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Parameter Determination of Heidler's Equation for the ESD Current

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Abstract: The International Standard IEC 61000-4-2 for the electrostatic discharge defines the current's waveform and its parameters, but it doesn't define an equation for the ESD current. Moreover, there is an aberration between the waveform that the Standard defines and the waveform produced by the circuit defined by the same Standard. In this paper, effort has been made in order to calculate the parameters of an equation, which will describe accurately and efficiently the ESD current. In that way the aberration in the Standard will be eliminated. For this purpose, a genetic algorithm has been developed and different optimization functions have been used. By comparing the results of each optimization function, the relative error is being proved to be the most suitable optimization function that gives the best fitting curve to the experimental data.

1 INTRODUCTION

Electrostatic Discharge (ESD) is a common and destructive phenomenon. Robustness of the electric and electronic equipment towards ESD is tested according to the IEC 61000-4-2 Standard [1]. The Standard describes the test procedure of electric and electronic equipment under electrostatic discharges and defines the waveform of the discharge current that the ESD generators must produce.

The Standard specifies only the parameters for the peak current, the rise time and the falling edge. In [2] specifications for the currents derivative, radiated fields and induced voltages are derived. The purpose of another study [3] was the determination of the parameters that characterize the discharge current waveforms of the ESD generators. Two accurate and efficient models of the ESD generators, which permit the reproducibility of the discharge current, are proposed in [4]. Murota in [5] presents the variations that appear on the discharge current, when various conditions alter during the test, using the simulation program PSpice.

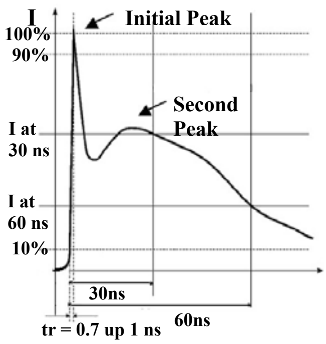
In the current Standard [1] there is an aberration between the defined waveform of the ESD current and the discharge current that the circuit of the ESD generator produces in reality. Therefore, simulation programs that use the existing circuit of the ESD generator insert an error in the calculated voltages and currents. In [6] the equation, proposed by Heidler [7], was proved to be the most suitable for the description of the ESD current, by using a genetic algorithm (GA) and the absolute error as an optimization function.

This paper aims to the optimization of the parameters of Heildler's equation. For that purpose, different optimization functions have been used. These optimization functions are the relative error, the absolute error and the L-infinity norm. By comparing the results of the GA for each optimization function, the most suitable function, derives.

2 THE DISCHARGE CURRENT OF THE ESD GENERATORS

In [6] it has been observed that by using the circuit of the ESD generator in computer simulations, the current's waveform in Fig. 1b differs from the waveform defined by the Standard as it is shown in Fig. 1a. Fig. 1b illustrates the simulation's results by using the PSpice software for ohmic EUTs and DC charging voltage +2kV.

It is noticeable that the error in the calculated voltages and currents is inserted by computer simulations of the circuit defined in the Standard. This error can be minimized either by developing a new circuit of the ESD generator or by using in simulation programs an equation, which will accurately describe the ESD current produced by an ESD generator. In this paper, a current source is being used. The current's waveform is a function of a number of parameters as it has been proposed in [7], [8].



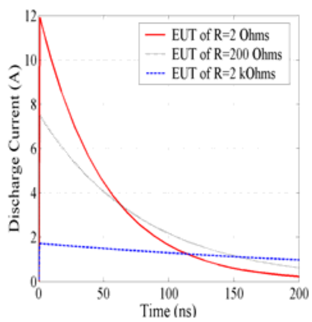


Fig. 1. a) Typical waveform of the ESD generator [1],
b) ESD current from the PSPICE simulation of the Standard's circuit for ohmic EUTs.

