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Applying genetic algorithms for the determination of the parameters of the electrostatic discharge current equation

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Abstract
The aim of this paper is the estimation of the parameters of possible equations, which describe the current during an electrostatic discharge using genetic algorithms. Aberrations between simulations and the waveform described in the standard render necessary the development of an equation that will describe the discharge current. The input data of the genetic algorithm are real current measurements produced by an electrostatic discharge generator. By using these data, the genetic algorithm is a means to find optimized parameters of the mathematical equations. The satisfactory agreement between the experimental and optimized data proves the efficiency of the genetic algorithm.

Keywords: discharge current, electrostatic discharges, electrostatic discharge generators, genetic algorithms, simulation

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

1. Introduction

Electrostatic discharge (ESD) is a common phenomenon that occurs when electric charge is transferred between bodies that have different electrostatic potentials. The phenomenon of electrostatic discharge is more crucial for electronic devices such as integrated circuits (IC), or fast complementary metal oxide semiconductor (CMOS) systems. The IEC 61000-4-2 [1] describes the test procedure for electronic equipment under electrostatic discharges and defines the shape of the discharge current that the ESD generators must produce.

A considerable amount of effort has been investigated to study the ESD current waveforms. In [2] it has been concluded that the amplitudes and the rise times depend on the charging voltages, approach speeds, electrode types, the relative arc length and humidity. It must be mentioned that for most ESD the arc lengths are below the static breakdown value and in order to take the reduced arc length into account the relative arc length is defined as the ratio of the real arc length to the gap distance. The purpose of another study [3] was to determine the parameters that characterize the discharge current waveforms of ESD testers. In particular, an equivalent circuit model based on the tester's structure and dimensions is proposed, and is verified by discharge experiments. Murota in [4] presents the variations that appear on the discharge current, when various conditions change during the test using the simulation program PSpice.

The ESD generators' influence on equipment under test (EUT) has been studied in two different ways. Firstly, it has been studied how the ESD current produced by the ESD generators affects various EUTs. In [5], the influence of the current derivative on various EUTs has been studied. It has been found that an EUT can pass a test at a certain discharge voltage, yet the same EUT may fail at the same voltage, when tested with another ESD generator, because of differences in the produced current. Secondly, it has been studied how the electromagnetic field radiated by the ESD generators and the related induced voltages affect various EUTs. Pommerenke examined in recent publications [6, 7] the radiating field and concluded that the most important factor for an EUT is the transient field.

There have been various publications which propose an improved circuit for the ESD generators. A modified commercial generator with a reference waveform close to that defined by the standard and an equation describing the reference waveform have been proposed [8]. Another proposed equation [9] for the reference waveform has been developed in order to study the ESD phenomenon in coaxial cable shields. In [10], the adopted human body model is divided into 11 elemental blocks and treated by the diakoptic method in analogy with network theory, using the simulation program PSpice. Apart from the circuits for the ESD generators, an equation which will accurately give the ESD current can be estimated. This equation can be used in simulation programs in order to describe accurately the ESD generator.

In the current standard [1], there is an aberration between the defined waveform of the ESD current and the discharge current that the circuit of the ESD generator produces in reality. Therefore, simulation programs that use the existing circuit of the ESD generator insert an error in the calculated voltages and currents. Finding an accurate equation that can describe the ESD current can minimize this error. The correct equation is an indispensable requirement for the description of the ESD generators in simulation programs. This work aims at the optimization of the parameters of the discharge current equation using genetic algorithms (GA). This is the first time that such an attempt has been made, giving good results, since this method minimizes the error between the measured current and the current described by the equations. The method is applied on four different types of equations giving as results the optimum values of the parameters for each equation.

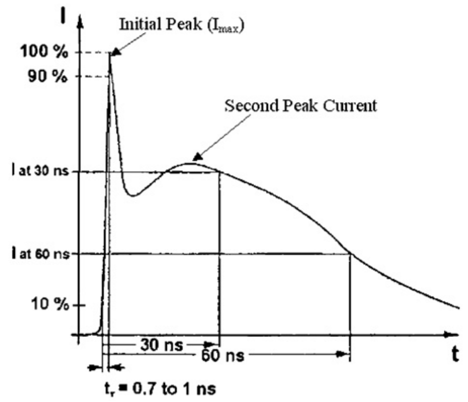

Figure 1. Typical waveform of the output current of the ESD generator [1].

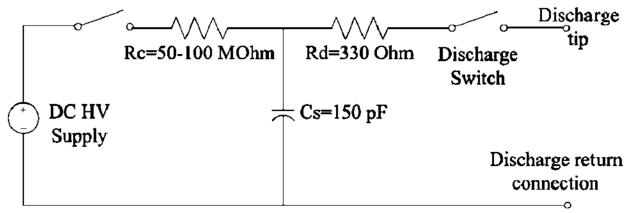

Figure 2. Simplified diagram of the ESD generator [1].

Table 1. Waveform parameters.

Voltage (kV)	I_{max} (A)	t_r (ns)	I_{30} (A)	I_{60} (A)
2	6.75–8.25	0.7–1	2.8–5.2	1.4–2.6
4	13.50–16.50	0.7–1	5.6–10.4	2.8–5.2
6	20.25–24.75	0.7–1	8.4–15.6	4.2–7.8
8	27.00–33.00	0.7–1	11.2–20.8	5.6–10.4

2. The discharge current of the ESD generators

2.1. The IEC 61000-4-2

ESD generators are used for testing the robustness of electronics towards ESD. Their aim is to simulate the discharge of a human through a small piece of metal (human–metal ESD). Electrostatic discharges can occur either as contact discharges or as air discharges. According to IEC 61000-4-2 [1] the application of contact discharges is the preferred test method and air discharges shall be used in cases where contact discharges cannot be applied. The test level voltages for the contact discharges range between 2 and 8 kV and for the air discharges between 2 and 15 kV. It must be underlined that for the verification of the ESD generators the discharges are contact discharges and not air discharges. The ESD generator must produce a human body model (HBM) pulse as shown in figure 1.

