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Published in IET Science, Measurement and Technology
Received on 1st March 2010
Revised on 5th July 2010
doi: 10.1049/iet-smt.2010.0021

ISSN 1751-8822

Estimation of uncertainty regarding soil breakdown parameters

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Abstract: The behaviour of a grounding system under fault currents differs from its steady-state behaviour. It has been observed that, when a high impulse current is injected into the grounding system, its impulse impedance drops because of the ionisation phenomenon. The critical parameter for the ionisation phenomenon is the soil critical electric field, which corresponds to the electric field threshold above which the soil ionisation occurs. In bibliography various attempts have been made aiming at its estimation. However, a physical quantity is determined not only by its value, but also by an estimation of the uncertainty. The 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. Therefore a series of measurements has been conducted by subjecting dry and wet soil samples to impulse voltages, while recording the voltage and the current. Based on these measurements the random uncertainty is calculated while an estimation of the systematic uncertainty is given taking into account the measuring equipment.

1 Introduction

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

It is known that the impulse behaviour of the grounding system differs from the behaviour at mains frequency. When the electric field in the soil around the grounding system exceeds the soil critical electric field (E_c), soil breakdown occurs and the soil resistivity of the affected section of soil decreases, resulting in decrease of impulse impedance [1]. Thus, the soil critical electric field is a fundamental parameter for the investigation of the impulse behaviour of grounding systems.

Various values for E_c have been proposed by numerous researchers. In the experiments conducted by Towne [1] E_c ranges between 160 and 520 kV/m. Bellaschi [2] and Bellaschi *et al.* [3] calculated E_c in the range of 120–420 kV/m. In 1974, Liew and Darveniza [4] used a value of 300 kV/m for E_c. Loboda and Pochanke [5] and Loboda and Scuka [6] investigated the electrical properties of different soils when current pulses are injected into the grounding system and calculated the E_c between 560 and 900 kV/m. In impulse tests on several types of soil, conducted by Oettle [7], E_c varied in the range of 600–1850 kV/m. The value of 400 kV/m is used by CIGRE [8]. Mousa [9] suggested that 300 kV/m should be used for E_c. Gonos and Stathopulos [10] studied the variation of E_c against the soil resistivity. Moreover, E_c was estimated 200 kV/m for wet soil samples. Nor *et al.* [11, 12] and Nor and Ramli [13, 14] 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 influence of the field uniformity on the value of E_c has also been investigated by Lima and Visacro [15].

This diversity of the E_c values indicates that the determination of E_c engages the scientific community while the research is inconclusive, deeming necessary the conduct of experiments for various soil samples. The experiments aim at measuring the voltage, above which breakdown of the soil occurs. This voltage is characterised as the breakdown voltage ($U_{50\%}$) and the procedure for its determination is defined in IEC 60060-1 [16]. However, the experimental measurements are characterised not only by their values, but also by an uncertainty factor. The uncertainty of the measuring procedure is of great importance since it contributes to the validity/credibility of the experimental results and the experimental procedure. The uncertainty regards the credibility of the measuring equipment, the experimental procedure and the ability of the person who conducts the experiments. Many difficulties lie in the determination of those components which contribute to the uncertainty. As far as the uncertainty of soil breakdown regards, no attempt has been made until now to this direction.

The majority of researchers [10–15, 17–19], dealing with breakdown voltage of soil, conduct experiments by using soil samples. This is, partly, because of the difficulties that arise when conducting full-scale experiments such as the variation of the ambient conditions (temperature, humidity etc.) while conducting experiments in the field, the fact that full-scale experiments are equipment- and cost demanding etc. On the other hand, laboratory tests are conducted under controlled conditions. Therefore this approach has been followed in the present paper. However, Chen and Chowdhury [20] and He *et al.* [21] have conducted field (full-scale) and laboratory experiments and have correlated successfully the results derived by both methods. It should be mentioned, although, that the procedure proposed in this paper can be implemented on full-scale experiments and similar estimation can be conducted, on condition that calibration certificates of the experimental equipment are provided.

