Parameter evaluation for the equation of the electrostatic discharge current, using genetic algorithms as optimization tool

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Abstract— **The aim of this paper is the parameter evaluation of possible equations that can describe the current during an electrostatic discharge, using a genetic algorithm. Aberrations between simulations and the waveform described in the Standard make it necessary to find an equation for the electrostatic discharge current. In this work the genetic algorithm has been applied on the parameters of four equations. The genetic algorithm has as input data real measurements of the discharge current produced by an electrostatic discharge generator and by using these data optimizes the parameters of the mathematical equations. The efficiency of the algorithm is proven by the fact that the error between the experimental and the optimized data is small. Comparing the results of the four equations the most suitable equation for the discharge current derives.**

Index Terms— **Discharge current, electrostatic discharge, genetic algorithms, optimization.**

I. INTRODUCTION

Electrostatic Discharge (ESD) is a very common phenomenon. It occurs when an amount of electric charge is being transferred between conducting bodies that have different electrostatic potentials. The IEC 61000-4-2 [1], which describes the test procedure of electronic equipment under ESD defines the shape of the discharge current that the ESD generators must produce.

A considerable amount of effort has been made in order to study the ESD current waveforms. In [2] it has been shown that the amplitudes and the rise times vary with the charging voltages, approach speeds, electrode types, the relative arc length and humidity. The purpose of another study [3] was to define the parameters that govern 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 deviations that there are on the discharge current, when various conditions change during the test. This is achieved using Spice by which he changes the values in components of the ESD generator's circuit.

The IEC 61000-4-2 [1] has an aberration between the typical waveform of the output current of the ESD generator and the discharge current that the ESD generator of the Standard produces in reality. There have been various publications that propose an improved circuit for the ESD generators. A modified generator with a reference waveform very close to the one that the Standard defines and also the equation of the reference waveform has been proposed [5]. In another work [6] the adopted human body model is divided into 11 elemental blocks and treated by the diakoptic method in analogy with network theory, using the SPICE software. Another proposed equation [7] for the reference waveform has been developed in order to investigate the ESD phenomenon in coaxial cable shields. Apart from the circuits for the ESD generators an equation, which will accurately give the ESD current, could be estimated. This equation could be used in simulation programs describing accurately the ESD generator.

This work aims the optimization of the parameters of the current discharge equation using genetic algorithms (GA). Such an attempt gives very good results, since minimizes the error between the measured current and the current produced by the equations. The method is applied on four different types of equations giving as results the optimum values of the parameters of the equation.

II. THE DISCHARGE CURRENT OF THE ESD GENERATORS

A. The IEC 61000-4-2 and the need for an analytical equation for the discharge current

It has been observed [8] that using the circuit defined in the Standard and for various loads (EUT) the current's waveform in Fig. 1b differs from the waveform defined by the Standard shown in Fig. 1a. Fig. 1b presents the simulation results obtained by using the Spice software for ohmic EUTs and a DC charging voltage of +4 kV.

It is noticeable that computer simulations of the circuit defined in the Standard insert an error in the calculated voltages and currents. This error should be minimized and in order to obtain this there are two possible ways. The first one

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Manuscript received April 19, 2006. The project is co - funded by the European Social Fund (75%) and National Resources (25%) - (EPEAEK II) – PYTHAGORAS II. G.P. Fotis is supported by a Ph.D study scholarship from the State Scholarships Foundation of Greece.

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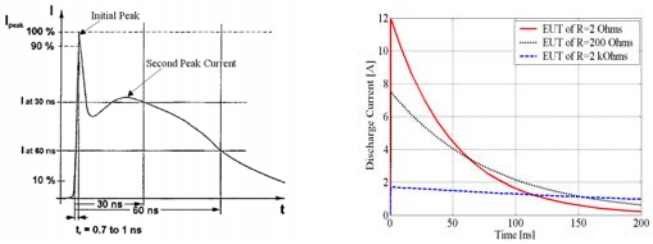
is a new circuit of the ESD generator to be proposed similar to the work that has been done in [5] and [6]. The second is the use of an ESD current source, where the produced current waveform is a function of a number of parameters as it has been proposed in [3], [5] and [7].

In this paper the second way has been followed. Using a number of equations, which describe mathematically the discharge current a methodology based on a GA has been developed. The parameters of these equations are calculated using measured discharge currents from an ESD generator.



(a) (b)

Fig. 1. a) Typical current waveform of an ESD generator [1], b) ESD current from the PSPICE program for Standard's circuit for ohmic EUT [8].

B. *Equations of the discharge current*

A very known equation, which does not correspond to the discharge current, but it will be used in the further analysis for the application of the GA is the one of the lightning current given by the following equation [9]:

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

A first approximate equation of the discharge current for simulators was first introduced by [10] using a double exponential function:

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

According to [7] the discharge current is:

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

The pulse described in Fig. 1a 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 $A \cdot e^{-\left(\frac{t-t_1}{\sigma_1}\right)^2}$ and $B \cdot t \cdot e^{-\left(\frac{t-t_2}{\sigma_2}\right)}$ represent the narrow and broad Gaussian respectively.