The pulse of figure 1 is divided into two parts: a first peak called the 'initial peak', caused by a discharge of the hand, where there is the maximum current and a second peak, which is caused by a discharge of the body. The rise time (t_r) of the initial peak is between 0.7 ns and 1 ns and its amplitude depends on the charging voltage of the ESD simulator.

Figure 2 shows a simplified diagram of the ESD generator [1]. According to the standard it consists of the charging resistor R_c (50–100 MΩ), the energy-storage capacitor C_S (150 pF ± 10%), the discharge resistor R_d, representing the resistance of the skin (330 Ω ± 10%), and the EUT. It must be mentioned that the reference model of the ESD waveform is the human–metal discharge. Therefore, a human holding a piece of metal and its skin are crucial for the discharge current. Consequently, when a discharge takes place the spark will not land on the skin, but on the metal. It is clear that R_d represents the total skin resistance and not only the resistance of the skin close to the discharge point. The value of the energy-storage capacitor C_S is representative of the electrostatic capacitance of the human body, while the resistance of 330 Ω is close to the skin resistance of the human body.

According to the specifications of the standard for the verification of the ESD generators there are four parameters whose values must be confined by certain limits. These parameters are: the rise time (t_r), the maximum discharge current (I_{max}), and the current at 30 ns (I_{30}) and 60 ns (I_{60}). As is shown in figure 1 these two current values are calculated for time periods of 30 and 60 ns respectively starting from the time point when the current equals 10% of the maximum current. The limits of these parameters are shown in table 1 and are valid for contact discharges only.

2.2. *The need for an analytical and accurate equation of the discharge current for commercial ESD generators*

In [11], it has been observed that using the circuit defined in the standard for various loads (EUT) the current's waveform differs from the waveform defined by the standard shown in figure 1. As a result, computer simulations of the circuit defined in the standard insert an error in the calculated voltages and currents. It is imperative this error be minimized. There are two possible alternatives to achieve this. The first one is to propose a new circuit of the ESD generator as the work that has been done in [8, 10]. The second one is the use of an ESD current source, where the produced current waveform is a function of a number of parameters as has been proposed in [3, 8, 9].

In this paper the second way has been followed. Using a number of equations, which describe the discharge current mathematically, a methodology has been developed. The parameters of these equations are calculated using measured discharge currents from a commercial ESD generator, which is constructed according to the standard. The developed methodology is a GA, which is described in a following section.

2.3. *Equations of the discharge current*

An ESD generator has to be able to reproduce electrostatic discharges in a reliable and accurate way. The standard defines the values of the waveform parameters of the discharge current that an ESD generator produces. A known equation, which does not correspond to the discharge current, but will be used in the further analysis for the application of the GA, is the following equation of the lightning current [12]:

$$i(t) = i_0 \cdot \left(\mathrm{e}^{-\frac{t}{t_1}} - \mathrm{e}^{-\frac{t}{t_2}}\right). \tag{1}$$

A first approximate equation of the discharge current for commercial simulators was first introduced by [13] using a double exponential function:

$$i(t) = i_1 \cdot \mathrm{e}^{-\frac{t}{t_1}} - i_2 \cdot \mathrm{e}^{-\frac{t}{t_2}}. \tag{2}$$

The reference waveform for the discharge current according to [9] is

$$i(t) = A \cdot \mathrm{e}^{-\left(\frac{t-t_1}{\sigma_1}\right)^2} + B \cdot t \cdot \mathrm{e}^{-\left(\frac{t-t_2}{\sigma_2}\right)^2}. \tag{3}$$

The pulse described in figure 1 may be viewed as the sum of two Gaussians in the time domain, one narrow and the other broad. Equation (3) is closer to this observation, since the factors $A \cdot \mathrm{e}^{-\left(\frac{t-t_1}{\sigma_1}\right)^2}$ and $B \cdot t \cdot \mathrm{e}^{-\left(\frac{t-t_2}{\sigma_2}\right)}$ represent the narrow and broad Gaussians respectively.

In [8] based on the equation of the lightning current of Heidler [14], the referred waveform is given by the formula below:

$$i(t) = \frac{i_1}{k_1} \cdot \frac{\left(\frac{t}{\tau_1}\right)^n}{1 + \left(\frac{t}{\tau_1}\right)^n} \cdot \mathrm{e}^{-\frac{t}{\tau_2}} + \frac{i_2}{k_2} \cdot \frac{\left(\frac{t}{\tau_3}\right)^n}{1 + \left(\frac{t}{\tau_3}\right)^n} \cdot \mathrm{e}^{-\frac{t}{\tau_4}} \tag{4}$$

where

$$k_1 = \mathrm{e}^{-\frac{\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{\frac{1}{n}}} \tag{5}$$

and

$$k_2 = \mathrm{e}^{-\frac{\tau_3}{\tau_4}\left(\frac{n\tau_4}{\tau_3}\right)^{\frac{1}{n}}}. \tag{6}$$

