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NEW FUNCTION FOR REPRESENTING IEC 61000-4-2 STANDARD ELECTROSTATIC DISCHARGE CURRENT

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Abstract. *New function for representing electrostatic discharge (ESD) currents according to the IEC 61000-4-2 Standard current is proposed in this paper. Good agreement with the Standard defined parameters is obtained. This function is compared to other functions from literature. Its first derivative needed for field calculations is analyzed in the paper. Main advantages are simplified choice of parameters, possibility to obtain discontinuities in the decaying part, and zero value of the function first derivative at $t=0^+$. Parameters of the function are obtained by using Least-squares method (LSQM).*

Key words: *Analytically extended function, electromagnetic compatibility, electrostatic discharge current, IEC 61000-4-2, least-squares method*

1. INTRODUCTION

Nowadays, electromagnetic compatibility (EMC) gains in its importance with the development and global marketing of electronic components, electrical devices and systems, so as with public concern for electromagnetic pollution. Electrical engineers and industrial professionals, dealing with the design and manufacture of such products, have to take into account many aspects of EMC in order to obtain and market a product which complies with EMC standards and directives. Besides utility and functionality, better appearance but lower costs as possible, any device, equipment or system has to comply with its electromagnetic environment and to function satisfactorily - without introducing intolerable electromagnetic disturbances (EMDs) to other in its environment or being disturbed by an external influence from the environment [1].

Electrostatic discharges (ESDs) are common phenomena and among very important EMC aspects of concern. Lightning discharges are discharges of static electricity, although their processes are in fact transient, and far from being "static" phenomena. These discharges produce the most powerful EMDs for electrical systems. In general, electrostatic discharges are dangerous in many technological processes: in textile industry, petrol industry, powder production, food industry, chemical industry, manipulating with various substances and transporting them, etc. However, there are also useful applications of ESDs: in medical

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devices as defibrillators, in photocopiers, spray painting, electrostatic precipitators, electrostatic dusters, some technological processes in producing fabrics, etc.

An ESD occurs between two objects at a distance close enough for the sufficient difference of their electrostatic potentials to produce breakdown. Static electricity may appear not only on parts of machines and after separating different materials in contact, but also on humans. In every day's life, human body may discharge through fingers or other body parts via skin or small metal pieces, such as keys, to some objects. This may happen at working places which is dangerous in production of electronic components. It is well known that integrated circuits and fast complementary metal oxide semiconductor components, so as digital devices in general, are more sensitive than analog, although ESD may have influence on any kind of electrical devices and systems.

The Standard IEC 61000-4-2 [2], [3], and European standard EN 61000-4-2 (issued by CENELEC) deal with the typical waveform of electrostatic discharge current, range of test levels, test equipment, test set-up and procedures related to electrostatic discharge immunity requirements for the equipment under test (EUT). Scientific Committee SC77B, WG 10, is also maintaining the Standard 61000-4-3 on radiated radio-frequency electromagnetic field immunity test, ([4],[5]). Recent status of these standards and the elements of maintenance are discussed in [6].

Test generators current waveform is defined in IEC/EN 61000-4-2 standards for contact ESD testing: its initial peak current, current level at 30ns, current level at 60ns, so as rise time from 10% to 90% of the initial peak current. In order to improve the repeatability of tests, tolerance of the rise time of electrostatic discharge current waveform was expanded in the Ed.2 of the standard [3]. The oscilloscope bandwidth was increased beyond 1GHz, so to measure rise time more accurately [7]. Minimum 2GHZ oscilloscope bandwidth is needed according to the IEC 61000-4-2, Ed.2. ESD generators simulate real discharges thus enabling repetitive test procedures for EUT. However, ESD test generator current waveshape depends on various conditions, as discussed in [8], and these are: charging voltages, approach speeds, types of electrodes, relative arc length, humidity, etc. Parameters of the real ESD testers are also discussed in [9], and the influence of various conditions on current waveshape is investigated using simulation with PSpice in [10]. A modified test generator with a reference waveshape close to the standard one and the corresponding equation for that waveshape are discussed in [11]. Another equation was proposed already in [12] in order to study ESD in coaxial cable shields. A mathematical function accurately representing standard ESD current is necessary for computer simulation of such phenomena, for verification of test generators and for better modeling of ESDs.

