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CIRCUIT EQUIVALENT FOR COMMERCIAL ELECTROSTATIC DISCHARGE GENERATORS

Pavlos S. KATSIVELIS, Chrysanthos N. POULIASSIS, Ioannis F. GONOS, Ioannis A. STATHOPULOS
pkatsivelis@gmail.com, hrysanth@gmail.com, igonos@ieee.org, stathop@power.ece.ntua.gr
High Voltage Lab., School of Electrical and Computer Engineering, National Technical University of Athens

Summary: Two commercial ESD generators' current wave shapes are used as a basis, in this paper, to design a circuit that will produce the demanded ESD-current wave shape. A typical current output of each one of these generators was recorded and treated as a reference current wave shape. Then by considering these wave shapes to be the step responses of the circuits-to-be-designed, we apply an approximation method on them in order to obtain the correspondent transfer functions. Then, a theoretical realization is proposed using ideal operational amplifiers.

***Keywords*:** circuit design, electrostatic discharge current, approximation methods.

1. Introduction

The IEC 61000-4-2 Standard [1] for Electrostatic Discharges (ESD) deals with the immunity of electric and electronic devices against electrostatic discharges and describes the procedures that have to be followed during the electrostatic discharge tests on electric and electronic devices. However, it is well understood that in IEC 61000-4-2 there is an aberration [2] between the typical waveform of the output current of the ESD generator and the discharge current that the circuit, described in this Standard, actually produces. The last is a very simple RC circuit and the output current is the capacitor's discharge current, hence rather different from the standard one.

However, the commercial ESD generators actually produce an ESD current wave shape, like the one demanded. The problem of designing an accurate circuit is dealt in this paper, considering the output of two commercial generators, as the reference waveform each time.

The methodology adopted here is based on the Prony method [3]. The Prony method [3-5] is an algorithm, which is used to obtain the impulse response of a circuit, the output of which is a known waveform. Moreover, when considering a known input to the circuit, the transfer function of the circuit can be found. The method developed needs to be able to deal with the sophisticated form of the output current of these commercial generators. The method can be efficient not only to this, but also in other applications of similar difficulty.

The transfer function acquired in the above way was used to select the components of a circuit that produces the current of electrostatic discharge of these commercial generators. Thus, beginning from the transfer function in question, we end up with the schematic of the circuit. Then, a simulation of the circuit takes place in order to verify the correctness of the circuit s output. The developed method provides very accurate results for the ESD current wave shape.

2. The two commercial ESD generators

The two commercial generators used in this work TESSEQ's NSG 438, and EM TEST's DITTO. The two ESD generators are demonstrated in Figure 1.

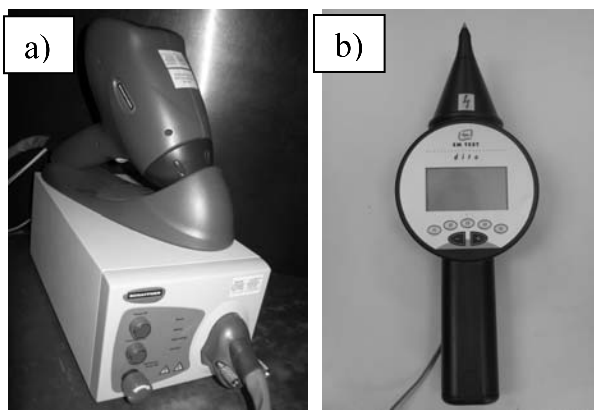

Fig.1. The two ESD generators used in the paper. a) NSG 438, b) DITTO

The typical waveform of the ESD current, defined by the Standard [1, 6], is demonstrated in Figure 2.

