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Estimation of parameters for the electrostatic discharge current equation with real human discharge events reference using genetic algorithms

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Abstract

Thorough study of the electrostatic discharge (ESD) current equation shows that it may be different from the equation proposed in the IEC 61000-4-2 Standard. This problem is dealt with in this paper. Using a 2.5 GHz digital oscilloscope and a 50 Ω Pellegrini target as the measuring system, and a dc power supply to provide a charging voltage of 2 kVdc, a series of measurements were performed, so real human-to-metal ESD current waveforms were recorded. Treating the average waveform as a reference, a genetic algorithm (GA) was applied to the equation of the IEC 61000-4-2 Standard for the ESD current, in order to achieve its best fitting to the data set. Four different error norms were used for the GA applications. The best result of the applications of each of them was saved and compared to the others. Thus, a very satisfactory modification of the Standard's equation is presented, which is closer to the real ESD current waveform.

Keywords: electrostatic discharge, genetic algorithm, measurements

(Some figures in this article are in colour only in the electronic version)

1. Introduction

As electromagnetic compatibility issues become crucial for product manufacturing and more popular among scientists, certain subjects reveal their lack of sufficient documentation. The case of electrostatic discharge (ESD) is one of them. A vivid debate is still on, around the globe, as far as the parameters involved in the phenomenon are concerned.

Barth [1], some years ago, had already noticed the need not only for new experimental data, but also for the modernization of corresponding Standards to meet the contemporary needs. Measurements on real ESD events are still being carried out by various researchers [2–5], necessary for the establishment of any critique on the values of certain parameters describing the phenomenon, defined by related standards.

The IEC 61000-4-2 [6] Standard for ESDs deals with the immunity of electric and electronic devices against ESDs and describes the procedures that have to be followed during the ESD tests on electric and electronic devices. Moreover, it describes the standard 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 the standard (IEC 61000-4-2:2008) [6] contains an equation for the ESD current, with respect to the contact discharge mode.

However, contact discharge is an ideal case, according to which the charged body is supposed to touch the body of the victim and then discharge on it. This is a case of purely academic interest since the charged body cannot avoid the generation of an arc while it approaches the body of the victim.

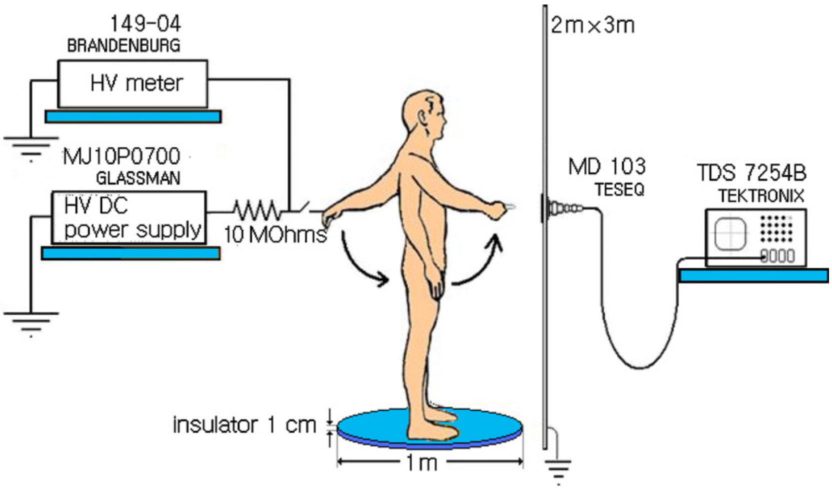

Figure 1. The experimental set-up.

Nevertheless, there is a great deal of reluctance when it comes to proposing an equation for the air discharge case. More data are needed worldwide, in order to support such a project. The small amount and limited repeatability of the measurements, and, in many cases, the inadequate equipment employed to perform such experiments, make it difficult to come up with a documented proposal for an ESD current curve.

In this paper, an approach to this issue is proposed. The aim is to use experimental data in order to obtain an analytical formula complying with them. As an application, the equation of the IEC 61000-4-2:2008 Standard [6] for the ESD current is considered, and processed to fit to the data. Taking into consideration this equation, and performing a series of measurements of real human-to-metal ESD events (air discharges), we propose new parameter values for the equation by means of a genetic algorithm (GA).

