UNCERTAINTIES CALCULATION OF REAL ELECTROSTATIC DISCHARGE CURRENT MEASUREMENTS

P. S. Katsivelis, G. N. Psarros, I. F. Gonos and I. A. Stathopulos

High Voltage Laboratory, School of Electrical and Computer Engineering,
National Technical University of Athens
E-mail: pkatsivelis@gmail.com

Abstract. Electrostatic Discharge (ESD) typical current waveform and parameters are defined by the related Standards. As more experiments, concerning real human ESD events, are carried out, new findings occur which can be used to re-evaluate such standardizations. However, such measuring procedures are very demanding. Specific equipment and proof of the measurement quality are needed. In this work we introduce a method for calculating the uncertainties of real human-to-metal ESD current measurements, by considering not only all available equipment data, but also experimental data and certain uncertainty sources which are considered to undermine the measurement accuracy. This method is presented here, through an application for the case of the procedure followed by our accredited laboratory, for human ESD current measurements.

1   INTRODUCTION

The electrostatic discharge (ESD) phenomenon is a very complex one and has many parameters to be dealt with. An effort to systematize the approach towards certain types of electrostatic discharges has been taking place for years [1, 2]. The EN 61000-4-2:2009 Standard [2] has well defined the values of crucial parameters of the electrostatic discharge current with respect to the human body model. There is an ongoing debate on whether these values are representative of a real ESD event or not. More measurements of crucial parameters are needed, in order to achieve a better approach to the phenomenon.

Researchers have been carrying out measurements on real ESD events [3-8], in order to quantify the parameters of the human ESD current. New proposals for parameter values should be consistent with these findings. However, while performing such measurements, it is important to use such kind of equipment that meets, at least, the requirements of EN 61000-4-2:2009, in order to claim that the results are acceptable and usable in conclusions and suggestions. This implies, appropriate oscilloscope and measuring system (bandwidth should be at least 2GHz), Faraday cage, and of course calibrated equipment. However, the wide frequency content of the ESD phenomenon, the stiffness of the ESD current waveforms, and the inherent difficulty in the repeatability of the real ESD measurements, make it necessary to provide proof of the measurements' quality. Thus, it is important to be able to calculate the uncertainties, and, of course, restrain them within narrow limits.

The EN 61000-4-2:2009 Standard describes, among other, the typical ESD current waveform, which ESD generators should comply with. Except for the values of certain parameters of the ESD current waveform, the last version of [2] contains instructions on the computation of the uncertainties for the ESD generators calibration. Furthermore, the United Kingdom Accreditation Service (UKAS) Publication M3003 [9] contains extended instructions on the calculation of the uncertainties of measurements. However, no similar procedure is determined or even described

from a certified principle or a research group for the cases of real human-to-metal ESD events. No specific way of calculating and handling the uncertainties of the real ESD measurements is available at this time.

Treating [9] as reference, and considering the specialties of real human ESD experiments, a method for calculating the related uncertainties is presented in this work. The uncertainties calculation method is applied on the case of the equipment and measuring procedure of the accredited High Voltage Laboratory (HVLab) of the National Technical University of Athens (NTUA), concerning discharge events of human subjects under charging voltage of 2 kV.
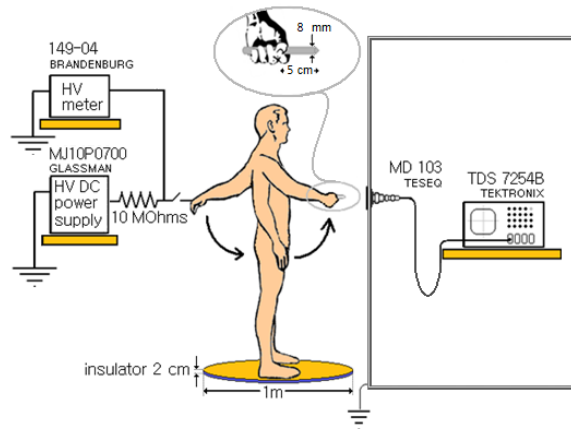
2   MEASUREMENTS

2.1   Test Setup

The equipment used in this work, fulfils the demands set by the EN 61000-4-2:2009 [2]. Due to the wide frequency content of the human ESD phenomenon, the related equipment should present the highest bandwidth possible. Thus, the Standard [2], demands that it is no less than 2 GHz.