The aim of this paper is the analysis of the components of uncertainty which influence the value of the breakdown voltage. Furthermore, the uncertainty of parameters that derive from the oscillograms is estimated. These parameters include the peak current (I_{peak}), the time to breakdown ($t_{U50\%}$) and the time of peak current ($t_{I\text{peak}}$). Thus, it is necessary, for the values of interest to be accompanied by an estimation of the uncertainty, so as for the results to be reliable and utilisable. For that reason, series of impulse measurements have been conducted by using dry and wet soil samples as described in Section 2. Following, the breakdown voltage is estimated in Section 3 as well as the random uncertainty in Section 4. Then, the parameters contributing to the systematic uncertainty are investigated. Subsequently, the overall uncertainty is estimated, while in Section 5 useful conclusions are drawn.

2 Measurement setup

In Fig. 1 the experimental setup for the determination of $U_{50\%}$ according to IEC 60060-1 [16] of the soil sample is presented. A 1.2/50 μs positive impulse voltage is generated by a high impulse generator with charging capacity of up to 200 kV and energy of up to 3 kJ. The main supply is regulated to a constant value of 230 V ± 0.1% AC, 50 Hz by means of a voltage stabiliser. 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 current transformer with 0.002 A/V sensitivity. The signals are recorded by 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 isolating transformer shield the power supply from noise and disturbances. It must be mentioned that calibration of the measuring equipment is conducted by accredited laboratories on a yearly basis.

The soil sample being used in the laboratory experiments is sieved in order to become free of stones and other foreign materials. Then the soil is dried in an oven (at 105°C) for several days. Before being used for the experiment, the soil is cooled at room temperature. Deionised water is then added and carefully mixed with the soil in order for a specified moisture content (0 and 5% by weight in our case) to be achieved. The soil sample is placed in a PVC cylinder of 7 cm in height and 14 cm in diameter between parallel plates and is compacted with a weight of 20 kg.

3 Breakdown voltage

Impulse tests with positive polarity were carried out for voltage amplitudes up to 200 kV for dry and wet soil samples by using the experimental setup of Fig. 1. The breakdown level was estimated by applying the up and down method according to [16]. Therefore 12 shots were applied to each soil sample. The voltage is increased stepwise until the breakdown of the gap G. 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 and 3 show typical voltage (Ch1) and current (Ch2) waveforms during the breakdown of dry and wet soil samples. Some initial oscillations are observed. Similar oscillations have been recorded by Nor and Ramli [13] and are attributed to the capacitive effects of small air gaps between soil grains and the interface between the soil and the electrode. Soil critical electric field E_c is computed by

$$E_c = \frac{U_{50\%}}{d} \tag{1}$$

where $U_{50\%}$ is the breakdown voltage determined by the up and down method according to IEC 60-1 [16] in kV and d is the distance between the parallel plates in cm.

4 Uncertainty

According to [22], 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.