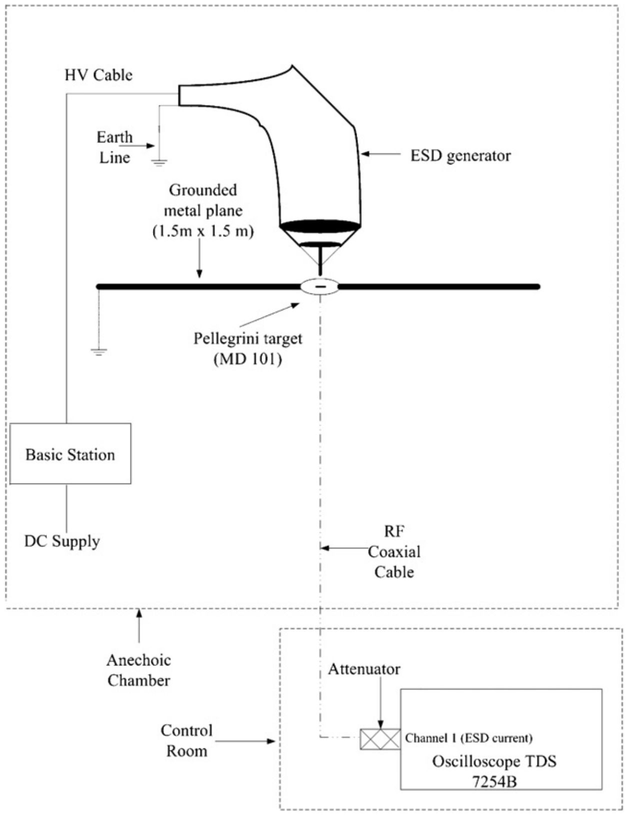

Figure 3. Scheme of the experimental set-up.

i_1, i_2 are currents in amperes, τ_1, τ_2, τ_3, τ_4 are time constants in ns and n signifies how many times the equation can be differentiated with respect to time.

The unknown parameters of these four different equations need to be optimized in order for the measured ESD current to be analytically described. This is where the GA can help and what this paper aims at.

3. Experimental setup

Figure 3 shows the ESD current experimental set-up. The current for charging voltages of +2 kV and +4 kV was measured by a 4-channel Tektronix oscilloscope model TDS 7254B, whose bandwidth ranges from dc to 2.5 GHz. An ESD generator, model NSG-438 of Schaffner, produced contact discharges and it was grounded to earth via a ground strap. In order for the current to be measured, a resistive load, known as the Pellegrini target (MD 101 of Schaffner), was placed between the discharge electrode and the metal ground plane with dimensions 1.5 m × 1.5 m. The Pellegrini target was connected to the oscilloscope by a HF coaxial cable. This resistive load was designed to measure discharge currents by ESD events on the target area and its bandwidth ranges from dc to above 1 GHz. The measurements were conducted in an anechoic chamber in order for the measurement system to be unaffected by the surrounding equipment and the cables were set away from the discharge point. It is known that the position of the ground strap affects the falling edge of the current's waveform. In order to minimize the uncertainty of this fact into the GA application the ground strap was at a distance of 1 m from the target as the standard defines and the loop was as large as possible. The measurement system of figure 3 is in accordance with the standard [1] and provides high fidelity data.

4. The genetic algorithm

GAs are adaptive methods, which may be used to solve search and optimization problems. Genetic algorithms are now widely applied in science and engineering as adaptive algorithms for solving practical problems. Certain kinds of problems can be tackled by using a GA approach. The general assumption is that GAs are particularly suited to multidimensional overall problems, where the search space potentially contains multiple local minima. Unlike other methods, correlation between the search variables is not generally a problem. The basic GA does not require extensive knowledge of the search space, such as solution bounds or functional derivatives. A task for which simple GAs are not suitable is a rapid local optimization; however, coupling the GA with other techniques to overcome this problem is trivial. Whenever multidimensional systematic searching is the technique of choice, although the large number of comparisons makes that approach intractable, a GA should be considered the best choice for the reasons outlined in the sections below [15, 16].

This paper proposes a methodology which uses the developed GA for the optimization of the parameters of the discharge current equations (1)–(4), which were described previously. This GA has been developed using Matlab. The same GA produces excellent results in several optimization problems [17–20]. It has been applied for computation of the parameters of the earth structure [17], factorization of multidimensional polynomials [18], the calculation of discharge parameters for polluted insulators [19] and for the estimation of the parameters of possible equations, which describe the current during an electrostatic discharge [20].

A simple GA is based on the processes of reproduction, crossover and mutation to reach the overall or 'near-overall' optimum. To start the search, the GA requires the initial set of the points P_{s}, which are called population, in analogy with a biological system. A random number generator creates the initial population. This initial set is converted to a binary system and is considered as chromosomes, actually sequences of '0' and '1'. The next step is to form pairs of these points that will be considered as parents for a reproduction. Parents come to reproduction and interchange N_{p} parts of their genetic material. This is achieved by crossover. After the crossover there is a small probability P_{m} for mutation. Mutation is the phenomenon where a random '0' becomes '1' or a '1' becomes '0'. Assume that each pair of 'parents' gives rise to N_{c} children. Thus the GA generates the initial layouts and obtains the objective function values. The above operations are carried out and the next generation with a new population of strings is formed. Through reproduction, the population of the 'parents' is enhanced with the 'children', increasing the original population since new members are added. The parents always belong to the considered population. The new population has now $P_{\mathrm{s}} + N_{\mathrm{c}} \times P_{\mathrm{s}}/2$ members. Then the process of natural selection is applied. According to this process only P_{s} members of the $P_{\mathrm{s}} + N_{\mathrm{c}} \times P_{\mathrm{s}}/2$ members survive out. These P_{s} members are selected as the members with the lower values of F_{g}, since a minimization problem is solved.

