PARAMETER ESTIMATION FOR THE EQUATION OF THE ELECTROSTATIC DISCHARGE CURRENT USING GENETIC ALGORITHMS

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ABSTRACT

This paper presents the parameter estimation of equations that describe the current during an electrostatic discharge, using a genetic algorithm. The necessity of this has to do with the aberrations between simulations and the waveform described in the Standard. The two equations that have been used have three and seven parameters, respectively. The genetic algorithm has as input data real measurements of the discharge current produced by an electrostatic discharge generator and using these data optimizes the parameters of the mathematical equations. The genetic algorithm gives very good results with a small error between experimental and optimized data, proving its efficiency.

Keywords: Electrostatic Discharge, Discharge Current, Genetic Algorithm, optimization

1. INTRODUCTION

Electrostatic discharge (ESD) is a very common phenomenon in our lives. The human body can be charged up to a potential of 10-15 kV by walking on a carpet due to the triboelectric phenomenon. When the discharge takes place the discharge current may come up to a few Amperes. This makes clear that the electrostatic discharge may be destructive for electronic or integrated circuits, which are very sensitive to these currents although the ESD phenomenon lasts a few hundred nanoseconds [1].

A considerable amount of effort has been made in order the ESD current waveforms to be studied and 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 [2]. In a recent publication [3] it has been presented that the most important factor for the Equipment Under Test (EUT) is the transient field.

The EN 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, which propose an improved circuit for the ESD generators. A modified commercial generator, with a reference waveform very close to this that the Standard defines and also the equation of the reference waveform has been proposed in [4].

Other researchers having studied ESD from the aspect of the uncertainty in measurements, proposed an accurate measurement system for the discharge current [5, 6]. Computer simulation of this circuit using the PSpice program proved that there are aberrations between the simulations and the waveform described in the Standard [7]. This fact proves the necessity that the next revision of the Standard must include either a new circuit for the ESD generators or a current source, which will give accurately the discharge current following a mathematical equation. In this paper the second way is followed.

2. EQUATIONS OF THE DISCHARGE CURRENT

The basic constructive demand for the ESD generators is their reproducibility. This means that they have to reproduce the ESD pulse in the same way each time. The Standard [1] has defined the limits for the four parameters of the discharge current. These parameters are the rise time (t_r), the maximum current (I_{max}), the current at 30 ns (I_{30}) and 60 ns (I_{60}).

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 equation of the impulse current. This equation is very similar to the PSpice results presented in [7] and it is given by the following equation [8]:

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

In [4] the referred waveform, which is very similar to the current waveform of [1] is given by the below formula:

$$i(t) = \frac{i_1}{k_1} \cdot \frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n} \cdot e^{-\frac{t}{\tau_2}} + \frac{i_2}{k_2} \cdot \frac{\left(\frac{t}{\tau_3}\right)^n}{1+\left(\frac{t}{\tau_3}\right)^n} \cdot e^{-\frac{t}{\tau_4}} \quad (2)$$

where $k_1 = e^{-\frac{\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{\frac{1}{n}}}$ (3)

and $k_2 = e^{-\frac{\tau_3}{\tau_4}\left(\frac{n\tau_4}{\tau_3}\right)^{\frac{1}{n}}}$ (4)

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.

3. EXPERIMENTAL SETUP AND MEASUREMENTS

The current for a charging voltage of +2 kV, was measured (Figure 1) 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 was producing contact discharges and it was grounded to the earth via a ground strap. The discharge electrode of the ESD generator used for the measurements had a sharp point in order to produce contact discharges. In order the current to be measured a resistive load known as Pellegrini target (MD 101 of Schaffner) was used and placed between the discharge electrode and the metal ground 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 the measurement system to be unaffected by the surrounding equipment and the cables were set away from the discharge point.

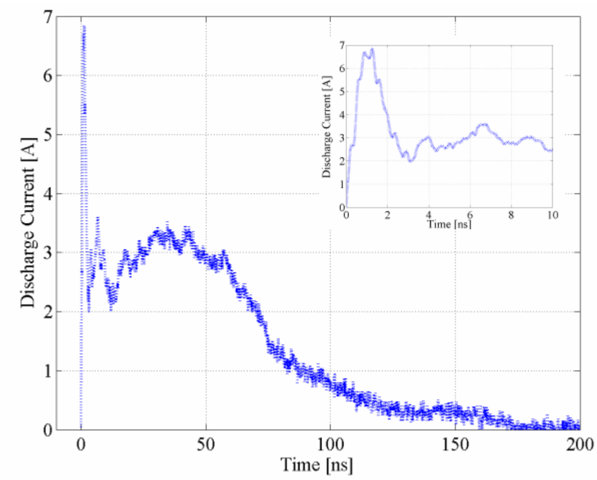

Figure 1: Current waveform taken by the oscilloscope TDS 7254B for a charging voltage of +2kV. In the upper right part of the figure the first 10 ns of the ESD current are presented in detail.