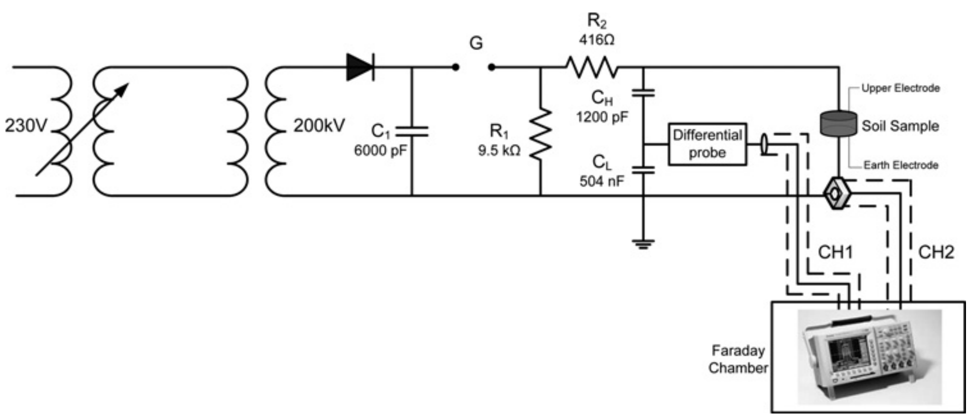

Fig. 1 *Experimental setup*

doi: 10.1049/iet-smt.2010.0021

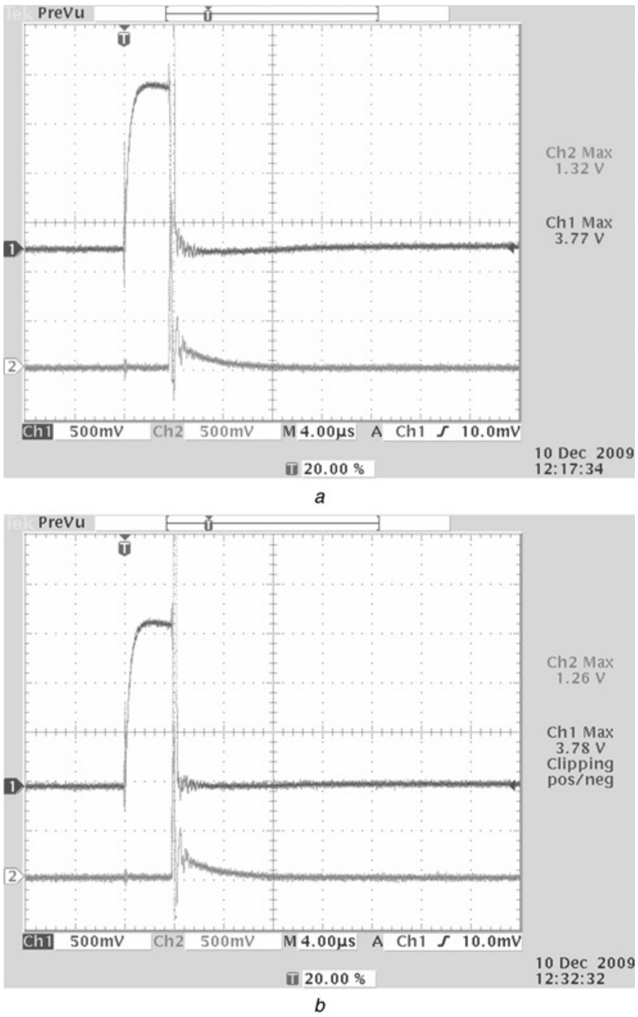

Fig. 2 *a, b Two typical voltage (Ch1) and current (Ch2) waveforms for dry soil*

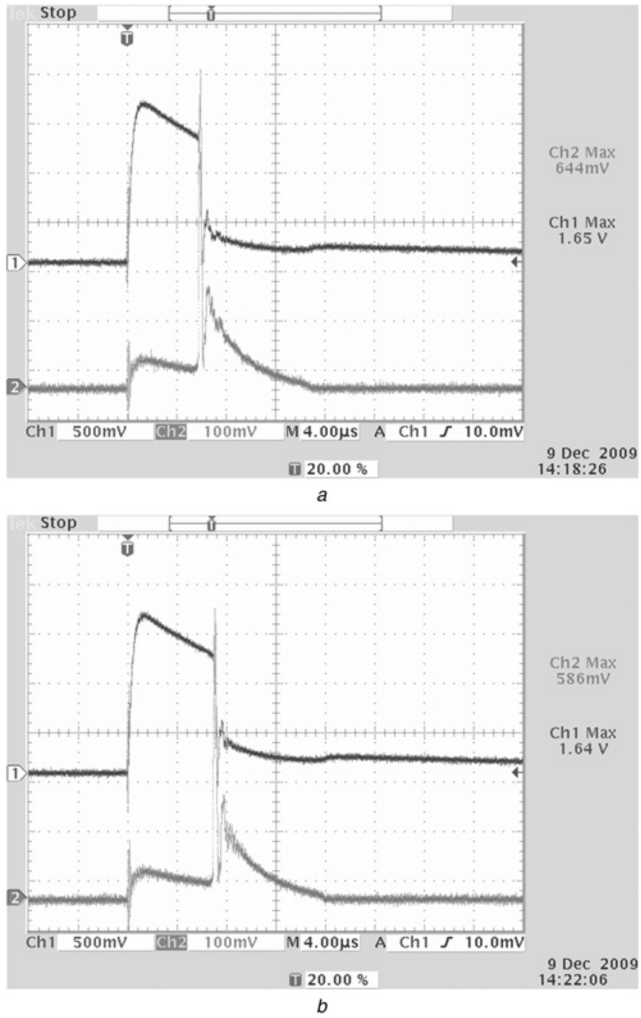

Fig. 3 *a, b Two typical voltage (Ch1) and current (Ch2) waveforms for wet soil*

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 characterised by experimental standard deviations. Other components, which can also be characterised by standard deviation, are evaluated from assumed probability distribution based on the experience or other information.

4.1 Uncertainty 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 values (2) is being used [22]

$$U_r = \frac{ts_r}{\sqrt{n}} \tag{2}$$

where t is the Student's factor selected according to the required confidence level (for a 95% confidence level and 6 measurements, $t = 2.57$)

$$s_r = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(u_i - \overline{u})^2} \tag{3}$$

where u_i is the measured value, $\overline{u}$ is the mean of the measured values and n is the number of measurements, $n = 6$ in our case.

The random uncertainty expressed as a percentage ($U_{r\%}$) is calculated by (4)

$$U_{r\%} = \frac{s_r}{\sqrt{n}}\frac{100}{\overline{u}} \tag{4}$$

where n is the number of measurements, s_r is the standard deviation and $\overline{u}$ is the mean of the measured values ($n = 6$ in our case).