In [6] it was proved that the most suitable equation for the description of the ESD current waveform is the one presented by Heidler [7] and adopted by Pommerenke [8]. The analytical formula is:

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

where $$k_1=e^{-\frac{\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{\frac{1}{n}}} \qquad (2)$$

and $$k_2=e^{-\frac{\tau_3}{\tau_4}\left(\frac{n\tau_4}{\tau_3}\right)^{\frac{1}{n}}} \qquad (3)$$

i_1, i_2 are currents in Amperes, τ_1, τ_2, τ_3, τ_4 are time constants in ns and n is a constant.

3 MEASUREMENT SETUP

In Fig. 2 the experimental setup for the measurement of the ESD current is presented. The current for the charging voltage of +2kV was measured by a 4-channel Tektronix oscilloscope model TDS 7254B, whose bandwidth ranged from DC to 2.5GHz. A Schaffner ESD generator model NSG-438 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 a grounded metal plane with dimensions 1.5m x 1.5m. The Pellegrini target was connected to the oscilloscope by a HF coaxial cable.

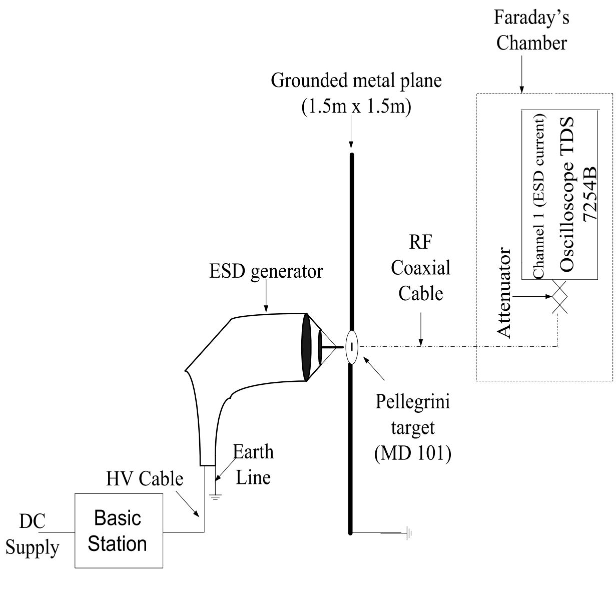


Fig. 2: Scheme of the experimental setup.

The measured discharge current, for a charging voltage of +2kV, has been used as input data for the application of the GA.

4 THE GENETIC ALGORITHM

Genetic algorithms are adaptive algorithms widely applied in science and engineering for solving practical search and optimization problems. Many problems can be efficiently tackled by using a GA approach because correlation between the variables is not a problem. The basic GA does not require extensive knowledge of the search space, such as solution bounds or functional derivatives.

This paper proposes a methodology, which uses the developed GA for the optimization of the parameters of the discharge current equation (1). This GA has been developed using the software package Matlab. The same GA produces excellent results in several optimization problems [6], [9]-[11].

The applied GA starts with a randomly generated population of P_s=40 random values for each parameter of (1). Each parameter's value is converted to a 20-bit binary number. The next step is to form pairs of these points that will be considered as parents for reproduction. By crossover each pair of parents produces N_c=4 children. After crossover there is a P_m=7% probability of mutation. Through reproduction the population of the "parents" is enhanced with the "children". By applying the process of natural selection only 40 members survive. These are the members with the lower values of the objective function, since a minimization problem is solved. In this paper three different optimization functions have been used.

F_1 represents the relative error between the measured and the optimized data. For the computation of the parameters of (1) the minimization of the function F_1 is necessary. F_1 is given by the following equation:

$$F_1=\sum_{i=1}^{N}\frac{\left|I_i^m-I_i^c\right|}{I_i^m} \qquad (4)$$

where I_i^m is the i^{th} measured value of the discharge current, I_i^c is the computed value of the discharge current for the unknown parameters of (1) and N is the total number of points selected from the measured data of the discharge current.