F_{g} represents the error between the measured and the optimized data. For the computation of the parameters for each equation the minimization of the function F_{g} is necessary. F_{g} is given by the following equation:

$$F_{\mathrm{g}} = \sum_{i=1}^{N} \frac{\left|I_i^{\mathrm{m}} - I_i^{\mathrm{c}}\right|}{I_i^{\mathrm{m}}} \tag{7}$$

where I_i^{m} is the ith measured value of the discharge current.

Apart from (7) another objective function that could be used and minimized by the GA is given by the following equation (8), also known as the L-infinity norm or the ∞-norm:

$$F_{\mathrm{L}} = \max_i \left|I_i^{\mathrm{m}} - I_i^{\mathrm{c}}\right| \tag{8}$$

with $i = 1, \ldots, N$, I_i^{m} the current's measured value and I_i^{c} the computed value of the discharge current for the unknown parameters of (1)–(4).

By repeating the iterations of reproduction under crossover, mutation and natural selection, GAs can find the minimum of F_{g} or F_{L}. The best values of the population converge at this point. The termination criterion is fulfilled if either the mean value of F_{g} or F_{L} in the P_{s}-members population is no longer improved or the number of iterations is greater than the maximum number of iterations $N_{\max}$.

5. Results

The GA was applied on experimental data, obtained by the experimental setup described previously. Giving as input data the discharge current of the ESD generator, the GA calculates and optimizes the parameters for (1)–(4). In equation (4) n is constant and equals 3. Therefore (4) has six unknown parameters, like (3). The error (F_{g} or F_{L}) of each equation gives useful conclusions about the best and most accurate equation derived.

A careful selection of the experimental data, as the oscilloscope has saved them, has to be made. In this application, the use of the GA does not require the use of all the measured data, which is an extremely time consuming procedure. A proper use of the selected number of the measured data and an application of a greater number of parents and iterations is preferable to applying the GA to the whole number of measured points. In order for the proposed GA to be more efficient, a procedure for the selection of the measured data has to be followed.

In all cases and for both charging voltages the total number of measured data was 2250 and the duration of the discharge current was 90 ns. The whole number of measured points has not been used. Instead, the waveforms' points have been selected as can be seen in table 2 for three different types of point selections. In the first case a function has been used, as is shown in table 2, in order to take more points at the first ns and for the GA to give more accurate results for this time period. In the second case the selected step width is constant and equals 20. This means that from the measured data of 2250 sequential points the 1st, 21st, etc will be

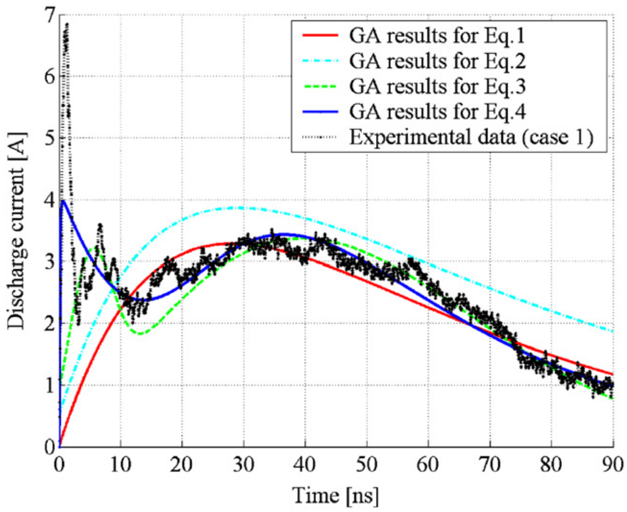

Figure 4. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)–(4) for the first case (charging voltage = +2 kV).

Table 2. Selection of the measured current's points (charging voltages +2 kV and +4 kV).

Cases	Step	Selected points for 90 ns
First case (Exp6)	$6(1+\text{round}(\exp(j/N)))$[a]	148
Second case (Idata20)	Constant equals 20	113
Third case (Idata20N)	0–2 ns: all points 2–90 ns: points from Idata20	161

[a] *j* is the *j*th point of the measured data of 2250 points.

selected. Due to the fact that the discharge current reaches its peak at 0.7–1 ns [1], the number of points before 1 ns is extremely small. In the third case the GA takes all the measured points in the first 2 ns, in order for the initial nanoseconds of the discharge current to be treated as the most important part of the waveform, as is shown in table 2.

It must be mentioned that the first nanoseconds of the electrostatic discharge are the most crucial, due to the fact that the highest levels of radiation and the largest values of the current derivative occur during this period. Case 3 takes that remark into consideration, because it includes all the measured points until the second nanosecond, expecting to have a good parameter determination for the first nanoseconds. However, in cases 1 and 2 the number of points in the first nanoseconds is lower than in case 3, due to the fact that it was attempted the GA to give accurate results for the whole time duration of the phenomenon and to describe an analytical equation for the waveform defined by the standard.

The GA was applied to the experimental data for all three cases. In figures 4–9 common graphs of the experimental data of the discharge current and the discharge current for the optimized parameter values for (1)–(4) are depicted. Tables 3–6 present the optimized values of the parameters of each equation and the errors calculated by (7).