The measuring equipment employed here is a TDS 7254B Tektronix oscilloscope (BW 2.5 GHz) and an MD 103 TESEQ calibrating system (coaxial target, attenuator, coaxial cable) calibrated up to 6 GHz. In order to charge the human body, a Glassman MJ20P0700 high voltage power supply and a 10 MOhms high voltage resistance were used. The measurement of the charging voltage was made using a Brendenburg HV meter (model 149-04). In figure 1, the set up is presented.

2.2   Measuring process

Eleven randomly selected individuals took part in our experiment. The measurements conducted aimed at calculating both the repeatability (uncertainty of the series of measurements of one person) and the reproducibility (uncertainty of measurements carried out using a different subject each time) of the measurements. We performed ten



Figure 1. The experimental set-up.

measurements using a single individual, and ten more measurements using a different individual, of the remaining ten, each time.

The subjects were exposed to 2 kV voltage for a time interval not shorter than 2 sec. Afterwards, each one of them would release the power supply probe and quickly approach the target with a metal rod, as seen in figure 1. This is the moment when the ESD takes place. The current signal was, then, recorded by the oscilloscope.
In our experiment, a high speed scenario is being simulated at all times. Speed of approach is kept constant at about 20-25 cm/s. This is to assure that minimum variations between arc lengths are going to take place, in order to affect the uncertainty values of the arc-related current parameters (I_p, t_r) [10, 11] as little as possible. Our results confirm this presumption.

2.3   Results

The ten recorded waveforms of the first individual, are shown together in figure 2. The fact that the experiment was conducted in the laboratory, where the individual was allowed to go through the charging and discharging process repeatedly, and the climate conditions were controlled, resulted in the noticeable repeatability of these measurements. The controlled speed yielded small variations of the maximum current and rise time of a single human-subject as shown in figure 2.
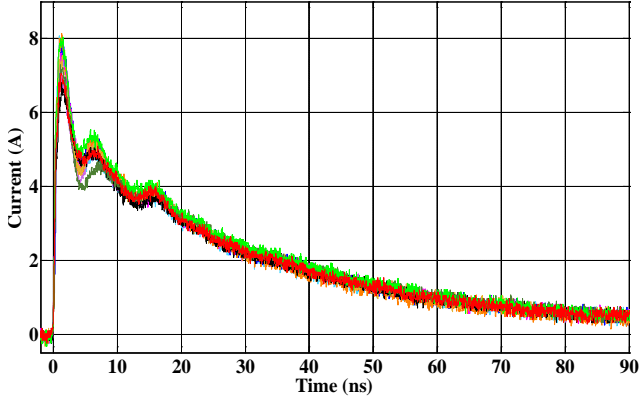
Figure 2. Experimental human-to-metal ESD current waveforms (single individual – ten discharges).

The recorded waveforms of the ten other individuals are shown together in figure 3. It comes as no surprise that variations are larger than the ones observed between successive recordings of a certain individual, even though the exact same process is followed. The reason for that lays in the persons' different electrical properties and the arc properties. However, the systematic effort that was made in order to maintain a stable arc length, deteriorates to a great extend the variations between successive recordings of each individual (similar to what is shown in figure 2 for the first person), so the differences seen in figure 2 can be considered as primarily based on different body electrical properties.
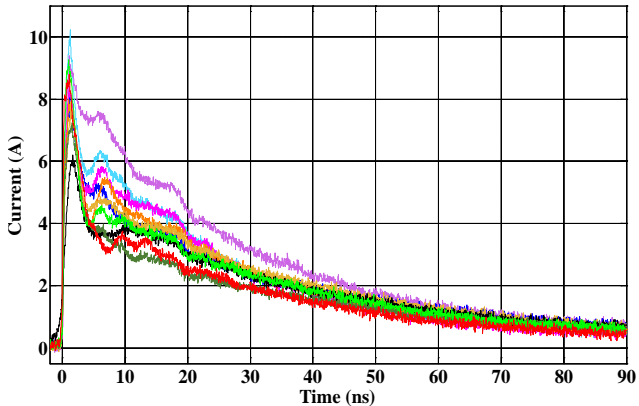
Figure 3. Experimental human-to-metal ESD current waveforms (ten different persons).