The measured discharge current is depicted in Figure 1, when the discharge occurred in contact discharge mode and the charging voltage was +2 kV. The temperature and relative humidity were measured and found in the ranges 23±1°C and 40±5%, respectively. The measured discharge current has been used as input data for the application of the Genetic Algorithm (GA). The GA as it will be explained, has been used for the optimization of the parameters for equations (1), (2).

4. THE GENETIC ALGORITHM

The GA has been developed using the software package Matlab and produces excellent results in a different optimization problem [9-11]. 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 equation (1) or (2), respectively. 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 probability of 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 the number of iterations is greater than the maximum number of iterations N_{max}.

5. RESULTS

The GA has been applied on equations (1) and (2) with 3 and 6 parameters respectively in order these parameters to be calculated. In equation (2) n is constant and equals to 3. Giving as input data the discharge current of the ESD generator and for the experimental setup described previously, the GA calculates and optimizes the parameters for (1), (2).

For the computation of the parameters for each equation the minimization of the functions F_g, F_{gtotal} which represent the error between the given and the optimized data is necessary. F_g is given by the following equation:

$$F_g = \sum_{j=1}^{N} \frac{\left|I_j^m - I_j^c\right|}{I_j^m} \quad (5)$$

where I_j^m is the j[th] measured value of the discharge current. I_j^c is the computed value of the discharge current for the unknown parameters of (1), (2).

The F_{gtotal} represents the total error and it is given by the following equation:

$$F_g = \sum_{j=1}^{N_{total}} \frac{\left|I_j^m - I_j^c\right|}{I_j^m} \quad (6)$$

From the errors (F_g) and (F_{gtotal}) and of each equation, useful conclusions about the best and more accurate equation derive.

In this application, the use of the GA does not require the use of the whole measured data. This is not only time consuming procedure, but also does not give more accurate solutions than using properly selected number of measured data and applying greater number of parents and iterations. In order the proposed GA to be more efficient a procedure at the selection of the measured data has been followed. The whole number of the measured points, which are 2250, has not been used, but instead of these the waveforms' points have been selected as it can be seen in Table I for seven different types of point selection.

Table I
Selection of the measured current's points

Cases	**Step**	**Selected points for 90 ns**	**Selected points for 50 ns**	**Selected points for 30 ns**
Exp4	4(1+round(exp(j/N)))*	222	144	95
Exp6	6(1+round(exp(j/N)))*	148	95	63
Exp8	8(1+round(exp(j/N)))*	111	72	47
Idata10	Constant equals to 10	225	126	76
Idata15	Constant equals to 15	150	84	51
Idata20	Constant equals to 20	113	63	38
Idata20N	0-2 ns: All points 2–90 ns: Points from Idata20	161	111	86

*: j is the jth point of the measured data of 2250 points

In Table I it can be seen that the point selection has been made for seven cases for three different time durations of the discharge current (90 ns, 50 ns and 30 ns). The number of the selected points can also be seen in Table I. A different point selection only for equation (2), which is named Idata20N, has been obtained by changing the point selection of Idata20. All the points of Idata20 for the 2 first ns have been replaced by the real measured data. Therefore, the number of points for the first 2 ns is 51, whereas in Idata20 it was only 3. This point selection has been made in order the waveform of equation (2) to simulate better the initial peak of the discharge current.

In all cases the selected number of points of the discharge current can be seen in Table I. The measured discharge current was obtained for a charging voltage of the ESD generator at +2 kV and for the contact discharge mode.

The GA was applied to the experimental data for all seven cases and for different current duration. Tables II and III present the optimized values of the parameters of each equation and their errors. In Table IV a comparison for the parameters' optimized values of (2) for the Exp4 case, but for different time durations of the discharge current (30, 50 or 90 ns) is presented.