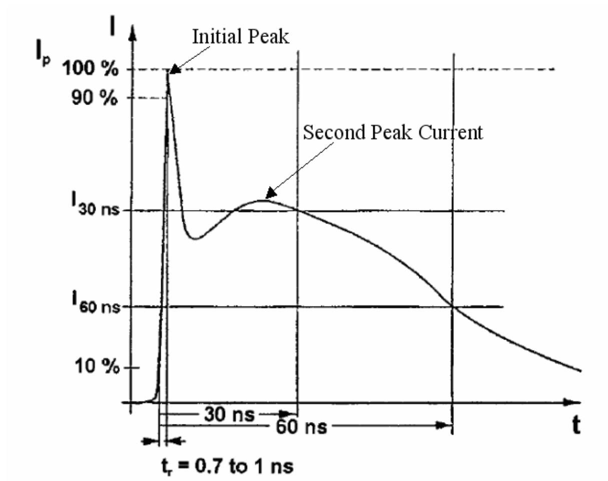

Fig.2. Typical waveform of the output current of the ESD generator [1]

Two typical outputs of the generators used are demonstrated in Figure 3.

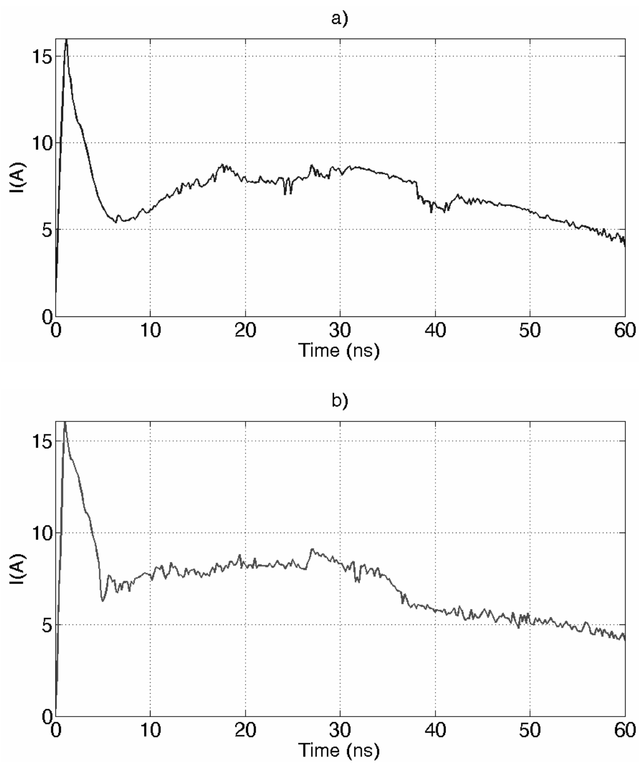

Fig.3. Typical snapshots of the ESD-current waveform of the two generators a) DITTO, b) NSG 438, under charging voltage +4 kV, on ohmic load 2 Ohms

Both ESD generators are calibrated on yearly basis, and verified on weekly basis.

3. The approximation method

The approximation method used here is the same with the one used in [3]. It is a modification of the Prony method, employed here to obtain an approximation of the step response of a circuit. The approximation is given in the form of a series of exponentials in time domain or series of fractions in frequency domain.

Shortly the method is described as follows:

Let $g_d(t)$ be a continuous function. Let us consider the values of $g_d(t)$ at a set of equally spaced points $t=kT$, $k=0,1,\ldots$ and form the matrix:

$$P_I = \begin{bmatrix} g(0) & g(T) & g(2T) & . & g(NT-T) \\ g(T) & g(2T) & g(3T) & . & g(NT) \\ g(2T) & g(3T) & . & . & . \\ g(3T) & . & . & . & g(2NT-2T) \\ . & . & . & . & 0 \\ . & . & . & . & 0 \\ . & . & g(2NT-2T) & . & 0 \\ . & g(2NT-2T) & 0 & . & 0 \\ g(2NT-2T) & 0 & 0 & . & 0 \end{bmatrix} \quad (1)$$

The matrix $P_1(2N,N)$ is now formed and linearly independent columns in the submatrix $P_1(2N\text{-}k,k)$ consisted by the first $2N\text{-}k$ rows and the first k columns of $P(N,M)$ are sought.