3   UNCERTAINTIES CALCULATION

3.1 Theoretical Background

In general, the uncertainty of a measurement consists of many components, which can be classified in two types, depending on the way of their calculation. **Type A** uncertainty is evaluated using statistical analysis of a series of observations, while **Type B** is calculated using any information available, concerning the variability of the measured quantity, such as verification certificates, former measurements data, measuring equipment specifications, operational procedure, experience and subjective judgment of the person making the measurements [9].

The combined standard uncertainty derives from the combination of all individual components, taking under consideration the probability distribution of each.

In this paper, Type A uncertainty is calculated as a combination of two components: the repeatability of the measurements (when a single individual repeats Electrostatic Discharge events [U_{A_1}]) and the reproducibility of the measurements (when various different individuals perform Electrostatic Discharge events [U_{A_2}]). The repeatability and reproducibility are calculated as shown in equations (1), resp. (2):

Repeatability:

$$U_{A_1} = \frac{s_{A_1}}{\sqrt{n_{A_1}}} = \sqrt{\frac{1}{n_{A_1} \cdot \left(n_{A_1} - 1\right)} \sum_{i=1}^{n_{A_1}} \left(x_i - x_m\right)^2} \qquad (1)$$

Where, n_{A_1} is the number of the discharges, x_i is the measured value, x_m is the mean value of the n_{A_1} measurements, and s_{A_1} is the standard deviation from the mean value.

Reproducibility:

$$U_{A_2} = \frac{s_{A_2}}{\sqrt{n_{A_2}}} = \sqrt{\frac{1}{n_{A_2} \cdot \left(n_{A_2} - 1\right)} \sum_{i=1}^{n_{A_2}} \left(y_i - y_m\right)^2} \qquad (2)$$

Where, n_{A_2} is the number of the persons, y_i is the measured value, y_m is the mean value of the n_{A_2} measurements, and s_{A_2} is the standard deviation from the mean value.

The total Type A Uncertainty is given by equation (3).

$$U_A = \sqrt{U_{A_1}^2 + U_{A_2}^2} \tag{3}$$

Having calculated Type A uncertainty, the combined standard uncertainty is calculated as a combination of uncertainties Type A and Type B.

Knowing the distribution followed by each source of uncertainty, uncertainty Type B is calculated as shown in equation (4), U_{B_i} being the contribution of each uncertainty source:

$$U_B = \sqrt{\sum_{i=1}^{N} U_{B_i}^2} = \sqrt{\sum_{i=1}^{N} \left(\frac{s_{B_i}}{k_i} \right)^2} \tag{4}$$

Where, s_{B_i} is the limit value of source i, and k_i is the coverage factor of the corresponding distribution.

The combined standard uncertainty is calculated as shown in equation (5):

$$U_C = \sqrt{U_A^2 + U_B^2} \tag{5}$$

The expanded uncertainty will be as in equation (6) :

$$U_C = k \cdot U_C \tag{6}$$

For a coverage probability of 95%, the coverage factor will be $k=2$.

3.2 Calculation Tables
The average values and uncertainty Type A of the four parameters that are set by [2] (peak current (I_p), rise time (t_r), I_{30}, and I_{60}), are presented in

Tables 1 and 2, as calculated for the waveforms of our experiment. In Table 1, the results for the single individual case are presented (Repeatibility).