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

	Exp4	**Exp6**	**Exp8**	**Idata10**	**Idata15**	**Idata20**
i_0 [A]	34.85	34.95	34.74	34.85	30.78	34.73
t_1 [ns]	31.95	31.96	31.95	31.95	32.03	32.01
t_2 [ns]	24.74	24.74	24.71	24.74	23.90	24.75
F_g	36.93	24.80	18.66	14.88	23.79	17.72
F_{gtotal}	348.9	348.7	348.7	348.8	348.6	348.87

Table III
The optimized values of the parameters for Eq. (2), using experimental data (for 90 ns duration of the discharge current)

	Exp4	**Exp6**	**Exp8**	**Idata10**	**Idata15**	**Idata20**	**Idata20N**
i_1 [A]	3.28	3.93	3.64	3.47	3.15	3.52	4.69
i_2 [A]	3.75	3.98	4.46	3.69	3.75	4.69	4.34
t_1 [ns]	0.38	0.14	0.31	0.27	0.78	0.75	0.19
t_2 [ns]	19.37	15.58	16.89	18.72	18.28	15.61	12.83
t_3 [ns]	39.07	37.06	45.83	37.18	35.88	48.00	39.70
t_4 [ns]	29.70	29.87	24.81	30.65	31.24	23.49	27.46
F_g	19.34	12.78	10.25	8.36	13.06	10.52	22.41
F_{gtotal}	185.4	184.3	187.5	182.8	194.87	202.3	200.9

Table IV
The optimized values of the parameters for Eq. (2), using experimental data (for 30 and 50 ns duration of the discharge current)

	Exp4 (30 ns)	**Exp4 (50 ns)**	**Exp4 (90 ns)**
i_1 [A]	3.38	3.34	3.28
i_2 [A]	3.47	3.12	3.75
t_1 [ns]	0.23	0.19	0.38
t_2 [ns]	17.48	23.91	19.37
t_3 [ns]	31.84	33.63	39.07
t_4 [ns]	29.95	38.77	29.70
F_g	9.49	10.86	19.34
F_{gtotal}	327.4	203.6	185.4

In Figures 2-6 common graphs of the experimental data of the discharge current and the discharge current for the optimized parameter values for (1), (2) are depicted. In Figs 2-4 the comparisons have been made between different cases, which have similar number of selected points and when the duration of the discharge current is 90 ns. In Figure 5 the comparison has been made for the same point selection (Exp4), but for different time duration of the discharge current. Also, in Figure 6 a curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of equation (2) for the Idata20 and Idata20N cases is presented.

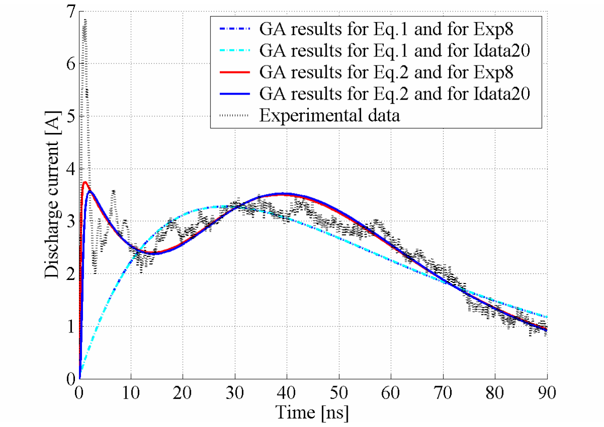

Figure 2: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of Eqs. (1)-(2) for the Exp8 and Idata20 cases.

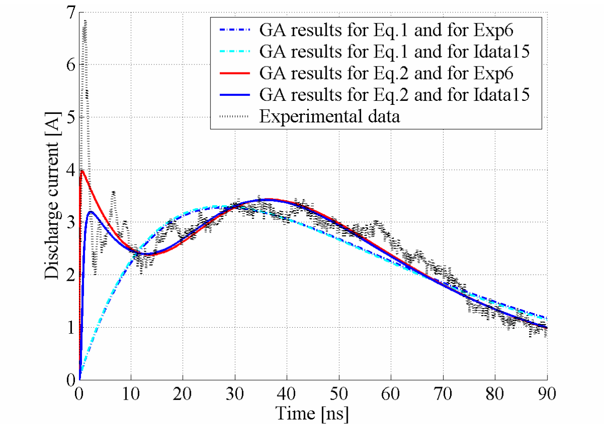

Figure 3: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of Eqs. (1)-(2) for the Exp6 and Idata15 cases.