If the first n+1 columns are linearly dependent, the minimum singular value (σ_{n+1}) of the matrix P_1 $(2N\text{-}n\text{-}1,n+1)$ is equal to zero. The order n of the approximation is defined as the minimum n such that:

$$\left|\sigma_{\min_d} P(2N-n-1, n+1)\right| < e_q \quad (2)$$

Obviously e_q is treated as an equivalent during the approximation method.
If $g_d(t)$ is the impulse response of a linear, time invariant system of finite order n, it can be written:

$$g_d(kT) = \sum_{i=1}^{n} A_i \exp(s_i kT) = \sum_{i=1}^{n} A_i z_i^k . \quad (3)$$

where,

$$z_i = \exp(s_i T) \quad (4)$$

Let us define the polynomial in z having roots z_i, $i=1,2,\ldots n$, as follows.

$$\psi(z) = \prod_{i=1}^{n}(z-z_i) = z^n + \sum_{m=0}^{n-1} b_m z^m \quad (5)$$

Equations (6) and (7), do not posses solutions. Best approximations of the solutions minimizing the euclidian norm of the errors are obtained using generalized inverses. So the vectors containing the parameters A_i, and then s_i, are determined as follows.

$$\begin{bmatrix} g(0) & g(T) & g(2T) & . \\ g(T) & g(2T) & g(3T) & . \\ g(2T) & g(3T) & . & . \\ g(3T) & . & . & . \\ . & . & . & . \\ . & . & . & g(2NT-2T-1) \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ . \\ . \\ . \\ b_{n-1} \end{bmatrix} = - \begin{bmatrix} g(nT) \\ g(nT+T) \\ . \\ . \\ . \\ g(2NT-2T) \end{bmatrix} \quad (6)$$

where b_i are the coefficients of $\psi(z)$, as in (5). Furthermore, the system of equations:

$$\begin{bmatrix} 1 & 1 & . & . & . & 1 \\ z_1 & z_2 & . & . & . & z_n \\ . & . & & & & . \\ . & . & & & & . \\ . & . & & & & . \\ z_1^{N-1} & z_2^{N-1} & . & . & . & z_n^{N-1} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ . \\ . \\ . \\ A_n \end{bmatrix} = \begin{bmatrix} g_d(0) \\ g_d(T) \\ . \\ . \\ . \\ g_d(NT-T) \end{bmatrix} \quad (7)$$

is consistent and has a solution.

4. Applying the approximation methods.

The approximation method was applied on the two wave shapes shown in Figure 3. Due to the noise of the measurements the series of exponentials was quite large in both cases. This will normally lead to someone to design a large circuit.

So, in this case the first few terms are taken under consideration in each application, depending on the desired preciseness. Keeping the number of the terms small gives a circuit quite small, and clears the wave shape from the unwanted noise.

4.1 ESD generator (DITTO)

For the DITTO case the first six terms of the output of the approximation were considered, and the step response acquired this way is the following:

$$G(s) = \frac{30.53}{s+0.03} - \frac{39.51}{s+0.07} + \frac{28.09}{s+0.25} - \frac{0.71-2.12i}{s+(0.68+3.07i)} - \frac{0.71+2.12i}{s+(0.68-3.07i)} - \frac{16.59}{s+2.51} \quad (8)$$

The time axis of the initial wave shape was scaled by multiplying by 10^9, to avoid writing large numbers.

When plotted the function gives what is shown in Figure 4. The tolerance for the ESD current wave shape set by [6] (Heidler equation ± 30% [7]) are also depicted in the same plot.