Mathematical functions for modeling lightning discharge currents are used in literature to approximate currents of ESD testing waveforms, but they have some disadvantages along with their complexity, as described in [13]. New function which may represent both typical ESD and lightning currents, as given in corresponding standards, is proposed in this paper in order to make further steps in research and use advantages of computer simulations of the problem. Any function is more useful for such purposes if simple as possible, whereas still capable to satisfactorily approximate experimentally measured characteristics. Channel-base current function (CBC) is proposed in [14] for typical and experimental lightning stroke currents, and two-peaked function in [15]. For representing ESD currents an analytically extended function (AEF), as the sum of two or three CBC expressions, is used in this paper.

The procedure of choosing function parameters has to be further investigated in order to make it simple for any user. These parameters may be estimated applying different procedures such as Genetic algorithm (GA) as in [17], or Marquardt least-squares method (MLSM) as done in [18] for the lightning currents. In this paper Least-squares method (LSQM) is used.

Firstly, the analysis of usually used functions is given, and after that the comparison of the proposed function to the IEC 61000-4-2 Standard one, so as the choice of its parameters and the analysis of the first derivative.

2. Functions for Approximating Electrostatic Discharge Currents

In IEC 61000-4-2 standard, ESD current peak is described with 3.75A/kV, current value $i_{30\text{ns}}$ at 30ns with 2A/kV, $i_{60\text{ns}}$ at 60ns with 1A/kV. The tolerance for ESD contact mode currents is $\pm 10\%$ for I_{peak} in Ed.1, $\pm 15\%$ in Ed.2, $\pm 30\%$ for $i_{30\text{ns}}$ and $i_{60\text{ns}}$ (in both Ed.1 and Ed.2). Rise time t_r in the range $0.7 \div 1$ns is defined in Ed.1 for a typical contact mode discharge, and $0.6 \div 1$ns in Ed.2 of the Standard. Parameters of ESD currents are given in Table 1, for the defined discharge test voltages. Discharges may be contact or air ESDs. According to the standard, application of contact discharges is preferably used for testing, whereas air discharge only if not available otherwise. Test level voltages range between 2 and 8kV for contact discharges, but between 2 and 15kV for air discharges. The arc lengths about 0.85mm are common for ESD test generators and for 5kV as discussed in [11], but level and rise time of ESD currents are less reproducible in the case of air discharge and depend significantly on humidity, shape of the tip, speed of the tip approach, etc. ESD of a human through a small piece of metal is simulated with ESD generators for testing robustness of sensitive electronics toward ESD. Current waveform parameters are given in Table 1 for 2, 4, 6 and 8kV discharge voltages.

Human-body model (HBM) discharge current may be approximately obtained with a simple electrical circuit having the charging resistor $50 \div 100\text{M}\Omega$, energy-storage capacitor 150pF$\pm$10%, and the discharge resistor of 330Ω value representing skin, as in Fig.1. The produced waveshape differs from the test generator ESD currents, so as from the Standard one. More complex circuits are also suggested in literature.

Table 1 Standard 61000-4-2 ESD Current Waveform Parameters

Discharge voltage [kV]	I_{peak} [A] $\pm 10\%$ (Ed.1) $\pm 15\%$ (Ed.2)	Rise time of the first peak t_r [ns] (Ed.1)	Rise time of the first peak t_r [ns] (Ed.2)	$i_{30\text{ns}}$ [A] $\pm 30\%$ (Ed.1, 2)	$i_{60\text{ns}}$ [A] $\pm 30\%$ (Ed.1, 2)
2	7.5	$0.7 \div 1$	$0.6 \div 1$	4	2
4	15	$0.7 \div 1$	$0.6 \div 1$	8	4
6	22.5	$0.7 \div 1$	$0.6 \div 1$	12	6
8	30	$0.7 \div 1$	$0.6 \div 1$	16	8

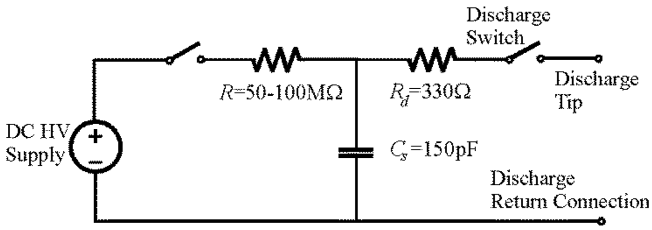

Fig. 1 Simple circuit for obtaining typical HBM current waveform [2]