2. Measurements

2.1. Test setup

When attempting to record the ESD current generated in a real human-to-metal ESD event, one must be very careful with the measuring equipment employed. In general, the ESD events involve high frequencies, so the related equipment should present the possible wider frequency response. For the purposes of this work, let us consider that the measuring equipment should have a frequency response not smaller than that set in IEC 61000-4-2:2008 [6], that is 2 GHz.

In our case we use a TDS 7254B Tektronix oscilloscope (2.5 GHz) and an MD 103 TESEQ calibrating system (Pellegrini target, attenuator, coaxial cable) (6 GHz). In order to charge the human body, we used a Glassman MJ20P0700 high voltage power supply and a 10 MΩ high voltage resistance. The measurement of the charging voltage was made using a Brandenburg HV meter (model 149-04). The connections are shown in figure 1.

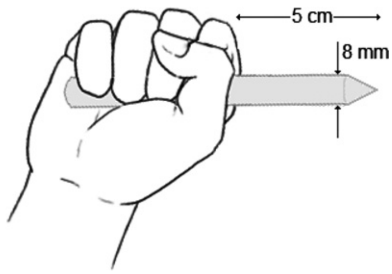

Figure 2. The metal rod.

2.2. Measuring process

A male individual of 174 cm and 77 kg was examined with respect to the ESD current that he injects when charged at 2 kV. At the beginning, the subject was exposed to the high voltage by touching the 10 MΩ resistor with the metal rod at the point where the HV meter was connected, for a time interval not shorter than 3 s. Afterward, the subject releases the power supply probe and approaches the target with a metal rod, as seen in figures 1 and 2. The subject simulates a quick approach scenario in all cases. The whole process is repeated ten times.

2.3. Results

The recorded wave shapes, as well as the average curve, are shown together in figure 3. Noticeable repeatability of these measurements can only be achieved under laboratory conditions where the same individual can go through the charging and discharging process repeatedly, and the climate conditions and charging procedure are controlled (employing a dc power supply).

Treating the average waveform as a reference, the values of four parameters (peak current (I_p), rise time (t_r), I_{30} and I_{60}) are calculated, as shown in table 1. The four parameters are defined in [6] and shown briefly in figure 4 with respect

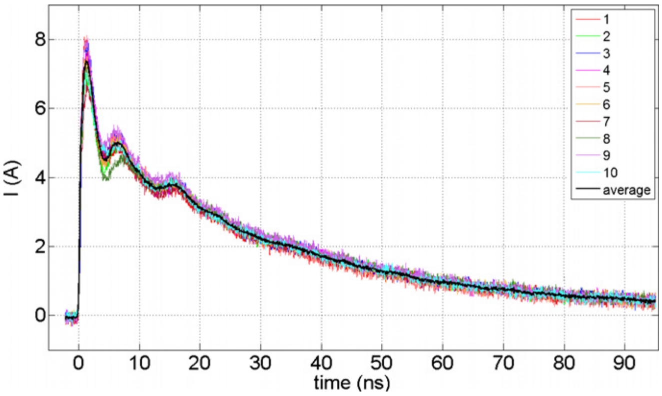

Figure 3. Experimental human-to-metal ESD events wave shapes.

Table 1. Values of the parameters I_p, t_r, I_{30}, I_{60}, calculated in the case of real human-to-metal ESD events.

	I_p (A)	t_r (ns)	I_{30} (A)	I_{60} (A)
Average values	7.37	0.73	2.24	1.00
Standard deviation	0.479	0.076	0.074	0.076

to 2 kV charging voltage. The standard sets specific values of the parameters for the contact discharge case.

3. Estimation of parameters

3.1. Equation

In order to present a method for acquiring an equation describing the ESD current of real human-to-metal ESD events, equation (1) (introduced by IEC 61000-4-2:2008 [6]) is treated as the starting point:

$$I(t) = I_1 \cdot \frac{\left(\frac{t}{\tau_1}\right)^n}{1 + \left(\frac{t}{\tau_1}\right)^n} \cdot e^{\left(\frac{-t}{\tau_2}\right)} + I_2 \cdot \frac{\left(\frac{t}{\tau_3}\right)^n}{1 + \left(\frac{t}{\tau_3}\right)^n} \cdot e^{\left(\frac{-t}{\tau_4}\right)}. \quad (1)$$

Nevertheless, different values of the parameters are needed for an equation like this to be fitted to the experimental data.