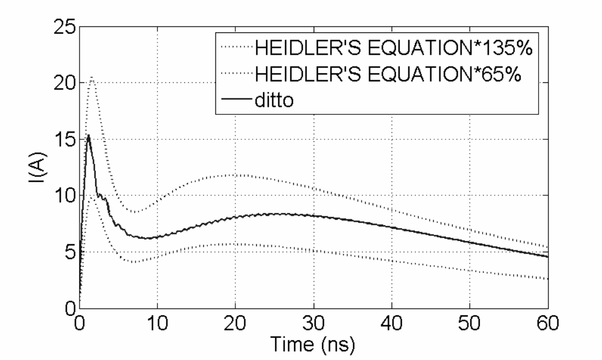

Fig.4. Approximation of the DITTO ESD current under +4kV, together with the barriers set by the [6]

4.2 ESD generator (NSG 438)

For the NSG 438 case the first four terms of the output of the approximation were considered, and the step response acquired, similarly to previously, is:

$$G(s) = \frac{12.55}{s+0.02} - \frac{15.58}{s+0.16} + \frac{2.52-17.37i}{s+0.52-0.57i} + \frac{2.52+17.37}{s+0.52-0.57i} \quad (9)$$

When plotted, similar to previously, the function gives what is shown in Figure 5. The barriers for the wave shape set by [6] are also depicted in the same plot.

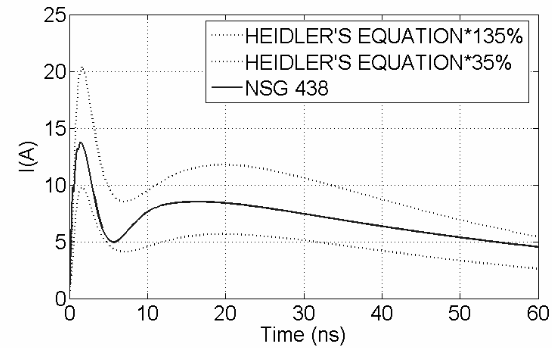

Fig.5. Approximation of the NSG ESD current under +4kV, together with the barriers set by the [6].

It is obvious that the current wave shapes of these two commercial generators, are within specifications. Let us now proceed and determine the equivalent circuits that could produce such acceptable ESD current wave shapes.

5. The circuits

5.1 ESD generator (DITTO)

Beginning from Eq. 8, we are going to determine the elements of the circuit and their values. If we choose to write Eq. 8 as follows,

$$G(s) = 1.0997 \frac{s}{s+0.03*10^9} \frac{s+25.63\cdot10^9}{s+0.07\cdot10^9} \frac{s^2+0.10\cdot10^9\cdot s+0.02\cdot10^{18}}{s^2+2.75\cdot10^9\cdot s+0.61\cdot10^{18}} \frac{s^2+0.99\cdot10^9\cdot s+15.07\cdot10^{18}}{s^2+1.35\cdot10^9\cdot s+9.90\cdot10^{18}} \quad (10)$$

we can match these fractions with their materializations, as follows using standard rules.

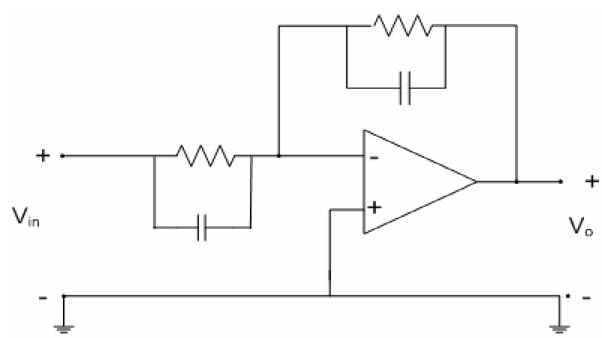

Fig.6. Form of the inverting connection used to design circuit that corresponds the first two factors of the transfer function

For each one of the first two factors, a circuit of the form of Figure 6 was considered. For creating a circuit that corresponds to the two last factors of the transfer function G(s), the Tow-Thomas circuit, depicted in Figure 7, was used.