The overall uncertainty (U) is obtained as a combination of several systematic and random contributions. In Tables 1 and 2 the values of the breakdown voltage, the peak current and the times corresponding to their appearance are presented. On the same tables, the values of U_r for a confidence level not less that 95% are presented.

As it can be easily observed, voltage presents high repeatability. More specifically, the uncertainty of voltage for dry soil sample is smaller than the voltage uncertainty for wet soil sample. However, this is not the case for the uncertainty of current and time.

doi: 10.1049/iet-smt.2010.0021

Table 1 Values of $U_{50\%}$, $t_{U50\%}$, I_{peak} and t_{Ipeak} for dry soil

Measurement	$U_{50\%}$, kV	$t_{U50\%}$, μs	I_{peak}, A	t_{Ipeak}, μs
1	68.92	3.63	0.61	3.80
2	69.06	2.44	0.65	2.64
3	69.28	2.95	0.66	3.12
4	69.53	3.17	0.60	3.97
5	67.32	3.48	0.62	3.64
6	68.97	2.16	0.66	2.37
$\bar{u}$	68.85	2.97	0.63	3.26
s_r	0.781	0.579	0.027	0.652
U_r	0.820	0.608	0.028	0.684
$U_{r\%}$	0.463%	7.957%	1.720%	8.166%

Table 2 Values of $U_{50\%}$, $t_{U50\%}$, I_{peak} and t_{Ipeak} for wet soil

Measurement	$U_{50\%}$, kV	$t_{U50\%}$, μs	I_{peak}, A	t_{Ipeak}, μs
1	47.97	7.44	0.23	7.60
2	61.66	2.78	0.39	3.02
3	54.19	5.60	0.31	5.95
4	50.86	6.73	0.28	7.11
5	57.54	4.28	0.25	4.63
6	49.80	7.20	0.27	7.71
$\bar{u}$	53.67	5.67	0.29	6.00
s_r	5.185	1.837	0.056	1.870
U_r	5.440	1.927	0.059	1.962
$U_{r\%}$	3.944%	13.225%	8.005%	12.719%

4.2 Uncertainty Type B

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

$$s_s = \sqrt{s_{sa}^2 + s_{sg}^2} \tag{5}$$

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

Type B uncertainty is calculated by applying the normal distribution factor (divisor) on the estimated standard deviation.