Heidler [11] presented an analytical formula for the lightning current, which was adopted by Pommerenke [5]. This waveform is given by the formula below:

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

where 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. Here n equals to 3.

The unknown parameters of these four different equations need to be optimized in order for the measured ESD current to be analytically described.

III. EXPERIMENTAL SETUP

Fig. 2 shows the ESD current experimental setup. The current for a charging voltage of +4 kV, was measured by a 4-channel Tektronix oscilloscope model TDS 7254B, whose bandwidth ranged from DC to 2.5 GHz. An ESD generator, model NSG-438 of Schaffner produced contact discharges and it was grounded to the earth via a ground strap. In order to measure the ESD current a resistive load (Pellegrini target, MD 101 of Schaffner) was used and placed on the center of grounded metal plane with dimensions 1.5 m x 1.5 m. The Pellegrini target was connected to the oscilloscope by HF coaxial cable. The measurements were conducted in an anechoic chamber in order for the measurement system to be unaffected by the surrounding equipment.

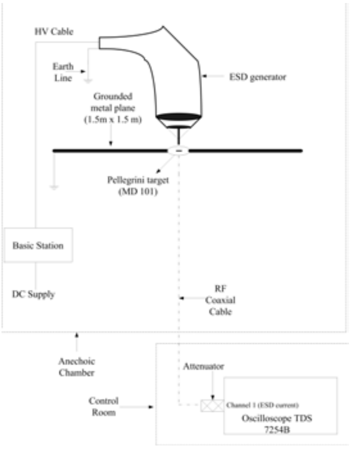


Fig. 2. Experimental setup.

The measured discharge current is depicted in Fig. 3, when the discharge occurred in contact discharge mode and the charging voltage was +4 kV. The measured discharge current has been used as input data for the application of the GA.

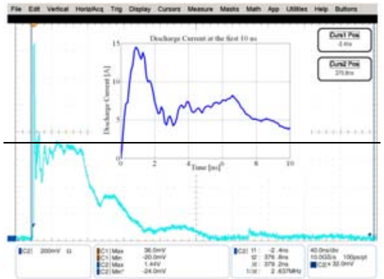


Fig. 3. Current waveform taken by the oscilloscope TDS 7254B for a charging voltage of 4 kV. In the upper right part of the figure the first 10 ns of the ESD current are presented in detail.

IV. THE GENETIC ALGORITHM

The GA has been developed using the software package Matlab and produces excellent results in different optimization problems [12-14]. The procedure of the GA starts with a randomly generated population of P_s=40 chromosomes. It generates 40 (P_s) random values for each time parameter

($0<t_i<100$, $1\leq i\leq 2*E$) and 40 (P_s) random values for each current parameter ($0<i_i<30$, $1\leq i\leq E$), with E=1 or 2 for equations (1)-(4). Each parameter is converted to a 20-bit binary number. Each chromosome has 3*E variables so (60*E) bits are required for the chromosome. Each pair of parents with crossover generates N_c=4 children. The crossover begins as each chromosome of any parent is divided into N_p=6 parts, the pair of parents interchange their genetic material. After crossover there is a P_m=7% probability for mutation. The termination criterion is fulfilled if either the mean value of F_g in the P_s-members population is no longer improved or if the number of iterations is greater than the maximum number of iterations N_{max}.

V. RESULTS

Giving as input data the discharge current of the ESD generator, the GA calculates and optimizes the parameters of (1)-(4). 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:

$$F_g = \sum_{i=1}^{N} \frac{\left| I_i^m - I_i^c \right|}{I_i^m} \tag{5}$$

The total number of the measured data was 2250 and the duration of the discharge current was 90 ns. The whole number of the measured points has not been used, but instead of these the waveforms' points have been carefully selected as it can be seen in Table I for three different types of point selection. In the first case a function has been used, as it is shown in Table I 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 stepwidth is constant and equals to 10. This means that from the measured data of 2250 sequential points the 1st, 11th , … will be selected. Due to the fact that the discharge current receives its peak between 0.7-1 ns [1] the number of points before the 1 ns is extremely small. The third case has been used in order for the GA to take all the measured points at 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 it is shown in Table I.

TABLE I
SELECTION OF THE MEASURED CURRENT'S POINTS FOR THE TWO CHARGING VOLTAGES

Cases	Step	Selected points for 90 ns
1st case (Exp4)	4(1+round(exp(j/N)))[a]	95
2nd case (Idata10)	Constant equals to 10	76
3rd case (Exp4N)	0-2 ns: All points 2–90 ns: Points from Exp4	139

[a] j is the jth point of the measured data of 2250 points

It must be mentioned that the first nanoseconds of the electrostatic discharge are the most crucial. This happens due to the fact that most of the radiation and the largest values of the current derivative occur during this period. Case 3 takes that remark into consideration, as it includes all the measured points until the 2nd nanosecond. However, in cases 1 and 2 the number of points at the first nanoseconds are less than in the third case, due to the fact that it was attempted the GA to give accurate results for the whole time duration of the phenomenon.

