Parameters' optimisation methods for the electrostatic discharge current equation

Vasiliki C. Vita, George P. Fotis, and Lambros Ekonomou

Abstract— In the current international standard IEC 61000-4-2 the equation describing the electrostatic discharge current needs a further investigation in order to describe the measured current accurately. In the current paper two different optimization methods are presented that have been developed in order to calculate the parameters of the electrostatic discharge current equation. The first method uses a quasi-Newton optimization algorithm, while the second one uses genetic algorithms and constitutes an extension of a methodology that has been used in a previous research work. Electrostatic discharge current data obtained from real measurements are also used in this work in order to compare them with the results obtained from the two proposed methods in an effort to prove their efficiency and accuracy. The proposed methods are extremely useful in the ESD studies, since an accurate electrostatic discharge current equation is an indispensable requirement for the description of the ESD generators in simulation programs.

Keywords— Discharge current, electrostatic discharge, electrostatic discharge generators, genetic algorithms, optimization algorithms.

I. Introduction

Electrostatic Discharge (ESD) is common phenomenon that is very crucial for electronic devices such as integrated circuits or fast complementary metal oxide semiconductor 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, which is different to the ESD current produced by the proposed ESD generator circuit. The proposed equation for the discharge current needs a further investigation in order to fit to the measured discharge current. An accurate equation is an indispensable requirement for the description of the ESD generators in simulation programs.

Many studies have been conducted worldwide to study the ESD current waveforms. In [2] it has been concluded that the amplitudes and the rise times depend on the charging voltages, the approach speeds, the electrode types, the relative arc length and the humidity. The parameters that characterize the discharge current waveforms of ESD testers have been studied in [3]. Murota in [4] presented the variations that appear on the discharge current, when various conditions change during the test using the simulation program PSpice. An improved circuit for the ESD generators with a reference waveform close to the one defined by the Standard and an equation describing the reference waveform have been proposed [5]. Another proposed equation [6] for the reference waveform has been developed in order to study the ESD phenomenon in coaxial cable shields. Finally the downhill simplex optimization method in [7] and genetic algorithms in [8] have been used in order to determine an accurate electrostatic discharge current equation considering all the known at that time discharge current equations that have been used in the technical literature.

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In the current paper two different optimization methods are presented that have been developed in order to calculate the parameters of the electrostatic discharge current equation proposed by the current international standard IEC 61000-4-2 [1], in an effort to describe the measured current with high accuracy. The first method uses a quasi-Newton optimization algorithm, while the second one uses genetic algorithms and constitutes an extension of a methodology that has been used in a previous research work [8]. The obtained results are compared with electrostatic discharge current data obtained from real measurements proving the efficiency of the proposed methods.

II. ESD Generators' Discharge Current

The ESD generators are used for testing the robustness of electronics towards electrostatic discharges. Electrostatic discharges can occur either as contact discharges or as air discharges. The test level voltages for the contact discharges range between 2 and 8 kV and for the air discharges between 2 and 15 kV. According to the Standard for the verification of ESD generators there are 4 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}).

A typical waveform of the output current of an ESD generator is shown in Fig. 1 and the limits of the 4 parameters (valid for contact discharges only) are shown in Table 1 [9, 10]. In Fig. 1 there are two peaks for the ESD pulse. The first peak (initial peak), where is the maximum discharge current is caused by a discharge of the hand, while the second peak is caused by a discharge of the body. The rise time of the initial peak is 0.7-1 ns, with its amplitude depending on the charging voltage of the ESD simulator.

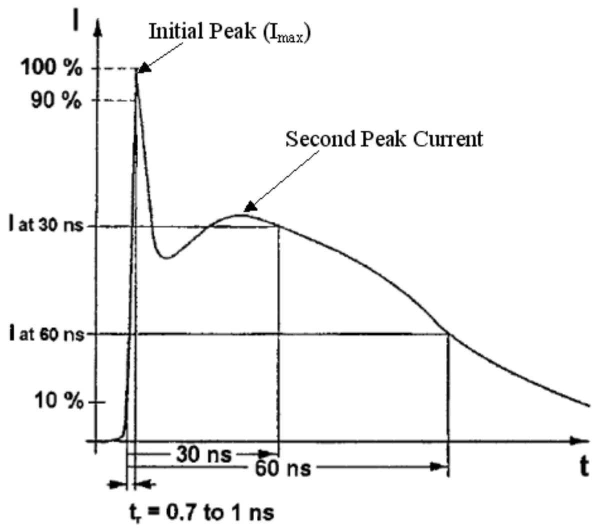

Fig. 1 Typical waveform of the output current of the ESD generator [1]