Table 1. Human body ESD current parameter values for ten measurements of a single individual (Height: 174 cm, Weight: 77 kgs)

	I_p(A)	t_r (nsec)	I_{30} (A)	I_{60} (A)
1	8.06	0.67	2.16	1.04
2	7.11	0.76	2.14	0.96
3	7.91	0.91	2.23	1.04
4	7.59	0.72	2.32	1.11
5	8.11	0.73	2.14	0.96
6	7.51	0.75	2.21	1.06
7	6.79	0.83	2.23	0.90
8	7.26	0.82	2.23	0.90
9	8.02	0.67	2.29	1.05
10	7.03	0.79	2.36	0.91
Average Values	7.54	0.77	2.23	0.99
Standard deviation	0.47	0.07	0.07	0.07
Uncertainty Type A$_1$	0.15	0.02	0.02	0.02
Relative Uncertainty Type A$_1$ (%)	2.00	3.32	1.04	2.40

Table 2. Human body ESD current parameter values for ten measurements of ten individuals

	Height (cm)	Weight (kgr)	I_p (A)	t_r (nsec)	I_{30} (A)	I_{60} (A)
1	164	66	7.21	0.73	1.70	1.08
2	165	42	8.76	0.56	1.93	0.83
3	168	66	7.96	0.91	2.39	0.99
4	170	52	9.24	0.56	2.26	1.12
5	174	74	10.20	0.89	2.26	1.03
6	175	74	8.40	0.77	2.44	1.03
7	177	84	9.38	0.95	3.11	1.49
8	183	82	8.05	0.90	2.17	1.18
9	183	102	9.12	0.68	2.33	1.16
10	185	79	7.89	1.09	2.54	1.29
Average Values			8.62	0.79	2.31	1.12
Standard deviation			0.88	0.19	0.37	0.18
Uncertainty Type A$_2$			0.28	0.06	0.11	0.05
Relative Uncertainty Type A$_2$ (%)			3.24	7.55	5.08	5.08

In Table 2 the results for the ten different individuals case are presented (Reproducibility). It is obvious that, under constant charging voltage, keeping the speed of approach almost constant results in very small uncertainty values for the ESD current parameters depending on arc properties (peak current (Ip), rise time (tr)). Of course the correspondent uncertainties for I30 and I60 are very low too.

The temperature was kept at about 22±1 ^{o}C and the relative humidity at 39±3 %. The combined standard uncertainty and the expanded uncertainty are calculated hereunder, in Tables 3 to 6.

Table 3. Combined Standard Uncertainty for the parameter I_p.

	Contributor	Distr.	Value (%)	Devisor	u_i (%)	u_i^2 (%)^2	Source
Type A	Repeatability	Normal	2.01	1	2.01	4.03	Table 1
Type A	Reproducibility	Normal	3.25	1	3.25	10.53	Table 2
Type B	Vertical reading of oscilloscope's indication	Normal	0.82	2	0.41	0.16	Calibration Certificate
Type B	Measuring chain target-attenuator-cable	Normal	1.04	2	0.52	0.27	Calibration Certificate
Type B	Failure: Chain to oscilloscope	U-Shaped	1.08	$\sqrt{2}$	0.76	0.58	Calibration Certificate
Type B	Target approach	Normal	1.00	2	0.50	0.25	Laboratory experience
	U_C^2					15.84	

According to equations (5) and (6), the values of the Combined Standard Uncertainty and the Expanded Uncertainty are calculated as follows:

- Combined Standard Uncertainty U_C = 3.980 %

- Expanded Uncertainty (for k=2) U = 7.960 %

Table 4. Combined Standard Uncertainty for the parameter t_r.

	Contributor	Distr.	Value (ps)	Devisor	u_i (ps)	u_i^2 (ps)^2	Source
Type A	Repeatability	Normal	24.12	1	24.12	581.62	Table 1
Type A	Reproducibility	Normal	60.42	1	60.42	3650.88	Table 2
Type B	Reading of peak value	Normal	50.00	2	25.00	625.00	Peak Value uncertainty 3%
Type B	Reading of time I_{90}	Rectangular	25.00	$\sqrt{3}$	14.43	208.33	Oscilloscope's sampling rate 20Gs/s
Type B	Reading of time I_{10}	Rectangular	25.00	$\sqrt{3}$	14.43	208.33	Oscilloscope's sampling rate 20Gs/s
Type B	Vertical reading of oscilloscope's indication	Normal	30.00	2	15.00	225.00	Calibration Certificate
Type B	Measuring chain target-attenuator-cable	Normal	30.00	2	15.00	225.00	Calibration Certificate
	U_C^2					156.25	