To achieve this, some optimization tools may be of use. However, the form of the curve is not easy to approximate, especially if the second peak is considered of importance. A nonlinear least-squares fit was attempted using Gauss–Newton-based algorithms, and, although they presented quite a good approximation in a short time, they failed to achieve good fitting at the second peak (4–10 ns). A GA was developed to deal with this demanding task. A brief introduction to the GA is presented in the following section.

3.2. Genetic algorithm

GAs are considered ideal methods to deal with optimization problems, particularly in multidimensional tasks, since they can perform very efficiently when applied on large groups of data. The limits of the data set as well as possible discontinuities and functional derivatives are not required to be known in order to apply the GA, as it tends not to get trapped in local extrema, unlike other methods. However, even though the GA is a simple and powerful tool, it may sometimes be time consuming due to the large amount of calculations involved.

The difference between GAs and other fitting tools is that in the case of GAs, the parameters are treated as genes in a chromosome. The process starts by marking a group of possible solutions, called population, within the given range. The GA achieves best-fitting results by means of natural selection, crossover and mutation of the chromosomes, which will be produced in future generations. In this way, the optimum values of the parameters in question are obtained.

The GA starts with a population of $N = 30$ random values for each of the seven parameters of equation (1). Each parameter value is converted to a 20-bit binary number, so chromosomes of 140-bit size are obtained. By crossover each pair of parents produces $N_c = 4$ children. After crossover there is a $P_m = 5$–10% probability of mutation. After mutation

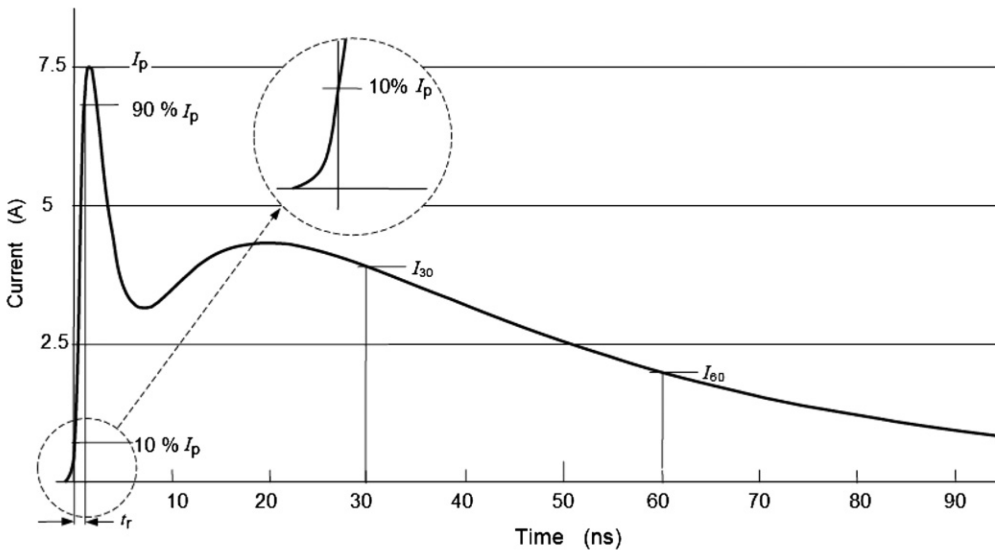

Figure 4. IEC 61000-4-2 ESD current waveform. I_p, t_r, I_{30} and I_{60} are expected to have certain values under certain charging voltage.

the population of the 'parents' is merged with the 'children' to a total population of 90 chromosomes. By applying the process of natural selection only $N = 30$ chromosomes survive. These are the ones that correspond to the lowest values of the objective function, since a minimization problem is solved.

In previous works [7–9], a similar GA was used to estimate the parameters of some equations for the ESD current, with ESD generators' current waveform reference, at the time when no such analytical formula was included in IEC 61000-4-2:1996 [10]. This GA had to undergo important modifications in order to produce useful results for the present case, where real ESD current waveforms (not theoretical curves or ESD generators' current waveforms) were treated as input data.

In the present work, a new kind of 'elitism' was applied for the 'parents' selection. The initial population consists of 30 parents (chromosomes). Each of them was produced by a few runs of the GA, considering a random input. Thus, the main tasks of the GA begin at a privileged point.

