraday cage with 50 dB signal attenuation up to 1GHz. A low pass filter and an insulating transformer shield the power supply from noise and disturbances. It must be mentioned that the calibration of the measuring equipment is conducted by accredited laboratories on a yearly basis.

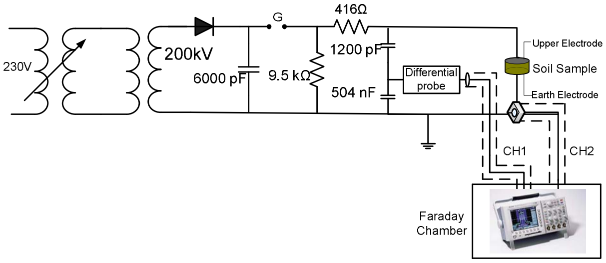

Figure 1. Experimental Set Up.

As far as the soil sample preparation concerns, the following procedure has been followed: the soil sample is sieved in order to become free of stones and other foreign materials. Then, it is dried in an oven. Deionised water is then added and carefully mixed with the soil in order for a specified moisture content (0%, 5% and 10% by weight) to be achieved. The resistivities of the soil samples were measured at 3000Ωm, 1800Ωm and 900Ωm respectively. The soil sample is placed in a PVC cylinder of 7cm in height and 14cm in

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diameter between parallel plates and is compacted with a weight of 20kg.

III. BREAKDOWN VOLTAGE

Impulse tests with positive polarity were carried out for voltage amplitudes up to 200kV for dry and wet soil samples by using the experimental set-up of Fig. 1. The breakdown level was estimated by applying the up and down method according to [15]. Therefore, 10 shots were applied to each soil sample. The voltage is increased stepwise until the breakdown of the spark gap G of the generator (Fig. 1). The breakdown in the sample occurs when the current increases rapidly while the voltage decreases. Whenever breakdown of the soil sample did not occur, the distance between the electrodes of the spark gap (G) was increased (resulting in higher impulse voltage) until the oscillograms indicated the presence of soil breakdown.

Figs. 2-4 show voltage (CH1, blue line) and current (CH2, red line) traces when breakdown occurred in soil with 0%, 5% and 10% water content. Due to the high resistivity of the dry soil sample, conduction current can only be detected once breakdown occurs. As the moisture content of the sample increases, the resistivity decreases and the conduction currents present higher values. Also, as the breakdown voltage increases (dry soil sample presents the higher breakdown voltage) the time to breakdown (t_B) decreases. Thus, the drier the soil, the earlier the breakdown occurs.

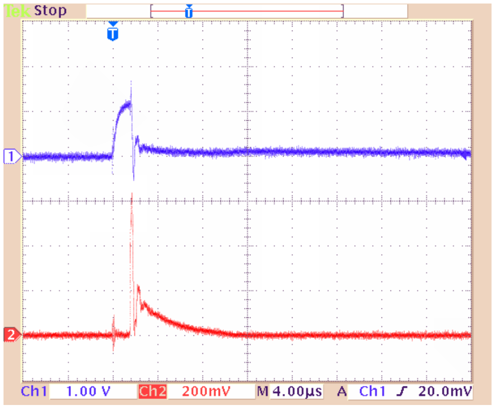

Figure 2. Typical voltage and current traces during breakdown in dry soil.

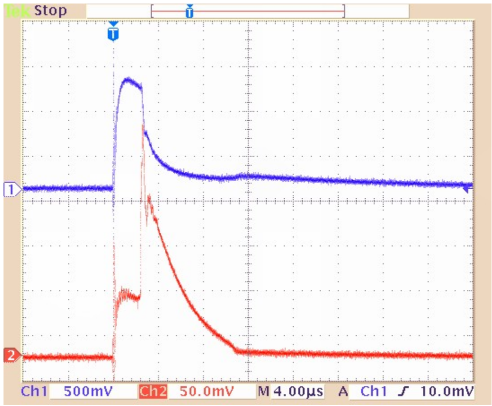

Figure 3. Typical voltage and current traces during breakdown in soil with a water content of 5%.

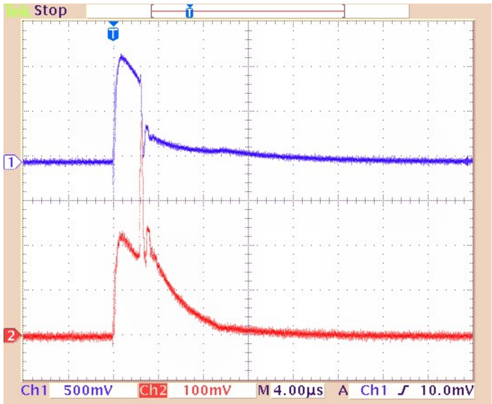

Figure 4. Typical voltage and current traces during breakdown in soil with a water content of 10%.

IV. UNCERTAINTY

According to [16] uncertainty is a statement of the limits of a range of values within which the true value of the measurement is expected to lie in relation to the recorded results and the probability of the true values lying within these limits.