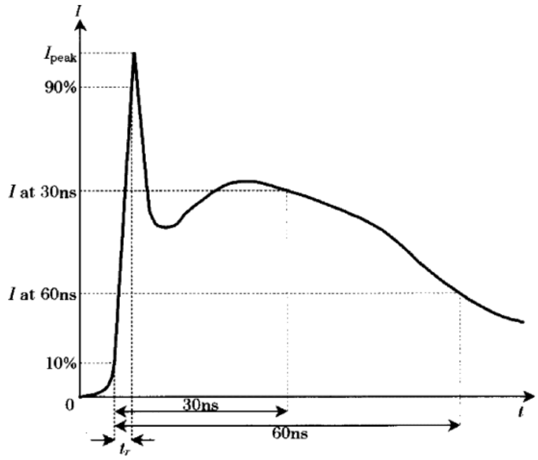

Fig. 2 ESD current waveform given in IEC 61000-4-2

HBM and contact mode discharges are used for verification of ESD test generators, and the standard ESD current pulse is given in Fig. 2. Some functions from literature are compared for 4kV ESD and the proposed function is compared to the best fit function of those and the Standard waveshape.

The following expression is proposed in [19], using four exponential functions

$$i(t) = i_1 \ [\exp(-t/\tau_1) - \exp(-t/\tau_2)] + i_2 \ [\exp(-t/\tau_3) - \exp(-t/\tau_4)], \tag{1}$$

for $i_1 = 498$A, $i_2 = 148.5$A, $\tau_1 = 1.4$ns, $\tau_2 = 1.3$ns, $\tau_3 = 23.37$ns, $\tau_4 = 20$ns as function parameters. This function is presented in Figs. 3 and 4 with the dash-dot line.

An expression using two Gaussian functions is proposed for ESD currents in [12] as the following:

$$i(t) = A \ \exp[-(t-t_1)^2/\sigma_1^{\ 2}] + B \ \ t \ \exp[-(t-t_2)^2/\sigma_2^{\ 2}], \tag{2}$$

for $A = 13$A, $B = 0.4$A/ns, $t_1 = 5$ns, $t_2 = 10$ns, $\sigma_1 = 1.414$ns, $\sigma_2 = 35.35$ns. This function is presented in Figs. 3 and 4 with the dash-dot-dot line for $A = 13.25$A, $B = 391$A/ns, $t_1 = 2$ns, $t_2 = -300$ns, $\sigma_1 = 0.6$ns, $\sigma_2 = 122.2$ns, as given in [13]. For the experimental ESD current described in [16] parameters of (2) are determined by using GA and minimizing relative error of the current as the following: $A = 4.95$A, $B = 0.27$A/ns,

t_1 = 5.18ns, t_2 = 1.62ns, σ_1 = 9.78ns, σ_2 = 54.72ns. Using GA method and minimizing relative error of the current, parameters of (2) in [21] are determined as: A = 5.29A, B = 0.33A/ns, t_1 = 6.07ns, t_2 = 9.48ns, σ_1 = 4.31ns, σ_2 = 52.03ns.

The pulse function [23] is given with the following expression

$$i(t) = I_0 \ [1-\exp(-t/\tau_1)]^p \exp(-t/\tau_2)\,, \tag{3}$$

and its binomial expression with

$$i(t) = I_0[1-\exp(-t/\tau_1)]^p \exp(-t/\tau_2) + I_1[1-\exp(-t/\tau_3)]^q \exp(-t/\tau_4)\,. \tag{4}$$

For 4kV ESD and the binomial expression (4) of pulse functions, for parameters: I_0 = 106.5A, I_1 = 60.5A, τ_1 = 0.62ns, τ_2 = 1.1ns, τ_3 = 55ns, τ_4 = 26ns, [13], the waveshape is presented in Figs. 3 and 4 with the long-dash lines.

The trinomial expression of pulse functions is given with

$$\begin{aligned} i(t) &= I_0[1-\exp(-t/\tau_1)]^p \exp(-t/\tau_2) + I_1[1-\exp(-t/\tau_3)]^q \exp(-t/\tau_4) \\ &\quad + I_2[1-\exp(-t/\tau_5)]^r \exp(-t/\tau_6), \end{aligned} \tag{5}$$

and the quadrinomial expression with

$$\begin{aligned} i(t) &= I_0[1-\exp(-t/\tau_1)]^p \exp(-t/\tau_2) + I_1[1-\exp(-t/\tau_3)]^q \exp(-t/\tau_4) \\ &\quad + I_2[1-\exp(-t/\tau_5)]^r \exp(-t/\tau_6) + I_3[1-\exp(-t/\tau_7)]^r \exp(-t/\tau_8). \end{aligned} \tag{6}$$

The trinomial (5) and quadrinomial (6) expressions provide better approximations [13] of the ESD current and give results more similar to the goal function, but these functions have too many parameters.