Notice that, for the uncertainty calculation of the parameter t_r, the values of the contribution of each uncertainty source are given in time units (ps) in our equipment documentation. Thus, the total uncertainty is computed in ps. According to equations (5) and (6), the values of the Combined Standard Uncertainty and the Expanded Uncertainty are calculated as follows:

- Combined Standard Uncertainty

    U_C = 76.684 ps

- Expanded Uncertainty (for k=2)
    U = 153.368 ps

5

Table 5. Combined Standard Uncertainty for the parameter I_{30}.

	Contributor	Distr.	Value (%)	Devisor	u_i (%)	u_i^2 (%)^2	Source
Type A	Repeatability	Normal	1.05	1	1.05	1.10	Table 1
	Reproducibility	Normal	5.08	1	5.08	25.80	Table 2
Type B	Vertical reading of oscilloscope's indication	Normal	7.96	2	3.98	15.84	Table 3
	Measuring chain target-attenuator-cable	Rect.	0.17	$\sqrt{3}$	0.10	0.01	Calibration Certificate
	Failure: Chain to oscilloscope	Normal	1.00	2	0.50	0.25	Laboratory experience
	U_C^2					43.01	

According to equations (5) and (6), the values of the Combined Standard Uncertainty and the Expanded Uncertainty are calculated as follows:

- Combined Standard Uncertainty U_C = 6.558 %
- Expanded Uncertainty (for k=2) U = 13.116 %

Table 6. Combined Standard Uncertainty for the parameter I_{60}.

	Contributor	Distr.	Value (%)	Devisor	u_i (%)	u_i^2 (%)^2	Source
Type A	Repeatability	Normal	2.41	1	2.41	5.81	Table 1
	Reproducibility	Normal	5.08	1	5.08	25.80	Table 2
Type B	Vertical reading of oscilloscope's indication	Normal	7.96	2	3.98	15.84	Table 3
	Measuring chain target-attenuator-cable	Rect.	0.17	$\sqrt{3}$	0.10	0.01	Calibration Certificate
	Failure: Chain to oscilloscope	Normal	1.00	2	0.5	0.25	Laboratory experience
	U_C^2					47.72	

According to equations (5) and (6), the values of the Combined Standard Uncertainty and the Expanded Uncertainty are calculated as follows:

- Combined Standard Uncertainty U_C = 6.908 %
- Expanded Uncertainty (for k=2) U = 13.816 %

4 DISCUSSION

The uncertainties play a very important role in the evaluation of the measurements. If the uncertainty values are large enough the quality of the measurements can be seriously downgraded, and the validity of any experiment-based arguing can be harmed.

The uncertainty calculation method of ESD current parameters, presented in our work, took under consideration certain uncertainty sources that may interfere with the results while the parameters that were kept steady (temperature and humidity) were not considered to participate in the uncertainty values. The arc was treated with special care. A quick approach scenario, that was simulated at all times, was part of an effort to keep the arc length steady and small. This resulted into obtaining very small variations between the successive ESD events of each individual.

The uncertainties' values obtained in our work are approximately twice as large as the respective ones recommended in [2] for the ESD current parameters values of the ESD generators. This comes as no surprise since real human-to-metal ESD measurements cannot be repeated nor reproduced so easily as in the ESD generators case. Physical quantities may vary quite a lot not only between different persons taking part in the experiment (e.g. height, weight), but also between successive repetitions of the experiment carried out by the same individual (e.g. target approach, body position). However, even if decent uncertainty levels were obtained for our experiments, the task of reducing the uncertainties values should be a constant challenge.