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

In Fig. 2 there is the proposed ESD circuit by the IEC Standard [1], which is consisted of the charging resistor R_c (50-100 MOhms), the energy-storage capacitor C_S (150 pF ± 10 %), the discharge resistor R_d, representing the resistance of the skin (330 Ohms ± 10 %) and the EUT (Equipment Under Test. The value of the energy-storage capacitor C_S is representative for the electrostatic capacitance of the human body, while the resistance of 330 Ohms has been chosen to represent the skin resistance of the human body. In Fig. 2 there are two switches. When the first switch is closed and the second (discharge switch) is open the capacitor C_S is being charged. After that the first switch opens and the discharge switch closes and so the electrostatic discharge on the EUT occurs.

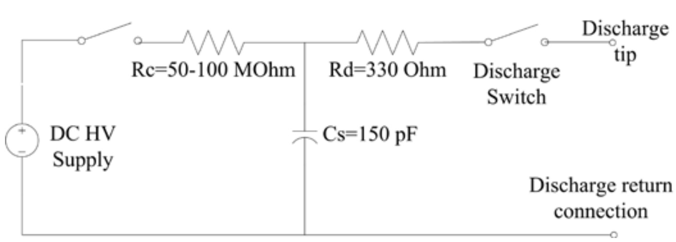

Fig. 2 Simplified diagram of the ESD generator [1]

The electrostatic discharge current is given by the following equation [1]:

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

where:

$k_1=e^{-\frac{\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{\frac{1}{n}}}$, and $k_2=e^{-\frac{\tau_3}{\tau_4}\left(\frac{n\tau_4}{\tau_3}\right)^{\frac{1}{n}}}$,

i_1, i_2 are currents in A,

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.

III. The Need for an Analytical and Accurate Equation of the Discharge Current for Commercial ESD Generators

In previous published work [11] it was proved that the circuit of Fig. 2 proposed by the IEC Standard [1] is not suitable. This circuit was simulated in the PSpice software using ohmic EUTs for a DC charging voltage of + 4 kV. In Fig. 3 it is obvious that the current's waveform for these different loads is different from the waveform defined by the Standard shown in Fig. 1.

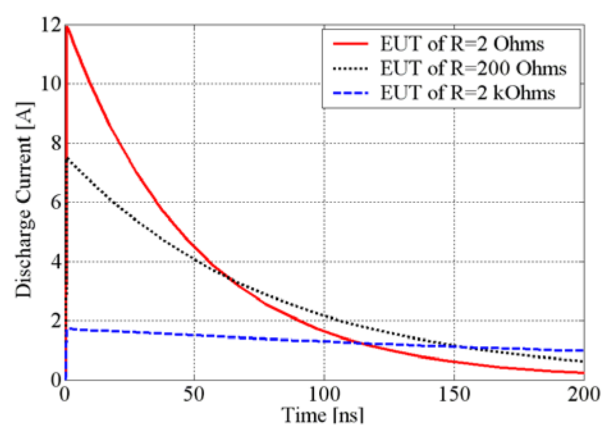

Fig. 3 Current waveforms from the PSpice program for the RC circuit with an ohmic EUT [11]

This mismatch between the simulation results of the IEC proposed circuit and the discharge current that the same IEC Standard defines has as a result computer simulations for the circuit defined in the Standard to insert an error in the calculated voltages and currents.

Therefore there is a need this error to be minimized. In order to obtain this, there are two possible ways. The first one is to propose a new circuit for the ESD generator as the work that has been done in [12]. The other one is to obtain an accurate equation for the ESD current as it has been proposed in [7] and [8]. The later way is used in this paper to calculate the optimum parameters of the electrostatic discharge current equation proposed by the current IEC Standard [1].