One function commonly used for lightning currents is applied in [11], having binomial expression of two Heidler's functions [20]

$$i(t) = \frac{i_1}{\eta_1}\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n}\exp(-t/\tau_2) + \frac{i_2}{\eta_2}\frac{(t/\tau_3)^n}{1+(t/\tau_3)^n}\exp(-t/\tau_4)\,, \tag{8}$$

for peak correction factors $\eta_1 = \exp\left[-\frac{\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{1/n}\right]$ and $\eta_2 = \exp\left[-\frac{\tau_3}{\tau_4}\left(\frac{n\tau_4}{\tau_3}\right)^{1/n}\right]$.

To approximate the measured human-metal ESD at 5kV current parameters are chosen as the following: i_1 = 21.9A, i_2 = 10.1A, τ_1 = 1.3ns, τ_2 = 1.7ns, τ_3 = 6ns, τ_4 = 58ns and n =3. For the 4kV discharge parameters values in [13] are chosen as: i_1 = 17.5A, i_2 = 10.1A, τ_1 = 1.3ns, τ_2 = 1.7ns, τ_3 = 8.7ns, τ_4 = 42ns and n =3. This function is presented in Fig.3 with the dot line. After choosing n = 3 as an initial value and using GA with minimizing relative error of the current, parameters are determined for the experimental ESD current described in [16] as the following: i_1 = 17.46A, i_2 = 7.81A, τ_1 = 0.75ns, τ_2 = 0.82ns, τ_3 = 3.43ns, τ_4 = 68.7ns. The waveform approximating the ESD current from IEC 61000-4-2 Ed.2 [3], for 4kV, is obtained for: i_1 = 16.6A, i_2 = 9.3A,

τ_1 = 1.1ns, τ_2 = 2.0ns, τ_3 = 12ns, τ_4 = 37ns, n = 1.8, and presented in Figs. 3 and 4 with the full lines. After choosing $n = 1.7$ as an initial value in [22] for GA procedure with minimizing relative error of the current, parameters are calculated for the ESD current as the following: i_1 = 16.3A, i_2 = 9.1A, τ_1 = 1.2ns, τ_2 = 2.05ns, τ_3 = 11.7ns, τ_4 = 37.3ns, n = 1.82.

In [21] is proposed the following function

$$i(t) = At\exp[-Ct] + Bt\exp\left[-Dt\right], \tag{9}$$

for approximating IEC 61000-4-2 Ed.2 ESD current with the following parameters: A = 38.1679A/ns, B = 1.0526A/ns, C = 1ns^{-1}, and D = 0.0459ns^{-1}. The function is presented in Figs. 3 and 4 with the short-dash lines.

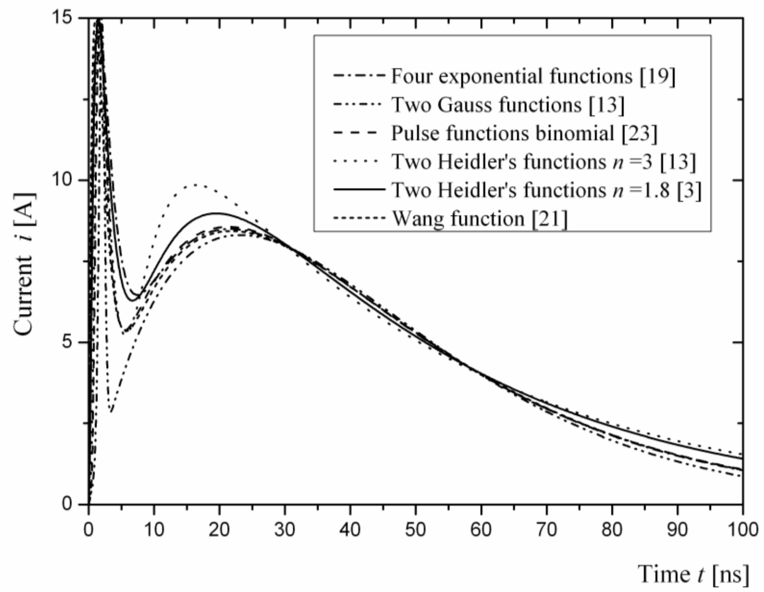

Fig. 3 Functions approximating the Standard 61000-4-2 ESD current waveform for 4kV