Former laboratory measurements can be of great use at this point. As the number of measurements (using our measuring system with no significant change made on it) increases, then the value of the standard deviation (assuming normal distribution) would be smaller. So, measurements

6

values could be declared with greater confidence, as the overall uncertainty could be limited even more. Thus, it is only time that will provide us with more experimental data that can help as adjust the uncertainties' values and present a better estimation of the measurements quality.

5   CONCLUSIONS

In this work, in order to evaluate the quality of the measurements of real human-to-metal ESD events, we dealt with the task of the calculation of their uncertainty. A method for the calculation of these uncertainties was proposed. Statistical analysis of real ESD measurements conducted in the NTUA HVLab provided us with an estimation of the measurements' behavior (uncertainty Type A); moreover, we also chose to take under consideration certain uncertainty sources (uncertainty Type B) for our uncertainty calculation. A complete numerical application of the method (concerning human ESD events under specific charging voltage) using the equipment and procedures of the HVLab of the NTUA, was elaborated and presented.

Appropriate equipment and experimental setup was, also, presented; the right equipment and setup contribute in achieving a satisfactory recording of the current waveform and keeping the uncertainties small.

As "faster" measuring devices become available, and the less known aspects of the phenomenon are lightened, stricter limits are demanded by researches for the ESD parameters. It is proposed that these findings, which constitute the basis for stricter demands, should always be accompanied with an uncertainty calculation as the one presented here.

Further work should consider reducing the uncertainties presented. For example employing a measuring system of higher bandwidth, could reduce the horizontal (time) reading uncertainty contribution to the expanded uncertainty of the parameter. Also, the experimental data that will accumulate over time, can help in acquiring a clearer view of the measurements behavior as explained before.

6   REFERENCES

[1]   J. Barth "Measurements of real ESD threats that have been ignored too long", IEEE Instrumentation & Measurement Magazine, Vol. 8, pp 61-68, 2005

[2]   EN 61000-4-2:2009: "Electromagnetic Compatibility (EMC) – Part 4 - 2: Testing and measurement techniques - Electrostatic discharge immunity test", 2009

[3]   Y. Taka, Y. Kagawa, O. Fujiwara "Measurement of Discharge Currents due to Human-ESD" EMC 2007 International Symposium on Electromagnetic Compatibility, pp 43 – 46, Qingdao, China, October, 2007

[4]   O. Fujiwara, Y. Taka "Dependence of breakdown fields on charge voltages for human ESD" 19th Int. Zurich Symp. on Electromagnetic Compatibility, pp 148-151, Singapore, May, 2008

[5]   O. Fujiwara, Y. Taka "Verification of spark resistance formula" 19th Int. Zurich Symp. on Electromagnetic Compatibility Singapore, pp 152-155, Singapore, May, 2008

[6]   H. Jiu-Sheng, L. Fang, D. Qi-bin, L. Pei-Zhu "An ultra wide band test system to test the transient electric fields and magnetic fields generated by electrostatic discharge" ISAPE 2000 Int. Symp. on antennas, propagation and EM theory, Beijing, China, pp 626-629, 2000

[7]   J.L. Muiioz, J. Tan, C. Adriano, E. Roldan, J. Sadie "Detecting ESD events using a loop antenna" Electrical Overstress/Electrostatic Discharge Symp. Proc. Anaheim, USA, pp 60-64, September, 2000

[8]   K. Kawamata, Y. Taka, S. Minegishi, A. Haga, O. Fujiwara "Time Domain Measurement of Voltage Rise Time and Current Rise Time Due to Low Voltage ESD using 12GHz Experimental System" EMC International Symposium on Electromagnetic Compatibility, pp 55 – 58, Qingdao, China, October, 2007

[9] UKAS M3003: "The expression of Uncertainty and Confidence in Measurement", 2007

[10] D. Pommerenke "ESD: transient fields, arc simulation and rise time limit", Elsevier Journal of Electrostatics, Vol. 36, pp. 31-54, 1995

[11] O. Fujiwara, Y. Taka "Gap Breakdown field caused by air discharge through hand-held metal piece from charged human-body", 4th Asia-Pacific Conference on Environmental Electromagnetics, pp. 103-106, Dalian, China, August, 2006