In Tables 3–6 the contribution of the uncertainty components as well as the probability distributions for $U_{50\%}$, $t_{U50\%}$, I_{peak} and t_{Ipeak} 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, bandwidth of the differential probe, amplitude error and droop rate of the current probe is derived from calibration certificates of the equipment and is given with a confidence level of 95%.

Table 3 Expanded systematic uncertainty for $U_{50\%}$

	Contribution	Value %	Probability distribution	Divisor	s_i	s_i^2
1	resolution of the oscilloscope	0.062	rectangular	$\sqrt{3}$	0.036	0.0013
2	voltage measurement accuracy	0.085	normal	2	0.043	0.0018
3	voltage linearity verification	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 4 Expanded systematic uncertainty for the $t_{U50\%}$

	Contribution	Value %	Probability distribution	Divisor	s_i	s_i^2
1	resolution of the oscilloscope	0.062	rectangular	$\sqrt{3}$	0.036	0.0013
2	horizontal resolution of the oscilloscope	0.167	rectangular	$\sqrt{3}$	0.096	0.0093
3	voltage measurement accuracy	0.085	normal	2	0.043	0.0018
4	bandwidth of the oscilloscope	0.290	normal	2	0.145	0.0210
5	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	

Table 5 Expanded systematic uncertainty for I_{peak}

	Contribution	Value %	Probability distribution	Divisor	s_i	s_i^2
1	resolution of the oscilloscope	0.062	rectangular	$\sqrt{3}$	0.036	0.0013
2	voltage measurement accuracy	0.085	normal	2	0.043	0.0018
3	amplitude error of the current probe	0.130	normal	2	0.065	0.0042
					s_s	$\sum s_i^2$
	combined standard uncertainty		normal		0.086	0.0073
	expanded systematic uncertainty (U_s)		normal	2	0.171	

Table 6 Expanded systematic uncertainty for the t_{Ipeak}

	Contribution	Value %	Probability distribution	Divisor	s_i	s_i^2
1	resolution of the oscilloscope	0.062	rectangular	$\sqrt{3}$	0.036	0.0013
2	horizontal resolution of the oscilloscope	0.111	rectangular	$\sqrt{3}$	0.064	0.0041
3	voltage measurement accuracy	0.085	normal	2	0.043	0.0018
4	bandwidth of the oscilloscope	0.290	normal	2	0.145	0.0210
5	droop rate	0.00096	normal	2	0.00048	2.3×10^{-7}
					s_s	$\sum s_i^2$
	combined standard uncertainty		normal		0.168	0.0282
	expanded systematic uncertainty (U_s)		normal	2	0.336	

Therefore 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 [23] 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, since there is no indication of confidence level [23, 24].

4.3 Overall uncertainty – discussion

In Table 7 the overall uncertainties for $U_{50\%}$, $t_{U50\%}$, I_{peak} and t_{Ipeak} for each soil sample are presented. Since the same experimental equipment has been used for impulse tests on dry and wet soil samples the systematic uncertainty is the same for both cases. $U_{50\%}$ for dry soil sample is 68.9 kV with an uncertainty of $\pm 0.5\%$ for a confidence level not less than 95% and the breakdown voltage for wet soil sample is 53.7 kV with an uncertainty of $\pm 4\%$ for a confidence level not less than 95%. Equation (1) gives the values of E_c for each soil sample (984 and 767 kV/m for dry and wet soils, respectively).

From these results it can be concluded that as the water content of soil sample increases E_c decreases. This is in accordance with the finding of other researchers [10–15, 17, 18]. Moreover, although E_c is higher than the values adopted by CIGRE [8], its value falls in the range of measurements carried out by other researchers [15, 18].