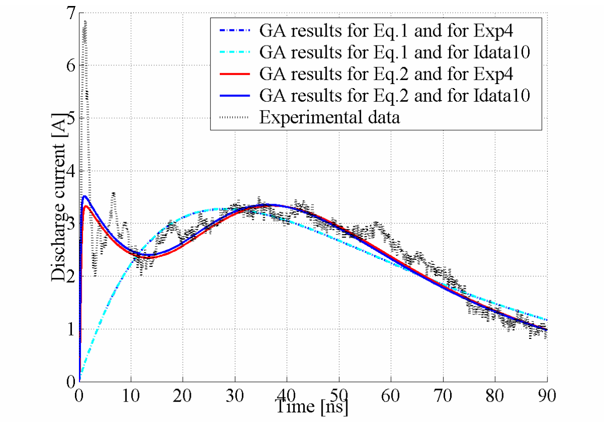

Figure 4: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of Eqs. (1)-(2) for the Exp4 and Idata10 cases.

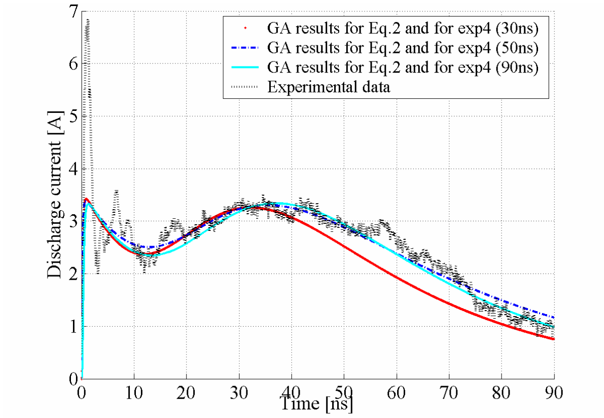

Figure 5: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of Eq. (2) for the Exp4 case and for different time durations.

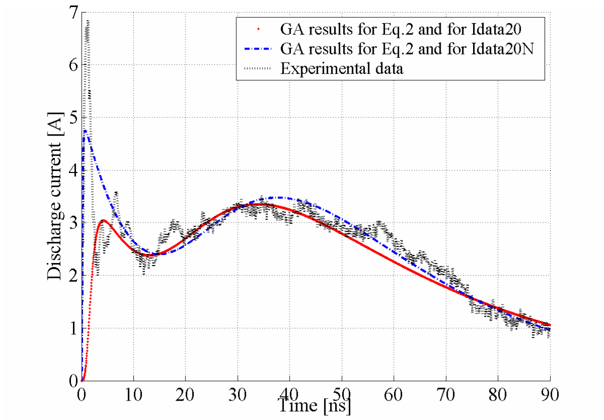

Figure 6: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of Eq. (2) for the Idata20 and Idata20N cases.

6. DISCUSSION

Observing Figs 2-4 a conclusion for the best equation that describes the discharge current and the best point selection can derive. It is obvious that equation (2) has the best fitting on the experimental data, since its waveform includes the initial peak of the discharge current. It also has lower error than equation (1) has for all the cases for the selected data. Equation (2) although it can simulate the first peak of the discharge current it calculates accurately the parameters of the double exponential function.

As far as the point selection concerns it must be mentioned that the case Idata10 has the minimum error (F_g) for both equations. This fact proves that the best fit on the experimental for each equation does not depend only on the equation, but also on the selection of the experimental data.

That was the reason that three more cases (Idata20N, Exp4 (30 ns), Exp4 (50 ns)) have been used. These point selections have been made only for equation (2) and in order the initial peak to be simulated in a better way. From Figure 5 it can be concluded that when the selected points are limited in the first 50 ns (Exp4 (50 ns)) the simulation of the initial peak is similar to this for the Exp4 (30 ns). This means that an enormous decrease of the selected points does not necessarily leads to a better simulation of the initial peak. Such an attempt also leads to a bad approach of the experimental data. This is obvious in Figure 6 where Exp4 (50ns) has a very good behavior to the experimental data, in addition to Exp4 (30 ns).

The Idata20N case has come from an idea that if the points for the first ns were increased then the simulation of the initial peak would be better. Therefore, Idata20N has become from Idata20 replacing the first 2 ns with the experimental data. From Figure 6 it can be seen that the curve for the Idata20N case approaches the initial peak in a better way and the approximation of the experimental data is better. Besides the error (F_{gtotal}) is smaller than this with the error of Idata20. This is a more accurate way for the GA application, but it is time consuming, since there is a need for more computing time.

7. CONCLUSIONS

In this work a methodology based on a GA has been proposed to calculate the parameters of the discharge current, produced by an ESD generator. The selection of the experimental data has been made using different ways. The results of the GA proved that the simulated discharge current is very close to the current that is measured. A comparison between two different equations proved that the most efficient is (2), since it simulates better the experimental data. A future revision of the Standard should take into consideration these remarks in order the waveform of the discharge current to be also defined mathematically.

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