Second, four objective functions were examined. More objective functions were employed in order to have a variety of choices, and, thus, increase the probability of better results.

Furthermore, in most cases the GA does not have to process the whole set of points, which it deals with, in order to give reliable results. A representative sample of the points could not only produce useful results but also save a lot of time. Since time is an issue in GA applications, a suitable sampling procedure is of essence. In the present work, three parts of the data set were considered ([0–3 ns] (first peak), [1.5–10 ns] (second peak), [10 ns to end] (tail)) and different sampling modes were applied on each of them. The density of the sampling was gradually decreasing, so we ended up with a data set very suitable for our application, with a total 395 points (beginning from a set of about 4002). This was because the first two peaks of the waveform were to be treated with extra care, since they contain the most interesting information of our findings. Briefly, in figure 5, the basic function of the algorithm is shown.

For 30 parents and 20 iterations our computer (dual-core, 32-bit, 3 GHz, 1 GB RAM) would produce results in about 1.5 min.

3.3. Optimization functions

Four optimization error functions were used by the developed GA in order to receive best values for the related parameters of the equation. The goal of the GA is to reduce their amplitude through successive repeats. These are as follows.

- Error norm 1: sum of absolute error $= \sum |I_{\text{measured}} - I_{\text{formula}}|$
- Error norm 2: maximum value of norm $|I^2_{\text{measured}} - I^2_{\text{formula}}|$
- Error norm 3: maximum absolute error $= \max |I_{\text{measured}} - I_{\text{formula}}|$
- Error norm 4: sum of relative error $= \sum |(I_{\text{measured}} - I_{\text{formula}})/I_{\text{measured}}|$

Each of the above error functions was treated as the objective function for different applications of the GA.

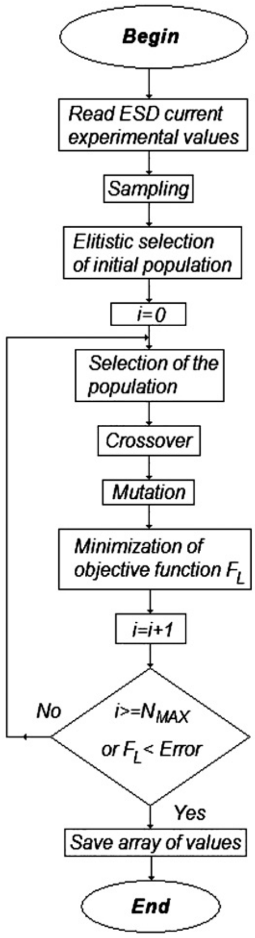

Figure 5. Flow chart of the GA.

3.4. Results

The GA was applied on the average waveform of the ten waveforms shown in figure 3. The GA produced different values for the parameters of the equation for each of the objective functions. Being a stochastic algorithm, the GA was run for more than 30 times for each of the objective functions, and the best results (one per function) were compared. In figure 6, graphic representations of the four modifications of (1) that occurred are shown in a common graph with the experimental data.

In table 2, the values of the equation parameters corresponding to each of the optimization functions are shown.

As obvious, the GA produces satisfactory values of the parameters, in order for the formula of the IEC 61000-4-2 Standard [6] to fit to the experimental data properly. Hereunder, in table 3, the crucial values of the four ESD current waveform parameters set by IEC 61000-4-2 (I_p, t_r, I_{30} and I_{60}), as well as the respective deviations from the experimental data, are presented. Deviations of the parameters $I_{\text{2nd peak}}$ and $t_{\text{2nd peak}}$ are additional metrics included because the second peak was considered an important goal of the approximation.