In Figs 4-6 common graphs of the experimental data of the discharge current and the discharge current for the optimized parameter values for (1)-(4) are depicted.

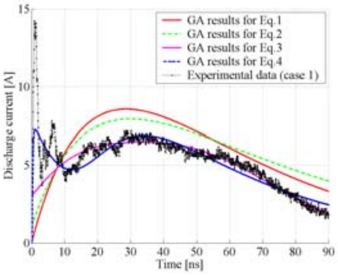


Fig. 4. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)-(4) for the 1st case.

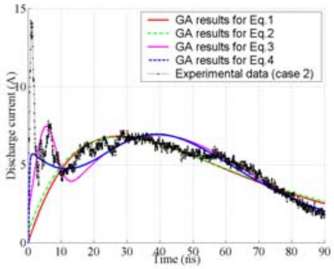


Fig. 5. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)-(4) for the 2nd case.

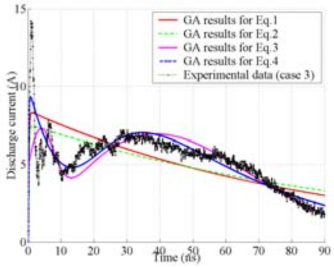


Fig. 6. Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1)-(4) for the 3rd case.

Tables II–V present the optimized values of the parameters of each equation and the errors calculated by (5).

TABLE II
THE OPTIMIZED VALUES OF THE PARAMETERS FOR EQ. (1).

	Case 1	Case 2	Case 3
i_0 (A)	46.99	35.75	8.44
t_1 (ns)	37.17	36.64	87.50
t_2 (ns)	22.53	21.68	0.20
F_g	31.86	31.93	59.50

TABLE III
THE OPTIMIZED VALUES OF THE PARAMETERS FOR EQ. (2).

	Case 1	Case 2	Case 3
i_1 (A)	20.43	25.76	7.55
i_2 (A)	19.37	25.08	6.87
t_1 (ns)	56.46	41.38	109.35
t_2 (ns)	19.23	20.35	0.20
F_g	31.11	31.16	58.34

TABLE IV
THE OPTIMIZED VALUES OF THE PARAMETERS FOR EQ. (3).

	Case 1	Case 2	Case 3
A (A)	3.26	5.96	6.25
B (A)	0.20	0.29	0.29
t_1 (ns)	6.25	4.99	3.13
t_2 (ns)	12.55	0.43	0.34
σ_1 (ns)	22.42	4.77	6.25
σ_2 (ns)	51.57	54.92	54.58
F_g	23.11	24.13	50.68

TABLE V
THE OPTIMIZED VALUES OF THE PARAMETERS FOR EQ. (4).

	Case 1	Case 2	Case 3
i_1 (A)	7.16	5.62	9.21
i_2 (A)	7.13	7.81	7.74
t_1 (ns)	0.31	0.34	0.19
t_2 (ns)	14.99	29.98	11.88
t_3 (ns)	28.71	48.12	29.70
t_4 (ns)	41.41	24.99	37.85
F_g	21.87	22.29	33.94

Comparing the error (F_g) for each equation and for the same case (sampling rate) the equations can be sorted as follows: (4)→(3)→(2)→(1), with (4) giving the best result. Also, from Tables II-V it can be seen that the minimum error (F_g) is in cases 1 and 2 having approximately the same value. The greater error is observed in case 3.

From Figs. 4-6 and for all cases it is obvious that the equation having 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. Although the second more suitable equation (3) can simulate the first peak in some cases (for example in Fig. 6) it has a very bad behavior 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 Fig 1.

From Figs. 4-6 useful conclusions for the three different cases can derive. It can be observed that in Fig. 6, where all the measured points have been selected for the first nanoseconds a better approximation of the discharge current for (4) is achieved at the first nanoseconds, comparing to Figs. 4 and 5. This proves that even though the whole number of the measured points is selected for the first nanoseconds, the determination of the parameters will not be the best.

From Figs. 4-6 it can be concluded that from all cases, cases 1 and 2 achieve a better approximation to the desirable of the discharge current. It can be concluded that with the point selection of case 3 and equation (4) the analytical expression for the discharge approximates to the one specified by the Standard, since it simulates better the two peaks although it has greater error.

VI. CONCLUSIONS

In this work a methodology based on a GA has been proposed in order to calculate the parameters of the discharge current produced by an ESD generator. The selection of the experimental data has been made using four different ways. The calculated discharge current is very close to the current that is measured. Evaluation of the equations and the sampling rates has shown that they can be sorted as: (4)→(3)→(2)→(1), and case 1→case 2→case 3, respectively, with equation (4) and case 1 having the best behavior. Therefore, a current source that produces the ESD current of (4) is preferable to the ESD generator circuit described by the IEC 61000-4-2.

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