The uncertainty of measurement is comprised of many components. Some of these components can be evaluated from the statistical distribution of series of measurements and can be characterized by experimental standard deviations. Other components, which can also be characterized by standard deviation, are evaluated from assumed probability distribution based on the experience, calibration certificates, and characteristics of the experimental equipment or other information.

A. Random Contributions (Type A)

Random contributions (U_r) derive from the statistical analysis of the series of measurements. For the computation of random uncertainty of a small number of measurements (1) is being used [16]:

$$U_r = \frac{t \cdot s_r}{\sqrt{n}} \tag{1}$$

where n is the number of measurements, n=5 in our case,
t is the Student's factor selected according to the required confidence level (for a 95% confidence level and n=5 measurements t =2.78),
s_r is the standard deviation given by (2)

$$s_r = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(u_i - \bar{u})^2} \tag{2}$$

where u_i is the measured value, $\bar{u}$ is the mean of the measured values and n is the number of measurements.

The random uncertainty expressed as a percentage ($U_{r\%}$) is calculated by (3):

$$U_{r\%} = \frac{s_r}{\sqrt{n}} \cdot \frac{100}{\bar{u}} \tag{3}$$

where n is the number of measurements, s_r is the standard deviation, $\bar{u}$ is the mean of the measured values.

In Table I the values of the breakdown voltage and the time to breakdown are presented. As it can be observed, higher values of U_{50} are recorded as the water content decreases. On the same tables the values of U_r for a confidence level not less that 95% are given.

TABLE I. RANDOM UNCERTAINTY OF BREAKDOWN VOLTAGE AND TIME TO BREAKDOWN

	0%		**5%**		**10%**	
	U_{50} [kV]	t_B [usec]	U_{50} [kV]	t_B [usec]	U_{50} [kV]	t_B [usec]
1	49.7	2.2	49.4	2.0	44.0	1.6
2	48.4	3.1	47.7	2.4	42.3	1.8
3	49.8	3.2	45.0	2.8	38.6	2.3
4	48.6	3.1	47.3	2.4	38.9	2.2
5	49.7	2.0	42.7	3.5	39.6	2.2
$\bar{u}$	49.3	2.7	46.4	2.6	40.7	2.0
s_r	0.7	0.6	2.6	0.5	2.4	0.3
U_r	0.9	0.7	3.2	0.7	2.9	0.4
$U_{r\%}$	0.6%	9.4%	2.5%	9.3%	2.6%	6.5%

B. *Systematic contributions (Type B)*

Systematic contributions (U_s) are evaluated by other means such as calibration certificates, characteristics of the measurement equipment, experience of the personnel carrying out the measurements or other information. It is possible that some systematic contributions have a rectangular (s_{sa}), while others have Gaussian probability distribution (s_{sg}). The overall standard deviation for all systematic contributions is given by:

$$s_s = \sqrt{s_{sa}^2 + s_{sg}^2} \tag{4}$$

where s_{sa} is the standard deviation of the rectangular distribution, s_{sg} is the standard deviation of the Gaussian distribution.

In Tables II and III the contribution of the uncertainty components as well as the probability distributions for U_{50}, and t_B are presented. The expanded systematic uncertainty is given for a confidence level not less than 95%. For that reason the divisor factor equals 2. The uncertainty regarding voltage measurement accuracy, voltage linearity, bandwidth of the oscilloscope, as well as, bandwidth of the differential probe derive from the calibration certificates of the equipment and is given with a confidence level of 95%. Therefore, it is assumed to have a Gaussian distribution and the respective divisor factor is selected equal to 2. The uncertainty of the resolution of the oscilloscope comprises of the half digit for zero and last digit for reading. According to the oscilloscope's manual [18] these parameters are equal to 0.031%. Therefore the uncertainty of oscilloscope's resolution is taken equal to 0.062% with a rectangular probability distribution (divisor factor equals $\sqrt{3}$), since there is no indication of confidence level [18], [19].

TABLE II. SYSTEMATIC UNCERTAINTY OF U_{50}

Contribution	**Value %**	**Probability Distribution**	**Divisor**	s_i	s_i^2
Resolution of the oscilloscope	0.062	Rectangular	$\sqrt{3}$	0.036	0.0013
Voltage measurement accuracy	0.085	Normal	2	0.043	0.0018
Voltage linearity	0.036	Normal	2	0.018	0.0003
				s_s	$\sum s_i^2$
Combined Standard Uncertainty		Normal		0.058	0.0034
Expanded Systematic Uncertainty (U_s)		Normal	2	0.117	