There are two possible ways in order to evaluate the best equation for the discharge current. The first is to compare the

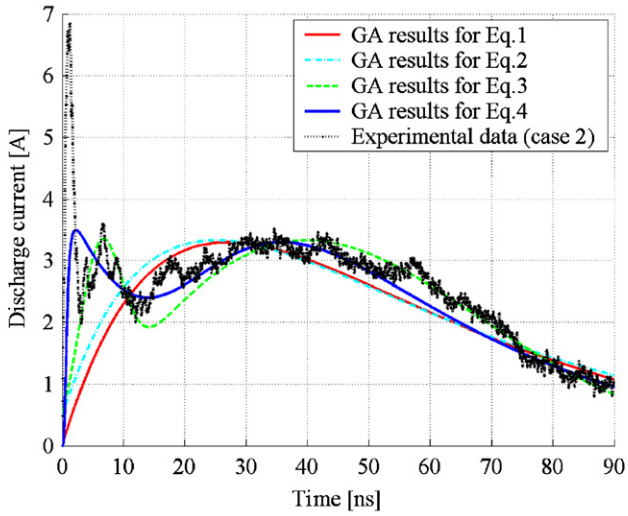

Figure 5. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)–(4) for the second case (charging voltage = +2 kV).

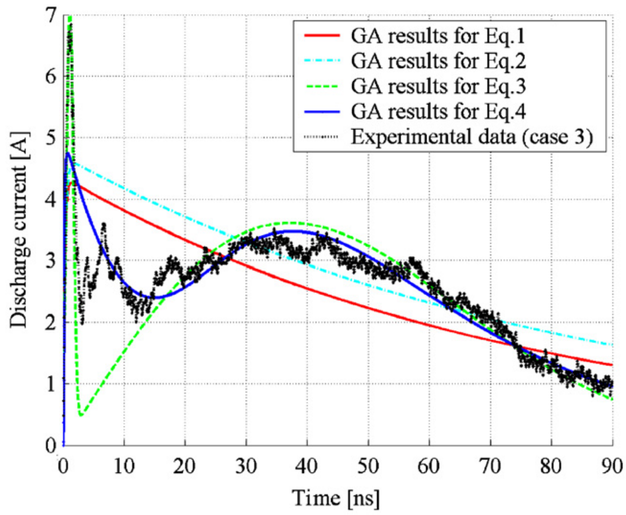

Figure 6. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)–(4) for the third case (charging voltage = +2 kV).

error (F_g) for each equation and for the same case (sampling rate). The second way is to compare the curves of figures 4–9 for all cases and to find which curve fits best the experimental data and especially in the first ns, which are the most crucial for the ESD phenomenon. Both ways are correct depending on one's point of view. If we take account of the four parameters (t_r, I_{max}, I_{30} and I_{60}), the limits of which are examined during the verification of the ESD generators, then a good fit of the curve up to 60 ns is required. Therefore, the best way to evaluate the best equation is to compare the error (F_g) from (7). If we take account of the fact that the most crucial part of the discharge current is the first ns (t_r and I_{max}) then the best way to evaluate the most appropriate equation is to compare the curves neglecting the later parts of the discharge current (e.g. the period from 20 ns to 90 ns).

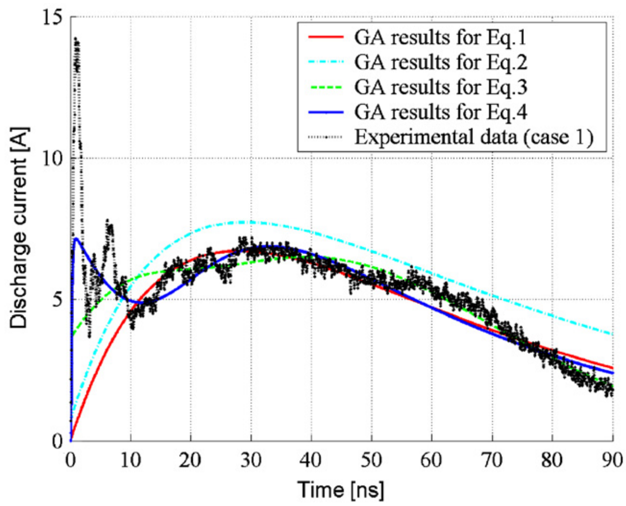

Figure 7. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)–(4) for the first case (charging voltage = +4 kV).

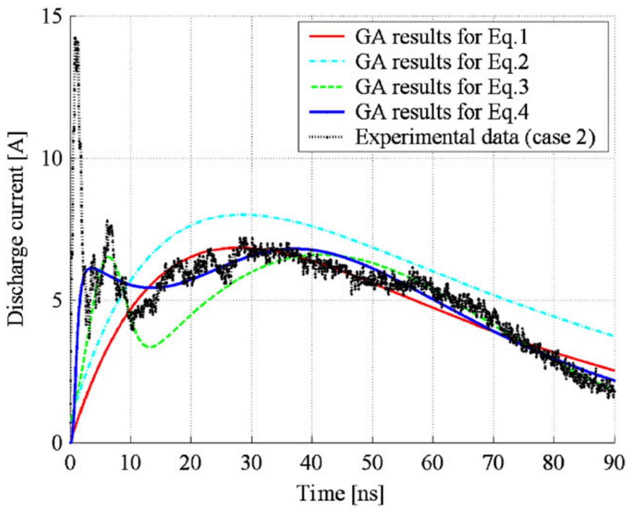

Figure 8. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)–(4) for the second case (charging voltage = +4 kV).

Following the first way and comparing the error (F_g) for each equation and for the same case (sampling rate) it can be concluded that the equations can be sorted as follows: (4)→(3)→(2)→(1), with (4) giving the best result. An error (F_g) comparison of an equation for different cases is not reasonable, because the experimental data, which have been used in this optimization, are different not only due to the different sampling rates, but also due to the different point distributions with respect to time.

Also, from tables 3–6 it can be seen that the minimum error (F_g) is achieved in case 2, a greater error is observed in case 1, while the maximum error appears in case 3. This was expected, since in case 2 the points are equally distributed in the first 90 ns of the ESD phenomenon. Therefore most of the points are after t_{max}. Furthermore, the transient behaviour of the experimental data in the first ns increases the error (F_g).