Rising time is the difference between t_B for 90% of the current peak ($i_{90\%}$=13.5A) and t_A for 10% of the current peak ($i_{10\%}$=1.5A). Rising times as in the Standard 61000-4-2 are obtained with very different waveshapes behaviour in the first 5ns of functions from Fig. 3 as presented in Fig. 4. All the functions are presented from t=0$^+$, for $i_{\max}$=15A, although the Standard function rises between 6 and 8 ns, given with tollerably lowered peak value $i_{\max}$=14A, if $i_{30\text{ns}}$ = 8A and $i_{60\text{ns}}$=4A are chosen as reference (Figs. 2 and 5). Two-Gauss function has the greatest rising time and Wang function the shortest. Four-exponential expression and Wang function don't have realistic rising parts. Two-Heidler's function for n=1.8, given with the full lines in Figs. 3 and 4, represent the Standard waveshape better than the others.

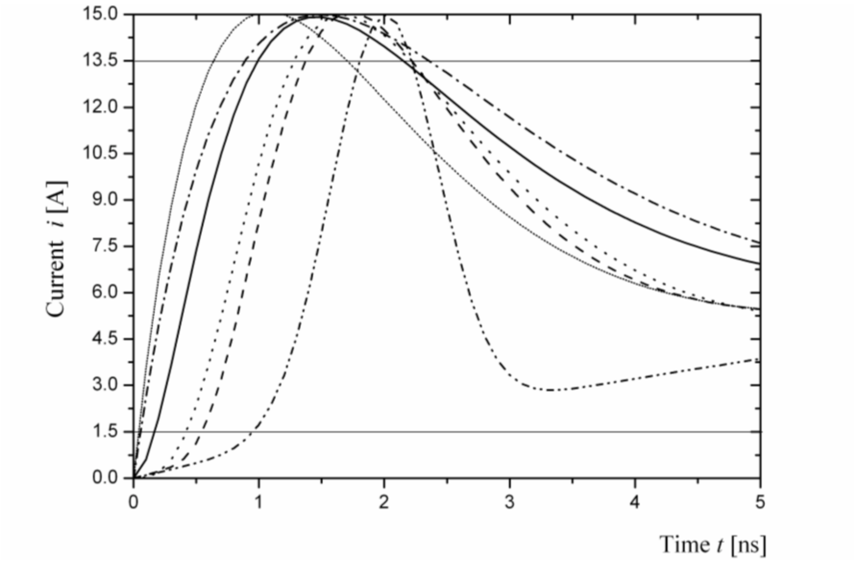

Fig. 4 Functions approximating the Standard 61000-4-2 ESD current waveform for 4kV in the first 5ns, with notations from Fig. 3

3. New Function for Approximating Electrostatic Discharge Currents

An analytically extended function (AEF), with the same expression before and after time moments of maxima, but for different parameters, is proposed for approximating ESD currents. Its main advantages are: simply adjustable derivative value, rise time value, time to the peak value, exact peak values chosen prior to adjusting other parameters and a suitable waveform with the zero first derivative at the point $t=0^+$. The function is continuous, with its first derivative also continuous at any t, so it is of differentiability class C^1. Higher order derivatives have discontinuities at the points of maximum/minimum, so the first derivative of the function belongs to class C^0.

Current function CBC [14] is given with the following expression

$$i_1(t) = \begin{cases} I_{m1}(t/t_{m1})^a \quad \exp[a(1-t/t_{m1})] \ , & 0 \le t \le t_{m1}, \\ I_{m1}(t/t_{m1})^b \quad \exp[b(1-t/t_{m1})] \ , & t_{m1} \le t < \infty, \end{cases} \tag{10}$$

and another with

$$i_2(t) = \begin{cases} I_{m2}(t/t_{m2})^c \quad \exp[c(1-t/t_{m2})] \ , & 0 \le t \le t_{m2}, \\ I_{m2}(t/t_{m2})^d \quad \exp[d(1-t/t_{m2})] \ , & t_{m2} \le t < \infty, \end{cases} \tag{11}$$

so that

$$i(t) = i_1(t) + i_2(t) \tag{12}$$

may represent ESD current. It is denoted with ESD2 and presented in Fig. 5. It may be written in another way as