For the last criterion (error norm 4) of table 2 the best fitting is achieved. It is closer to all of the parameters examined except for the amplitude of the second peak where a very good outcome has been achieved (relative error: 0.97%), yet

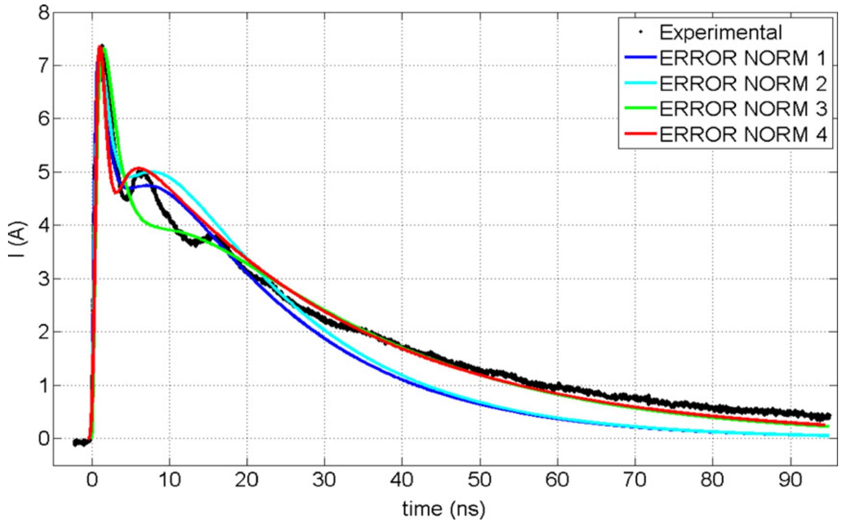

Figure 6. Plot of equation (1) for different values of the parameters as calculated from the GA.

Table 2. Values of the parameters I_1, I_2, t_1, t_2, t_3, t_4 and n produced by the genetic algorithm for each of the optimization functions.

	I_1 (A)	I_2 (A)	t_1 (ns)	t_2 (ns)	t_3 (ns)	t_4 (ns)	n (−)
Error norm 1	22.580	10.508	0.747	1.247	4.456	18.080	1.408
Error norm 2	29.563	12.137	1.189	1.250	5.222	17.606	1.378
Error norm 3	23.597	8.035	1.151	1.931	5.983	26.692	1.515
Error norm 4	31.365	6.854	1.226	1.359	3.982	28.817	4.036

Table 3. Values of the parameters I_p, t_r, I_{30}, I_{60} for each of the four formulas that have been developed in this work.

	I_p (A)	t_r (ns)	I_{30} (A)	I_{60} (A)	$I_{2nd\ peak}$ (A)	$t_{2nd\ peak}$ (ns)
Experimental values	7.37	0.73	2.24	1.00	5.02	6.39
Error norm 1	7.17	0.53	1.87	0.37	4.74	7.10
Relative error 1 (%)	−2.71	−27.40	−16.52	−63.00	−5.49	11.13
Error norm 2	7.01	0.66	2.02	0.39	5.00	7.70
Relative error 2 (%)	−4.88	−9.59	−9.82	−61.00	−0.37	20.52
Error norm 3	7.33	0.82	2.39	0.82	–	–
Relative error 3 (%)	−0.54	12.33	6.70	−18.00	–	–
Error norm 4	7.36	0.74	2.38	0.84	5.07	6.05
Relative error 4 (%)	−0.14	1.37	6.25	−16.00	0.97	−5.31

the second criterion (error norm 2) produced slightly better results. The last criterion also presented a very good fitting to the equation in the tail of the waveform. (Note that the equation produced by the use of error norm 3 did not produce a second peak.)

4. Conclusions

The need for an analytical formula for the ESD current waveform close to those recorded from real experiments is dealt with in this paper. The equation of the IEC 61000-4-2:2008 [6] for the ESD current can be fitted more successfully to the experimental data considering the new values for its parameters estimated in this paper with the help of the genetic algorithm. However, the form of this equation makes it impossible for it to be customized so that it can fit the data set, which occurred from our measurements, in detail. It is clear that three local peaks can be observed in figure 3 while the form of the equation proposed by the Standard is capable of producing only two.

A prospective revision of [6] should consider the inclusion of a more appropriate equation for the idealized waveform, closer to the experimental data (like those exposed in section 2.3), in order to estimate the devices' immunity level toward the ESD current, flowing from a charged human under specific charging voltage, more successfully. Should the committee not change the equation's form, the values of τ_i ($i = 1, \ldots, 4$) should, at least, be revised closer to our findings, so the current's time derivatives are more realistic and the second peak is described better.

Our future tasks are to consider more suitable forms of equations which will be fitted to an ESD current curve, which will occur from a more extended series of measurements. An even more broadband measuring system could also reveal more detailed information of the ESD current's waveform behavior.

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