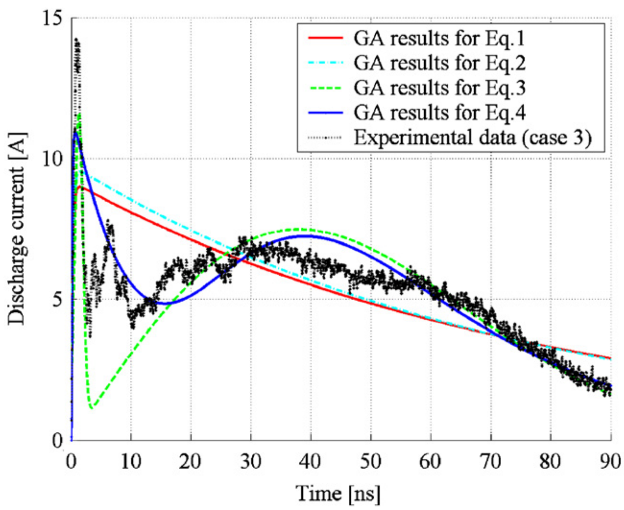

Figure 9. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)–(4) for the third case (charging voltage = +4 kV).

Table 3. The optimized values of the parameters for equation (1), using experimental data.

	+2 kV			+4 kV		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
i_0 (A)	34.95	34.93	4.35	28.67	33.90	9.18
t_1 (ns)	31.96	30.72	74.61	39.55	37.30	78.22
t_2 (ns)	24.74	23.75	0.25	20.70	21.39	0.24
F_g	24.80	17.59	37.55	21.12	15.80	36.71

Table 4. The optimized values of the parameters for equation (2), using experimental data.

	+2 kV			+4 kV		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
i_1 (A)	9.88	11.43	4.69	18.22	19.61	9.77
i_2 (A)	9.37	10.94	4.27	17.50	18.91	9.07
t_1 (ns)	55.31	40.26	85.05	58.05	55.31	73.36
t_2 (ns)	18.68	18.40	0.32	17.49	17.48	0.28
F_g	24.12	17.04	37.64	20.49	15.64	36.47

Table 5. The optimized values of the parameters for equation (3), using experimental data.

	+2 kV			+4 kV		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
A (A)	2.54	2.54	6.87	3.75	5.09	11.20
B (A)	0.13	0.13	0.16	0.25	0.23	0.31
t_1 (ns)	4.98	6.14	1.09	3.13	5.93	1.28
t_2 (ns)	7.88	6.65	1.53	3.13	9.41	2.99
σ_1 (ns)	4.97	4.84	0.78	17.50	4.25	0.95
σ_2 (ns)	50.10	51.45	51.56	55.35	51.58	51.56
F_g	16.51	10.46	23.57	16.95	12.67	28.85

Comparing the curves of figures 4–9 for all cases and for both charging voltages it is obvious that the equation which has the best fitting to the experimental data is (4). This is the most suitable of all the examined equations, since it simulates the discharge current in the best way. The second most suitable

Table 6. The optimized values of the parameters for equation (4), using experimental data.

	+2 kV			+4 kV		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
i_1 (A)	3.93	3.45	4.69	7.05	6.03	10.76
i_2 (A)	3.98	3.69	4.34	6.80	6.39	9.67
t_1 (ns)	0.14	0.80	0.19	0.24	1.13	0.19
t_2 (ns)	15.59	16.07	12.83	16.93	33.28	11.41
t_3 (ns)	37.06	35.74	39.70	28.11	43.38	43.65
t_4 (ns)	29.87	31.23	27.46	42.35	29.13	25.00
F_g	12.78	10.25	22.41	13.71	11.51	23.62

Table 7. Selection of the measured current's points (charging voltage = +2 kV).

Cases	Step	Selected points for 90 ns	Selected points for 50 ns	Selected points for 30 ns
First case (Exp6)	6(1+round (exp(j/N)))*	148	96	64
Second case (Idata20)	Constant equals 20	113	64	39
Third case (Idata20N)	0–2 ns: all points 2–90 ns: points from Idata20	161	112	87

equation (3), although it can simulate the first peak it has in some cases (for example in figures 6 and 8) bad behaviour compared to the measured data. This proves that (3) is not as flexible as equation (4). The other two equations (1) and (2) cannot simulate the first peak of the discharge current and they are similar to the waveform which occurs from the simulation of the standard's circuit, presented in [11].

From figures 4–9 it can be concluded that of all cases, case 3 is the one which achieves a better approach to the shape of the discharge current for the first ns. It can be concluded that with case 3 and equation (4), the analytical expression for the discharge current approximates to that specified by the standard. This proves that selecting the whole number of measured points for the first nanoseconds does not produce the best determination of the parameters.

Since equation (4) is the best of the four equations, another approach for the best fitting curve of (4) to the experimental data is to give as input to the genetic algorithm data with different time durations. In table 7 can be seen the point selection that has been made for three different time durations of the discharge current (90 ns, 50 ns and 30 ns), when the charging voltage is +2 kV. Table 8 presents the optimized values of the parameters of equation (4) and the errors calculated by (7).

From table 8 it can be seen that case 2 is the one which has the minimum error F_g. As the time duration of the measured data that are used as input to the GA decreases, the error F_g increases, something that is expected. From figures 10–12 it is obvious that the initial peak is better approached when the measured data have the time duration of 30 ns. The better approach of the initial peak is achieved for the third case as can be seen in figure 12. However, as the time duration decreases there is a worse approach of the rest of the waveform and this is why the error F_g increases.