$$i(t)=\begin{cases} I_{m1}(t/t_{m1})^{a} \quad \exp[a(1-t/t_{m1})]+I_{m2}(t/t_{m1})^{c} \quad \exp[c(1-t/t_{m1})], & 0<t<t_{m1} \\ I_{m1}(t/t_{m1})^{b} \quad \exp[b(1-t/t_{m1})]+I_{m2}(t/t_{m2})^{c} \quad \exp[c(1-t/t_{m2})], & t_{m1}<t<t_{m2} \\ I_{m1}(t/t_{m1})^{b} \quad \exp[b(1-t/t_{m1})]+I_{m2}(t/t_{m2})^{d} \quad \exp[d(1-t/t_{m2})], & t_{m2}<t<\infty \end{cases} \tag{13}$$

as a, b, c, and d are the constants, and $t_{m1} \le t_{m2}$. Using LSQM to approximate IEC 61000-4-2 Standard ESD current, the parameters are determined as I_{m1}=14A, I_{m2}=8.4A, t_{m1}=1ns, t_{m2}=21ns, a=2, b=0.3, c=3, and d=0.9. If three functions are used, based on the same expressions, their sum better represents the IEC 62305-1 Standard current, as given in Fig. 5 and denoted with ESD3.

$$i_1(t)=\begin{cases} I_{m1}(t/t_{m1})^{a}\exp[a(1-t/t_{m1})]\ , & 0\le t\le t_{m1}, \\ I_{m1}(t/t_{m1})^{b}\exp[b(1-t/t_{m1})]\ , & t_{m1}\le t<\infty, \end{cases} \tag{14}$$

$$i_2(t)=\begin{cases} I_{m2}(t/t_{m2})^{c}\exp[c(1-t/t_{m2})]\ , & 0\le t\le t_{m2}, \\ I_{m2}(t/t_{m2})^{d}\exp[d(1-t/t_{m2})]\ , & t_{m2}\le t<\infty, \end{cases} \tag{15}$$

$$i_3(t)=\begin{cases} I_{m3}(t/t_{m3})^{e}\exp[e(1-t/t_{m3})], & 0\le t\le t_{m3}, \\ I_{m3}(t/t_{m3})^{f}\exp[f(1-t/t_{m3})], & t_{m3}\le t<\infty, \end{cases} \tag{16}$$

so that ESD3 is

$$i(t)=i_1(t)+i_2(t)+i_3(t)\,. \tag{17}$$

This may be written also as

$$i(t)=\begin{cases} I_{m1}(t/t_{m1})^{a}\exp[a(1-t/t_{m1})]+I_{m2}(t/t_{m2})^{c}\exp[c(1-t/t_{m2})] \\ \qquad +I_{m3}(t/t_{m3})^{e}\exp[e(1-t/t_{m3})], & 0<t<t_{m1} \\ I_{m1}(t/t_{m1})^{b}\exp[b(1-t/t_{m1})]+I_{m2}(t/t_{m2})^{c}\exp[c(1-t/t_{m2})] \\ \qquad +I_{m3}(t/t_{m3})^{e}\exp[e(1-t/t_{m3})], & t_{m1}<t<t_{m2} \\ I_{m1}(t/t_{m1})^{b}\exp[b(1-t/t_{m1})]+I_{m2}(t/t_{m2})^{d}\exp[d(1-t/t_{m2})] \\ \qquad +I_{m3}(t/t_{m3})^{e}\exp[e(1-t/t_{m3})], & t_{m2}<t<t_{m3} \\ I_{m1}(t/t_{m1})^{b}\exp[b(1-t/t_{m1})]+I_{m2}(t/t_{m2})^{d}\exp[d(1-t/t_{m2})] \\ \qquad +I_{m3}(t/t_{m3})^{f}\exp[f(1-t/t_{m3})], & t_{m3}<t<\infty \end{cases} \tag{18}$$

as a, b, c, d, e and f are the constants, and $t_{m1} \le t_{m2} \le t_{m3}$. Using LSQM the parameters are determined as I_{m1}=14A, I_{m2}=8.2A, I_{m3}=2.2A, t_{m1}=1ns, t_{m2}=21ns, t_{m3}=50ns, a=2, b=0.3, c=2.5, d=1.5, e=15, and f=7. For both ESD2 and ESD3 the maximum peak value can be set to 15A simply by choosing I_{m1}=15A.

ESD3 better represents IEC 61000-4-2 Standard current waveform as given in Fig. 5, than ESD2 or Two-Heidler's function for n=1.8. Its derivative is also continuous, but of differentiability class C^0 as the first derivative has discontinuities at t_{m1}, t_{m2} and t_{m3}.