However, for the estimation of the uncertainty of E_c not only the uncertainty of $U_{50\%}$, but also the uncertainty regarding the distance between the two parallel plates has to be taken into consideration. Considering that voltage and distance are uncorrelated parameters, the law of propagation of uncertainty given by (6) can be used for the estimation of the standard combined uncertainty of E_c [24]

$$U_{E_c} = \frac{U_{50\%}}{d}\sqrt{\frac{U_{U_{50\%}}^2}{U_{50\%}^2} + \frac{U_d^2}{d^2}} \qquad (6)$$

where U_{E_c} is the uncertainty of the critical electric field in kV/m, $U_{50\%}$ is the voltage in kV, d is the distance between the plates in m, $U_{U_{50\%}}$ is the uncertainty of the breakdown voltage in kV and U_d is the uncertainty of distance between the plates in m.

For the breakdown voltages determined above, a distance of 7 cm between the plates and 2 mm uncertainty of the distance, the uncertainty of E_c is 31 and 64 kV/m for dry and wet soil samples, respectively.

As far as the time parameters concerns, the uncertainty is very high. This can be attributed to the statistical character of the ionisation phenomenon and the unknown stochastic procedures that take place in the soil sample during the shot. Moreover, by comparing the uncertainty results between dry and wet soil samples, it can be concluded that as the moisture content of the soil samples increases, the uncertainty of the parameters also increases. The fact that the sample is not being replaced after each impulse is imposed may affect the composition of the sample, since a percentage of the water may evaporate because of thermal processes developing into the soil. It is possible that replacing the sample after every shot could eliminate this

Table 7 Overall uncertainty for dry and wet soil samples

	U_s, %	U_r, %		U, %	
		Dry	Wet	Dry	Wet
$U_{50\%}$	0.117	0.463	3.944	0.5	4.0
$t_{U50\%}$	0.382	7.957	13.225	8.0	13.3
I_{peak}	0.171	1.720	8.005	1.7	8.0
t_{Ipeak}	0.336	8.166	12.719	8.2	12.7

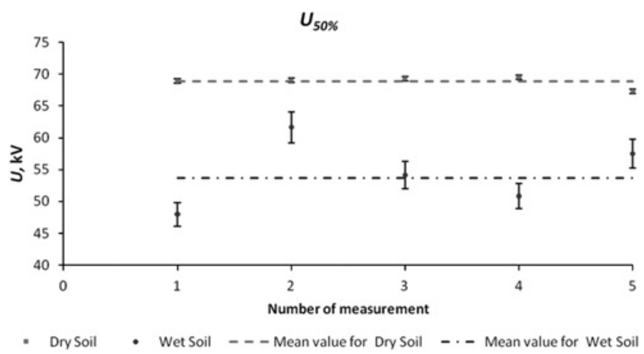

Fig. 4 *Voltage breakdown values along with their uncertainty for dry and wet soil samples*

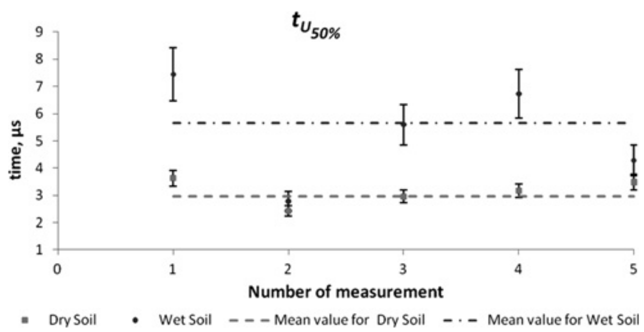

Fig. 5 *Time to breakdown values along with their uncertainty for dry and wet soil samples*

IET Sci. Meas. Technol., 2011, Vol. 5, Iss. 1, pp. 14–20
doi: 10.1049/iet-smt.2010.0021