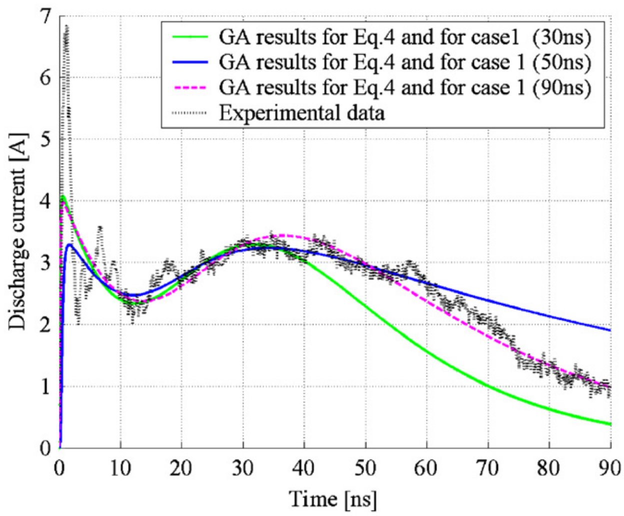

Figure 10. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of equation (4) for the first case and for different time durations.

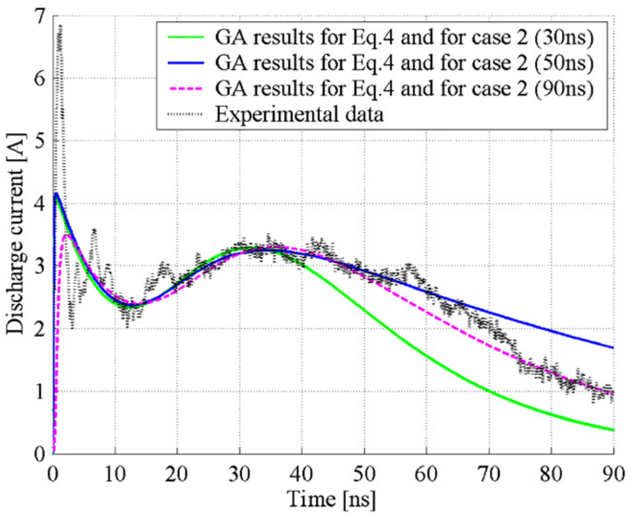

Figure 11. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of equation (4) for the second case and for different time durations.

In order to examine how the GA is affected if the error F_L is used as a criterion, this criterion has been applied for all cases in equation (4), since as was previously described it has the best fit to the experimental data. These optimum values are presented in table 9 for all cases, while figures 13–15 present common graphs of the experimental data of the discharge current and the discharge current for the optimized parameter values for (4) as they are presented in tables 6 and 9 for the charging voltage of +2 kV.

Comparing the curves of figures 13–15 it is obvious that minimizing equation (8) instead of equation (7) the initial peak can be approached better for all cases. Using the objective function of (8) we can see in figures 13–15 that the fit of the

Table 8. The optimized values of the parameters for equation (4), using experimental data (for 30 and 50 ns durations of the discharge current).

	30 ns			50 ns			90 ns		
	First case (Exp6)	Second case (Idata20)	Third case (Idata20N)	First case (Exp6)	Second case (Idata20)	Third case (Idata20N)	First case (Exp6)	Second case (Idata20)	Third case (Idata20N)
i_1 (A)	3.28	4.03	5.37	3.23	4.12	5.14	3.93	3.45	4.69
i_2 (A)	4.16	4.32	3.09	2.81	3.16	3.17	3.98	3.69	4.34
t_1 (ns)	0.28	0.14	0.30	0.49	0.12	0.27	0.14	0.80	0.19
t_2 (ns)	17.68	12.80	8.42	20.14	13.75	10.65	15.59	16.07	12.83
t_3 (ns)	39.84	39.17	20.39	24.74	25.02	22.59	37.06	35.74	39.70
t_4 (ns)	23.05	19.30	58.75	89.85	66.12	88.83	29.87	31.23	27.46
F_g	6.46	4.74	15.57	7.70	5.57	17.15	12.78	10.25	22.41

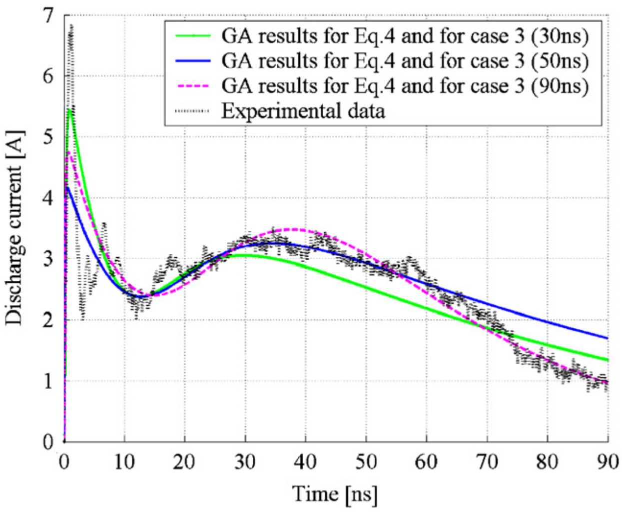

Figure 12. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of equation (4) for the third case and for different time durations.