IV. Experimental Set-Up

Fig. 4 shows the experimental set-up for the measurement of the ESD current. The discharge current for a charging voltage of + 4 kV, was measured by a Tektronix oscilloscope (model TDS 7254B), whose bandwidth ranged from dc to 2.5 GHz. The contact discharge current was produced by the NSG-438 ESD generator, of the Schaffner Company and it was grounded to the earth via a ground strap. The measurement of the current was conducted using a resistive load known as Pellegrini target (MD 101 of Schaffner) with its bandwidth ranged from dc to above 1 GHz. It was mounted in the center of a metal grounded plane, with dimensions 1.5 m x 1.5 m and it was connected to the oscilloscope by a HF coaxial cable.

In order to have the measurement system unaffected by the surrounding equipment the measurements were conducted in an anechoic chamber and the cables were set away from the discharge point. In order to minimize the uncertainty of the measurements the ground strap was at a distance 1 m from the target as the Standard defines and the loop was as large as possible. The measurement system of Fig. 4 is in accordance with the Standard [1] and provides high fidelity data. The current's waveform can easily be seen as it has been taken by the oscilloscope in Fig. 5.

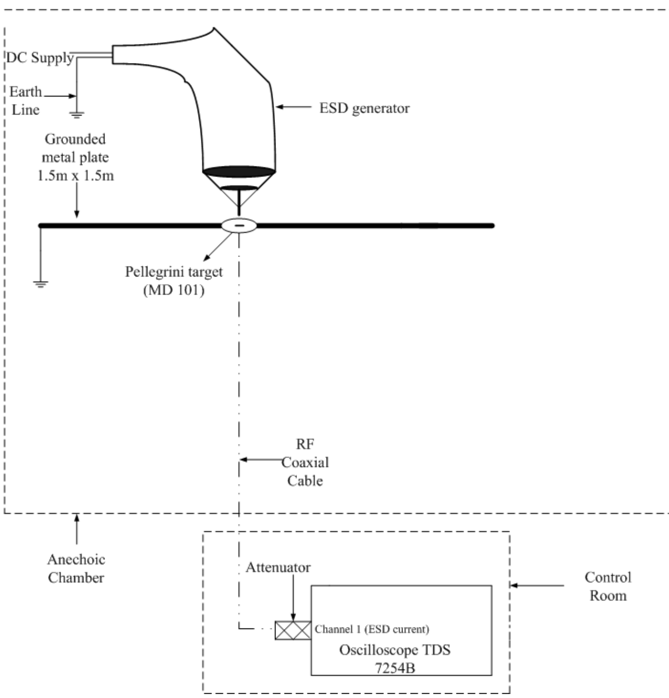

Fig. 4 Experimental set-up

V. Optimization Methods

A. *The Quasi-Newton Optimization Algorithm*

The waveform of the discharge current that occurs for the optimized parameter data of the four possible equations must be as much closer to the measured discharge current. Considering that the accuracy of the computed discharge current depends on the model parameters, these can be determined by minimizing the function:

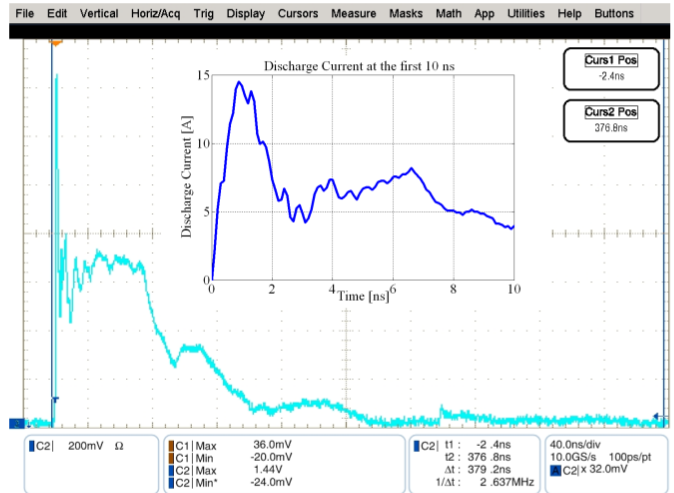

Fig. 5 Current waveform taken by the oscilloscope TDS 7254B for a charging voltage of + 4 kV. The first 10 ns of the ESD are presented in detail at the upper right part of the figure current

$$e = \frac{I_c(t,x) - I_m(t)}{I_m(t)} \cdot 100 \tag{2}$$

where:

$I_c(t, x)$ is the computed discharge current and

$I_m(t)$ is the measured discharge current.