TABLE III. SYSTEMATIC UNCERTAINTY OF TIME TO BREAKDOWN

Contribution	**Value %**	**Probability Distribution**	**Divisor**	s_i	s_i^2
Resolution of the oscilloscope	0.062	Rectangular	$\sqrt{3}$	0.036	0.0013
Horizontal resolution of the oscilloscope	0.167	Rectangular	$\sqrt{3}$	0.096	0.0093
Voltage measurement accuracy	0.085	Normal	2	0.043	0.0018
Bandwidth of the oscilloscope	0.290	Normal	2	0.145	0.0210
Bandwidth of the voltage divider and the differential probe	0.112	Normal	2	0.056	0.0031
				s_s	$\sum s_i^2$
Combined Standard Uncertainty		Normal		0.191	0.0365
Expanded Systematic Uncertainty (U_s)		Normal	2	0.382	

The overall uncertainty (U) is obtained as a combination of the systematic and random contributions, described in Tables II and III, and the estimated values of U for each soil sample are presented in Table IV. It can be observed that as the water content increases the uncertainty in voltage also increases. On the other hand, the uncertainty of t_B decreases as the water content increases. Also, we should mention that for all soil samples the uncertainty of t_B is higher than the uncertainty of the breakdown voltage.

In Fig. 5 the values of U_{50} for the three soil samples along with their respective overall uncertainty are depicted. In the same figure the mean values of breakdown voltage for each soil sample is shown in dashed lines.

In Fig. 6 the values of the t_B for each soil sample are presented along with their uncertainty. It can be easily noticed that the values of t_B present wide dispersion for each soil sample. As already reported by many authors [14], [15], the time to breakdown presents a wide dispersion, therefore the random uncertainty is highly contributing to higher values of overall uncertainty.

TABLE IV. OVERALL UNCERTAINTY OF BREAKDOWN VOLTAGE AND TIME TO BREAKDOWN

	U_s (%)	$U_{r\%}$ (%)			U (%)		
		0%	5%	10%	0%	5%	10%
U_{50}	0.117	0.6	2.5	2.6	0.64	2.51	2.61
t_B	0.382	9.4	9.3	6.5	9.43	9.31	6.54

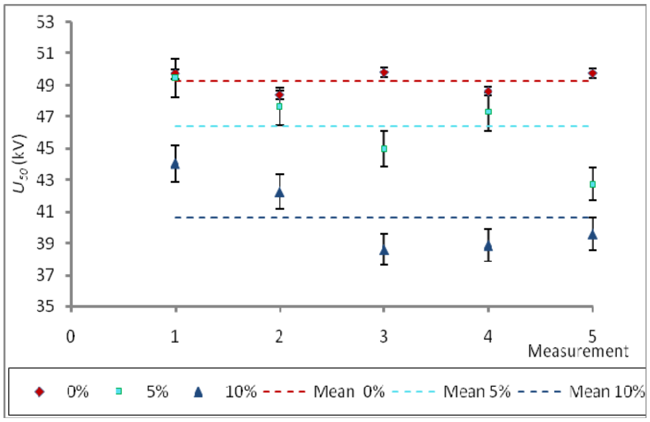

Figure 5. Breakdown voltage values along with their respective uncertainty for soil samples with various water contents.

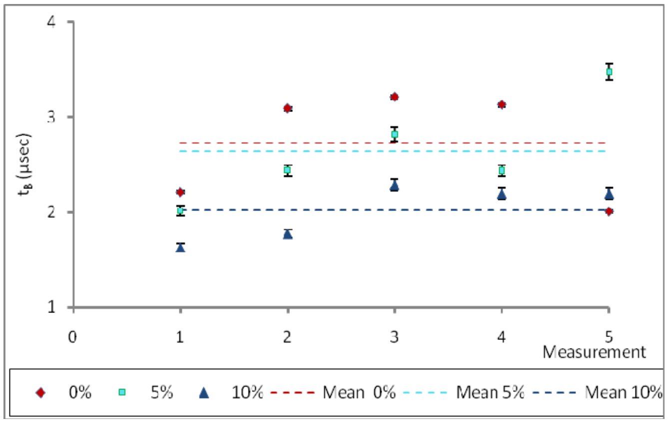

Figure 6. Time to breakdown values along with their respective uncertainty for soil samples with various water contents.

V. CONCLUSIONS

In this paper, the components of uncertainty regarding breakdown voltage and time to breakdown of soil samples under positive impulse currents were studied. More specifically, the parameters contributing to systematic uncertainty were analyzed and their influence has been evaluated, while the random uncertainty was estimated by using experimental results. Combining these two types of uncertainty the overall uncertainties of these parameters were calculated. It is concluded that the uncertainty of the breakdown voltage is lower than the uncertainty of the time to breakdown. Moreover, the water content of the soil influences the uncertainty. This paper focuses on the variation of the uncertainty in measurements concerning the breakdown procedure and highlights the need for using different E_c value-relevant to the specific soil sample, in which the grounding system is buried, since ionization phenomena influence the transient impedance of the grounding system. Thus, in simulating and designing a grounding system the uncertainty level accompanying the E_c value should be taken into consideration, since it affects the calculations regarding the performance of the grounding system (developed step and touch voltages).

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