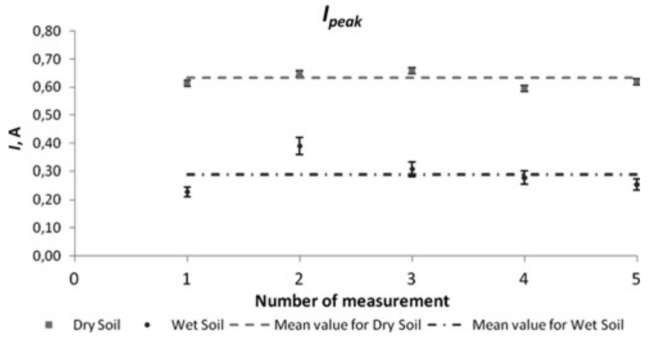

Fig. 6 *Peak current values along with their uncertainty for dry and wet soil samples*

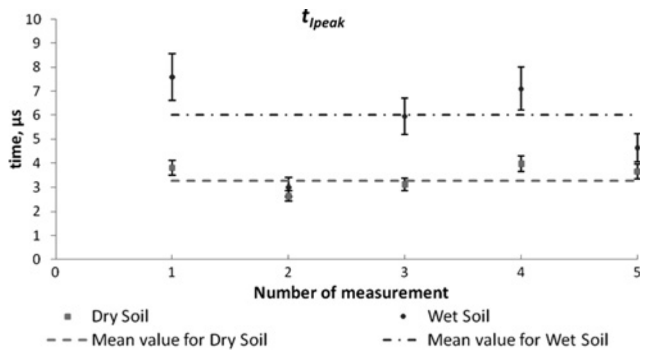

Fig. 7 *Time of peak current values along with their uncertainty for dry and wet soil samples*

effect; however, in that case the distribution of the soil particles would also change.

In Figs. 4–7 the experimental values, the corresponding uncertainty and the mean value of the $U_{50\%}$, $t_{U50\%}$, $I_{\rm peak}$ and $t_{I\rm peak}$ are presented.

The procedure described in this paper can be implemented on more experimental values. However, one has to have in mind that after every shot the soil temperature increases and the moisture content changes. Therefore an infinite number of shots, which would result in decreased levels of uncertainty, changes the properties and the composition of the soil sample under test and therefore the results can be compromised. Moreover, various researchers [17–19] have proposed that at least ten shots (in five of them breakdown occurs) are adequate for the determination of breakdown voltage.

5 Conclusions

Impulse tests were conducted on dry and wet soil samples placed on a parallel plate's configuration and the corresponding voltage and current were measured. Objective of the paper was the determination of the parameters that influence the uncertainty regarding the voltage and current measurements. The systematic uncertainty ($U_{\rm s}$) was evaluated taking into account the experimental equipment, while for the estimation of the random uncertainty ($U_{\rm r}$) the repeatability of the experimental procedure was evaluated. The results indicate that $U_{50\%}$ presents satisfactory repeatability. The overall uncertainty (U) for dry soil sample is smaller than that for wet soil sample. This result can be attributed to the distribution of the water, which is possible to be non-uniform. During the experiments on wet soil, the soil is heated leading to vapourisation of the contained water, and consequently to different water distribution.

Moreover, for each soil sample, the voltage presented smaller uncertainty than the current, which in turn was smaller than the uncertainty of time. As regards the determination of $E_{\rm c}$, (1) is used. Nevertheless, for the estimation of the uncertainty accompanying the measurement, the law of propagation of uncertainty is to be used. For such a simple configuration as the parallel plates, this includes the uncertainty regarding the distance between the plates, which can be calculated by (6). However, for cylindrical and hemispherical configurations not only the uncertainty of the geometrical characteristics of the containers but also the uncertainty of the estimation of the area in which the ionisation processes are developed, should also be taken into consideration.

Consequently, the determination of the uncertainty regarding soil breakdown is of great importance, since it pays creditability on the results and makes them utilisable. Furthermore, the knowledge of the uncertainty allows a review of the experimental results and leads to improvements of the experimental procedure. In this paper, an estimation of the components of uncertainty regarding the parameters of soil samples breakdown when subjected to positive impulse currents was presented. The parameters contributing to systematic uncertainty were analysed and their contribution has been evaluated. Hence, this paper underlines the importance of uncertainty in measurements and contributes to the credibility of the measurements of voltage, current and time regarding the breakdown procedure.

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