The equation (1) that describes the discharge current, is consisting of seven different parameters whose values may have various values. The objective is the minimization of the absolute error of (2), which is a function of seven variables. The equation's parameters form a column vector x:

$$x = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]^T = [i_1,\ i_2,\ \tau_1, \tau_2, \tau_3,\ \tau_4, n]^T \tag{3}$$

The application of an optimization algorithm will determine the optimal values x_i, with its goal the minimization of the relative error, which is a function of several variables. e(x) is the relative error, where x is the column vector presented in (3). The optimal solution can be found after the iteration of a formula of the form:

$$x_{n+1} = x_n - \lambda_n \cdot colM_n \tag{4}$$

where:

X_n is the value of the design characteristic vector at the n^{th} iteration,

λ_n is the coefficient vector, which accelerates the convergence,

$colM_n$ is the column vector formed from the Jacobian matrix M_n and

M_n is the Jacobian matrix, defined as:

$$M_n(x_1, x_2, \ldots, x_7) = \begin{bmatrix} \frac{\partial e_1}{\partial x_1} & \cdots & \frac{\partial e_1}{\partial x_7} \\ \ldots & \ldots & \ldots. \\ \frac{\partial e_7}{\partial x_1} & \cdots & \frac{\partial e_7}{\partial x_7} \end{bmatrix} \tag{5}$$

This method computes the first partial derivatives of the objective function in reference to the dependent variables [13]. It is internally made, by writing a suitable approximation of the objective function up to a desired degree.

The following algorithm based on quasi-Newton method has been implemented.

Step 1: Set initial values for the i_1, i_2, τ_1, τ_2, τ_3, τ_4, n of equation (1).

Step 2: Calculate e from (2), M_n from (5) and x_{n+1} from (4).

Step 3: As long as: $\| x_{n+1} - x_n \| < \varepsilon$, repeat Step 2,

where:

ε is a positive parameter, which defines the desired convergence precision.

Step 4: Display converged values X_n.

B. The Genetic Algorithm

In previous work [8] an efficient genetic algorithm (GA) for the calculation of the parameters of equation (1) was used. It was proven that the optimized values of these parameters could describe the discharge current, produced by an ESD generator calculated accurately with a minor error. The GA has as input experimental data of the discharge current and it gives as output the values of the optimized parameters. The flow chart of the GA is depicted in the flow chart of Fig. 6.

The GA does not require the use of the whole measured data. The whole number of the measured points, which is 2300, has not been used in the algorithm.

Furthermore in order the proposed GA to be more efficient, the existing method has been extended following a different procedure for the selection of the measured data. The function that was used for the selection of the measured points was the following:

$$\text{Stepwidth} = \begin{cases} \text{All measured points}, & 0\text{ns} \le t \le 5\text{ns} \\ 2(1 + \text{round}(\log(j))), & 5\text{ns} < t < 40ns \\ 3(1 + \text{round}(\exp\left(\frac{j}{N}\right), & 40\text{ns} \le t \le 90\text{ns} \end{cases} \quad (6)$$

where:

j is the jth point of the measured data of 2300 points.

As it can be seen, the stepwidth varies in order to take more points at the first ns (all measured points) and the GA to give more accurate results for this time period. The discharge current receives its peak at 0.7-1 ns and the number of points before the 1 ns is extremely small.

VI. Results

Table 5 presents the computed parameters for equation (1), as well as the optimum parameters' values obtained using the proposed genetic and quasi-Newton optimization algorithms. It is obvious that both proposed methods have provided similar results.

Fig. 7 presents in a single figure the comparison between the electrostatic discharge current waveform plotted using the experimental data that have been obtained through real measurements [14, 15] and the electrostatic discharge current waveforms plotted using the obtained optimized parameter values obtained using the proposed genetic algorithm (GA) and the quasi-Newton (QN) optimization algorithm.