Another objective function, which will be used by the GA, is the absolute error, which is given by the formula:

$$F_2=\sum_{i=1}^{N}\left|I_i^m-I_i^c\right| \qquad (5)$$

Apart from (4) and (5) the L-infinity norm (6) has been used as an objective function for the optimization of the values of the parameters of ESD current.

$$F_3=\max_i\left|I_i^m-I_i^c\right| \qquad (6)$$

for i=1,…,N.

By repeating the iterations of reproduction under crossover, mutation and natural selection, GAs can find the minimum error. The best values of the population converge at this point. The termination criterion is fulfilled when the mean value of the optimization function in the P_s-members population is no longer improved or the number of iterations is greater than the maximum defined number of iterations N_{max}.

5 RESULTS

The GA was applied on the experimental data, which were obtained by the experimental setup described previously. The discharge current of the ESD generator was the input data of the GA, which calculated the values of the parameters of (1). Useful conclusions about the accuracy of the equation can be drawn from the values of the errors F_1, F_2 and F_3.

The total number of the measured data was 2250 and the duration of the discharge current was 90ns. In order for the application of the GA to be more efficient and less time consuming, a careful selection of the points must be made. In Table 1 three different sampling functions of the measured data are presented. In the first case a function has been used in order for the GA to give more accurate results for this time period. In the second case, the selected step width is constant and equals to 15. As a result, the 1st, 16st, … points from the measured data will be selected. However, the discharge current receives its peak between 0.7-1ns [1] and most of the radiation and the largest values of the current derivative occur during this period. Therefore, the third case, which includes all the measured points until the 2nd nanosecond, is being used. Thus, the first nanoseconds of the discharge current are being treated as the most important part of the waveform. For the rest nanoseconds the selected step width is constant and equals to 22.

Table 1: Point selection of the measured current (charging voltage +2kV).

Cases	Step	Selected points for 90 ns (N)
1st case (Exp6)	6(1+round(exp(j/N)))[a]	148
2nd case (Idata15)	Constant equals to 15	150
3rd case (Idata22N)	0-2 ns: All points 2–90 ns: Points from Idata22	151

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

In Figs. 3 - 5 common graphs of the experimental data of the discharge current and the discharge current for the optimized parameters values of (1) are illustrated.

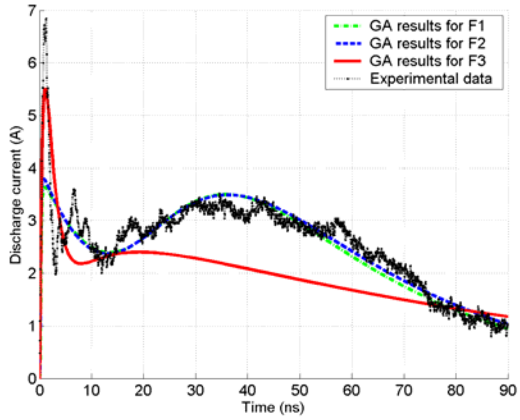


Fig. 3: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1) for the 1st case and different optimization functions (Charging Voltage= +2kV).

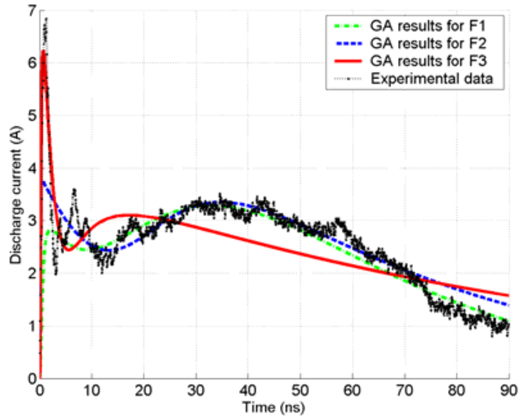


Fig. 4: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1) for the 2nd case and different optimization functions (Charging Voltage= +2kV).