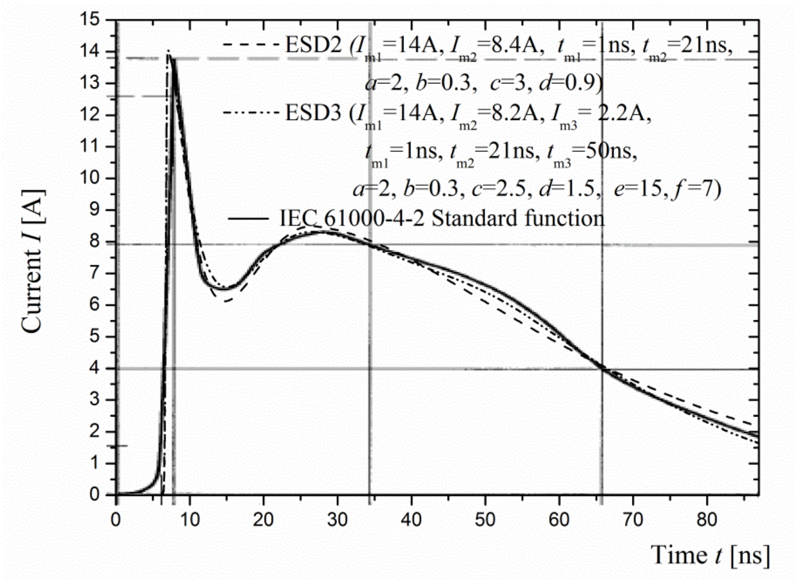

Fig. 5 AEF approximating IEC 61000-4-2 Standard current waveform for 4kV

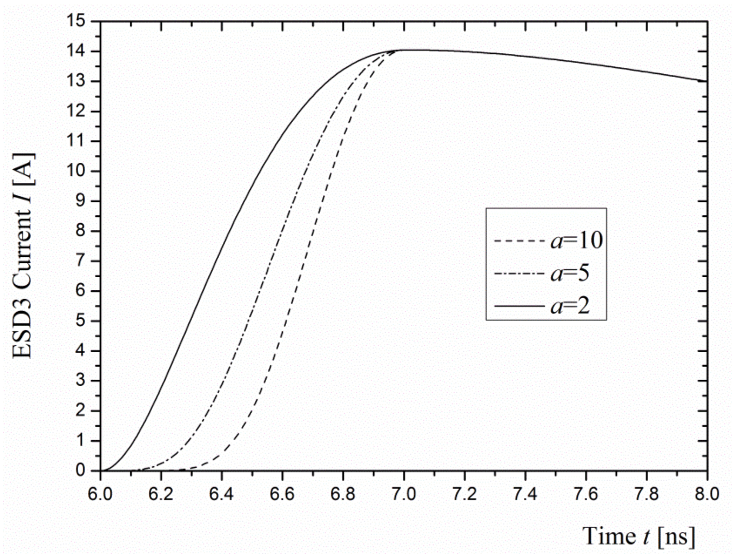

Fig. 6 ESD3 rising part from 6 to 8 ns

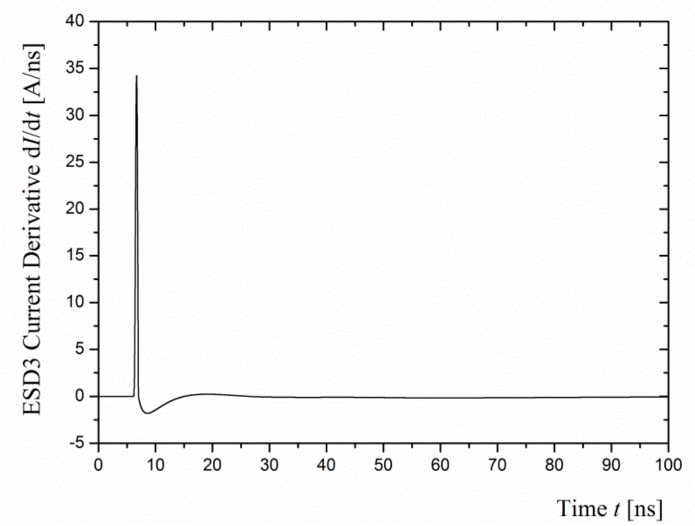

Fig. 7 ESD3 derivative for a=2

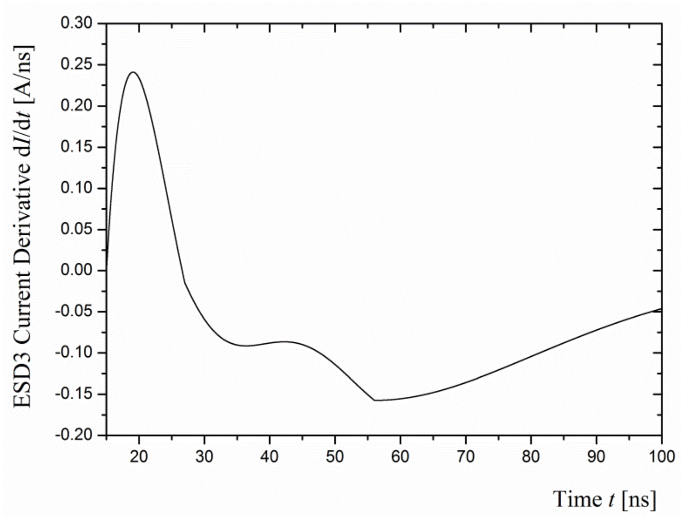

Fig. 8 ESD3 derivative from 15 to 100ns

The ESD3 function rising part is given in Fig. 6. The function derivative in the first 100ns is presented in Fig. 7. First derivative is greater for greater parameter a, so that for a=10 rising time is 0.4ns, for a=5 is 0.5ns, and for a=2 is 0.6ns as defined in IEC61000-4-2 Standard. Parameter a does not influence on the choice of other parameters. Fig. 8 shows the ESD3 derivative from 15 to 100ns, where the needed discontinuities according to the Standard current appear. ESD2, ESD3 and Two-Heidler's function (for n=1.8) are given in Fig. 9. For the comparison Two-Heidler's function is delayed for 6ns and its peak is set to the same value as for ESD2 and ESD3 representing the Standard current.

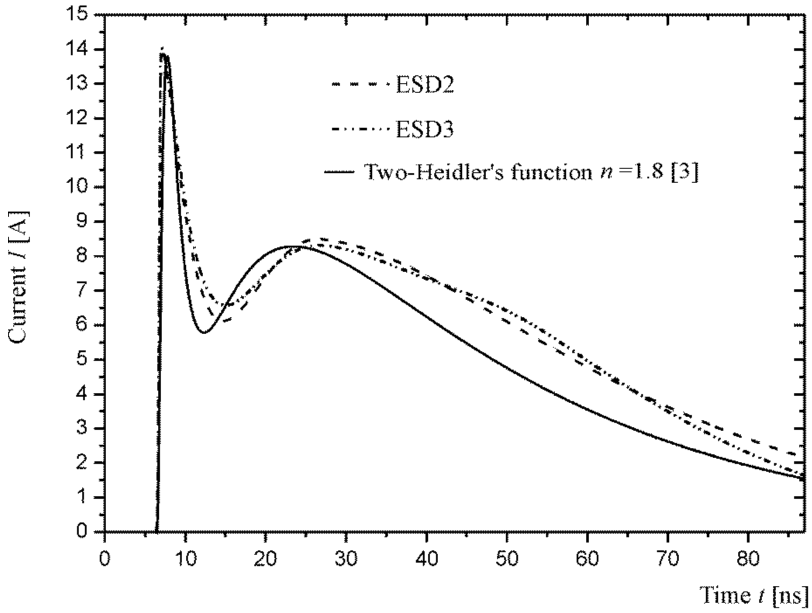

Fig. 9 ESD2, ESD3 and Two-Heidler's function representing the Standard current

CONCLUSIONS

Functions for approximating ESD currents are needed for simulation of different types of electrostatic discharges, calibration of test equipment and adequate representation of the IEC 61000-4-2 Standard current. Important features of such mathematical functions are good approximation of realistic waveshapes and discontinuities in specified time intervals, zero function derivative at $t=0^+$, and simple choice of function parameters.

New function presented in this paper in two forms, ESD2 and ESD3, may be used to approximate different electrostatic discharge currents. Their waveshapes are compared to other functions from literature and show better agreement with the IEC 61000-4-2 Standard current waveshape and its defined parameters. The function derivative is also analyzed. Rising time, maximum and minimum values, so as needed discontinuities, may be obtained for this function independently from other parameters and without peak correction factors simplifying any optimization algorithm used to obtain its parameters.

Further research will include calculation of parameters according to experimentally measured ESD currents, and application of different optimization procedures.

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