Comparing the curves of Fig. 7 it is obvious that both proposed optimization methods have a very good fit on the measured electrostatic discharge current waveform. The initial peak of the electrostatic discharge current has been achieved in both the genetic algorithm and the quasi-Newton method's results. However, the best behavior to the real electrostatic discharge current is achieved using the quasi-Newton method, where the second peak is achieved with noticeable accuracy.

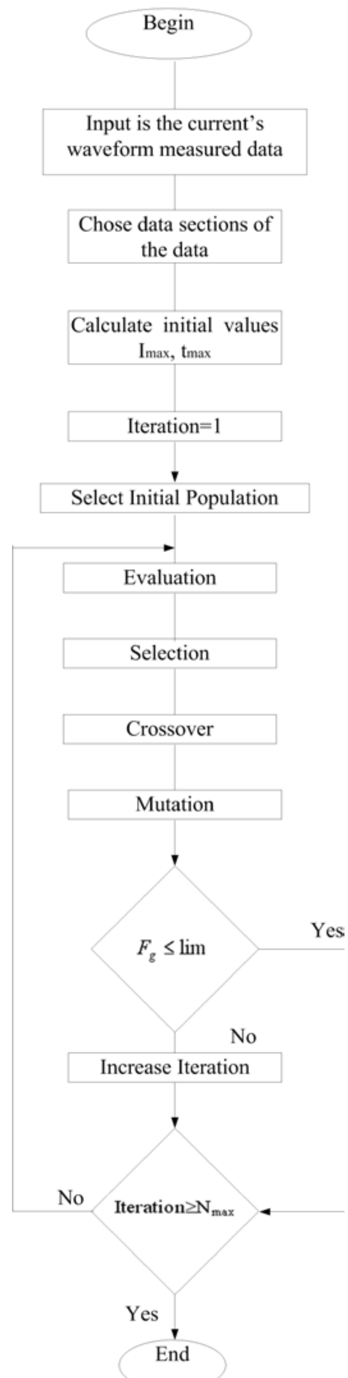

Fig. 6 The flow chart of the proposed GA

Table 2 Computed and optimized parameters' values for the electrostatic discharge current

Parameters	Computed values	Optimized values	
		Quasi – Newton	GA
i_1[A]	10.00	15.13	16.2
i_2[A]	6.10	8.95	9.2
τ_1[ns]	3.15	2.12	1.5
τ_2[ns]	1.67	2.22	2.1
τ_3[ns]	7.50	10.42	11.5
τ_4[ns]	35.00	37.36	37
n	1.70	1.91	1.82

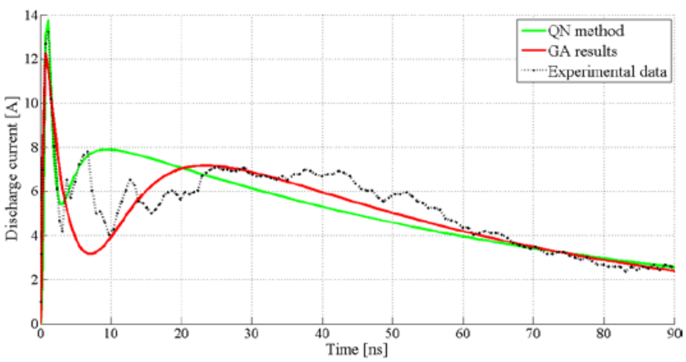

Fig. 7 Comparison between the experimental data of the electrostatic discharge current and the electrostatic discharge current for the optimized parameter values obtained from the genetic algorithm (GA) and the quasi-Newton (QN) optimization algorithm (charging voltage = + 4 kV)

VII. Conclusion

In this paper two different optimization methods were developed in order to determine the parameters of the electrostatic discharge current equation proposed by the international standard IEC 61000-4-2. The first method was based on a quasi-Newton optimization algorithm, while the second on a previous developed genetic algorithm that has been extended using a new sampling function. The obtained results have been compared with real electrostatic discharge current data obtained through experimental measurements in an effort to justify the efficiency and accuracy of the proposed methods. Although both methods have produced acceptable results the optimization quasi-Newton algorithm current waveform fits better with the experimental discharge current waveform. The proposed methods are extremely useful in the ESD studies, since an accurate electrostatic discharge current equation is an indispensable requirement for the description of the ESD generators in simulation programs.

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