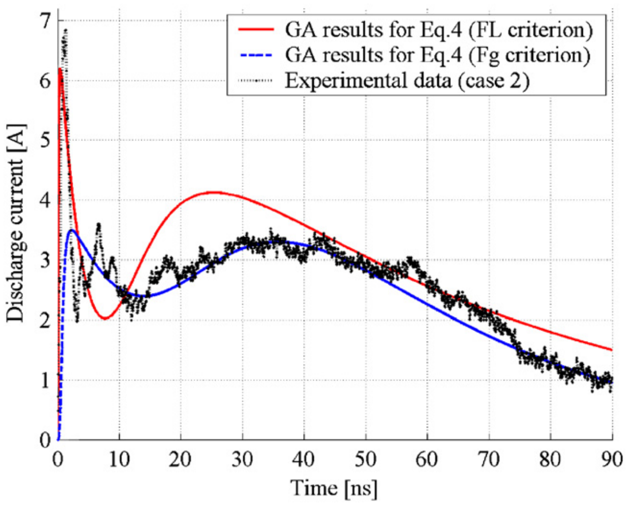

Figure 14. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of equation (4) for the second case and for different error criteria.

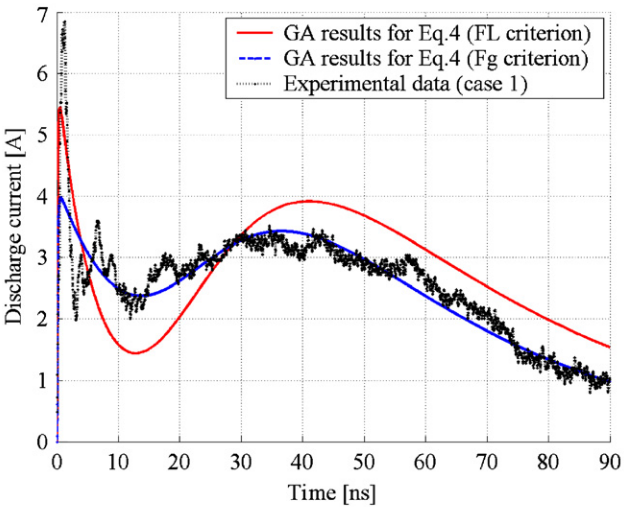

Figure 13. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of equation (4) for the first case and for different error criteria.

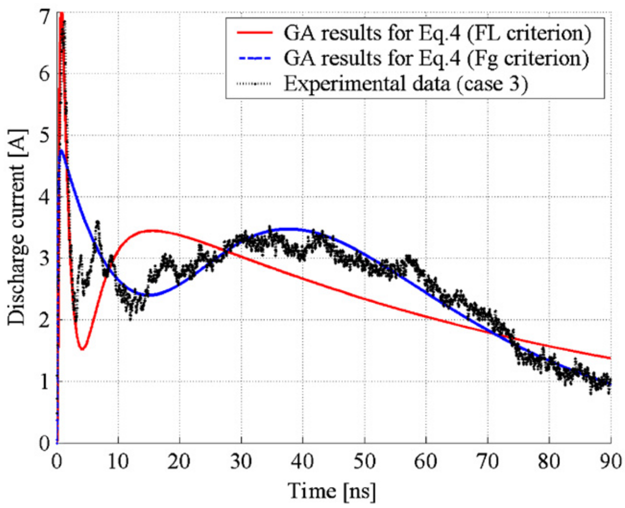

Figure 15. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of equation (4) for the third case and for different error criteria.

GA's results on the experimental data is worse than using (7) after the initial peak. Also, it is concluded that this criterion (minimization of (8)) should be used when we want to achieve better curve fit for the first ns. If we want to have better fit to

Table 9. The optimized values of the parameters for equation (4), using experimental data.

	+2 kV			+4 kV		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
i_1 (A)	5.39	6.14	7.56	12.81	14.26	11.57
i_2 (A)	4.81	4.28	3.43	6.03	6.98	8.68
t_1 (ns)	0.14	0.13	0.48	6.05	0.12	0.33
t_2 (ns)	6.33	4.31	1.29	0.04	2.85	4.07
t_3 (ns)	35.18	14.72	6.53	4.41	7.44	13.79
t_4 (ns)	35.91	54.67	75.42	8.16	70.56	67.36
F_L	1.40	1.38	1.57	2.52	2.34	3.22

the experimental data then the minimization of (7) should be used instead.

6. Conclusions

GAs are a useful optimization tool, appropriate for many applications. In this work, a methodology based on a GA has been proposed to calculate the parameters of four equations that can describe the discharge current produced by an ESD generator. The GA has as input experimental data of the discharge current and it gives as output the values of the optimized parameters. The selection of the experimental data has been made in three different ways. The calculated discharge current is close to the current that is measured, proving the efficiency of the GA. No matter how the evaluation of the best equation is made, either by comparing the error (F_g) in each case or by comparing the curves for each case, it is concluded that the best equation is (4). Equation (3) has worse behaviour than (4) since it is not as flexible as (4), but since it approximates the first peak of the discharge current it is better than (2) and (1). Also, comparing the three different cases for the same equation having F_g as a criterion the best behaviour is observed for case 2, with case 1 and case 3 following. However if the criterion is the best approximation of the discharge current for the first ns then the best behaviour is observed for case 3, since it includes all the measured points for the first 2 ns. Also, using two different objective functions for the GA as they were presented in equations (7) and (8), it is concluded that using equation (8) we achieve a better fit of the curve to the experimental data for the first ns, while equation (7) is better for the better fit to the experimental data for the whole duration of the ESD pulse. Therefore, a current source which produces the ESD current of (4) is preferable to the ESD generator circuit described by the IEC 61000-4-2. The next revision of the standard [1] should take the remarks of the work presented here into consideration, in order to define accurately the equation of the discharge current produced by electrostatic discharges.

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