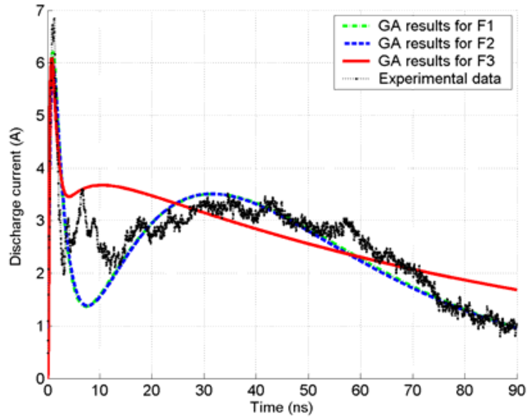


Fig. 5: Curve comparison between the experimental data of the discharge current and the discharge current for the optimized parameter values of (1) for the 3rd case and different optimization functions (Charging Voltage= +2kV).

In Tables 2 - 4 the optimized values of the parameters and the errors for each objective function are presented.

Table 2: Values for the 6 parameters of (1) for +2 kV charging voltage using F_1 as objective function

	Case 1	Case 2	Case 3
i_1 [A]	3.60	2.56	6.16
i_2 [A]	3.74	4.82	5.93
t_1 [ns]	0.29	0.58	0.54
t_2 [ns]	18.44	11.44	2.09
t_3 [ns]	34.34	47.24	17.61
t_4 [ns]	31.02	30.38	27.63
n	3.26	1.91	1.73
F_1	13.39	14.31	17.73

Table 3: Values for the 6 parameters of (1) for +2 kV charging voltage using F_2 as objective function

	Case 1	Case 2	Case 3
i_1 [A]	3.74	3.73	5.90
i_2 [A]	3.99	3.12	5.10
t_1 [ns]	0.21	0.11	0.54
t_2 [ns]	14.72	19.20	2.30
t_3 [ns]	35.83	28.33	37.11
t_4 [ns]	31.19	50.93	29.57
n	2.97	3.26	1.85
F_2	32.37	34.45	58.62

Table 4: Values for the 6 parameters of (1) for +2 kV charging voltage using F_3 as objective function

	Case 1	Case 2	Case 3
i_1 [A]	5.53	6.22	6.17
i_2 [A]	1.98	3.05	3.57
t_1 [ns]	0.76	0.31	0.41
t_2 [ns]	1.94	2.69	2.01
t_3 [ns]	6.25	6.94	4.06
t_4 [ns]	80.36	96.96	94.92
n	1.39	2.78	2.73
F_3	1.36	1.08	1.39

By comparing the graphs it is obvious that the initial peak is better approached when the L-infinity norm is being used as an objective function for all sampling functions. However, the discharge current waveform produced by the genetic algorithm using the L-infinity norm as a criterion does not give a satisfactory approximation to the experimental waveform for the rest time duration. The relative error gives the best fitting in the experimental data. Regarding the waveform produced when the absolute error is used as an objective function, it can be said that it offers a better approximation of the value of the initial peak, than the one achieved by using relative error as an objective function. In conclusion, it can be said that better fitting of the genetic algorithm for the first nanoseconds can be achieved by using the L-infinity norm, but if better fitting in the experimental data is desirable, the relative error should be used as an objective function.

6 CONCLUSIONS

In this paper the GA has been successfully applied for the estimation of the parameters of the discharge current produced by an ESD generator. By using different objective functions (4) - (6) for the application of the GA, it was concluded that by using (6) a better fitting to the experimental data for the first nanoseconds is achieved. The relative error, given by (4), is preferable when GA's results should fit the experimental data for the whole time duration. The next revision of the Standard should take these remarks into consideration, in order for an accurate equation, which will describe the discharge current, to be defined.

7 ACKNOWLEDGEMENT

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