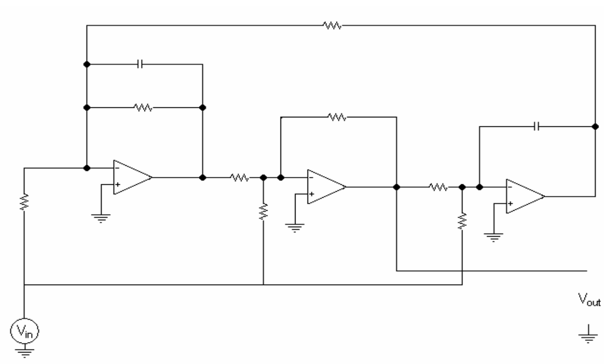

Fig.7. Form of the connection used to design circuit that corresponds the two last factors of the transfer function, the Tow-Thomas circuit

The circuit is realized as a cascade connection of these biquads. The elements' values can be seen in Tab. 1.

Table 1. Elements' values of the circuit in Figure 9, R_{ij}, C_{ij}

i \ j	1	2	3	4
1	R=3.90Ω C=10pF	R=∞ C=1nF	R=37.69Ω C=10pF	R=253.43Ω C=10pF
2	R=1338.70Ω C=10pF	R=33.22Ω C=1nF	R=36.28Ω C=10pF	R=74.13Ω C=10pF
3	x	x	R=10Ω	R=10Ω
4	x	x	R=10Ω	R=10Ω
5	x	x	R=10Ω	R=10Ω
6	x	x	R=10Ω	R=10Ω
7	x	x	R=1626.30Ω	R=100.98Ω
8	x	X	R=52438.40Ω	R=60.34Ω

The simulation of the circuit in Figure 8 with ideal operational amplifiers, in PSpice gave the output, shown in Figure 9. In the same figure DITTO's ESD current wave shape is presented in order to evaluate the behavior of the circuit.

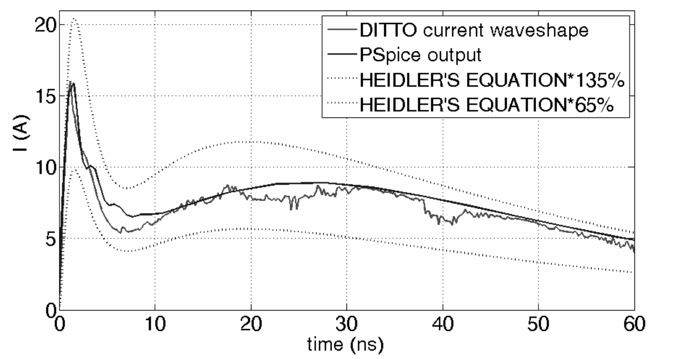

Fig.9. Plot of the simulation of the circuit, along with the Heidler's equation, as defined in [6]

The values of the crucial parameters of the designed circuit's output are shown in Tab. 2.

Table 2. Parameters' values of DITTO's equivalent circuit current wave shape.

	I_{max} [A]	Rise time [ns]	I_{30} [A]	I_{60} [A]
Specifications [1]	15±10%	0.7÷1	8±30%	4±30%
Recorded	16.02	0.89	8.30	4.14
Simulation	15.89	0.92	8.75	4.87

5.2 ESD generator (NSG 438)

Following a similar process beginning with Eq. 9, we are going to determine the elements of the circuit and their values.

Again, we write Eq. 9 as follows,

$$G(s) = 2.02 \frac{s}{s + 0.02 \cdot 10^9} \frac{s + 10.8 \cdot 10^9}{s + 0.17 \cdot 10^9} \frac{s^2 + 0.19 \cdot 10^9 \cdot s + 0.05 \cdot 10^{18}}{s^2 + 1.04 \cdot 10^9 \cdot s + 0.59 \cdot 10^{18}} \quad (11)$$

and follow the same procedure in order to design the circuit and determine the price of its components.

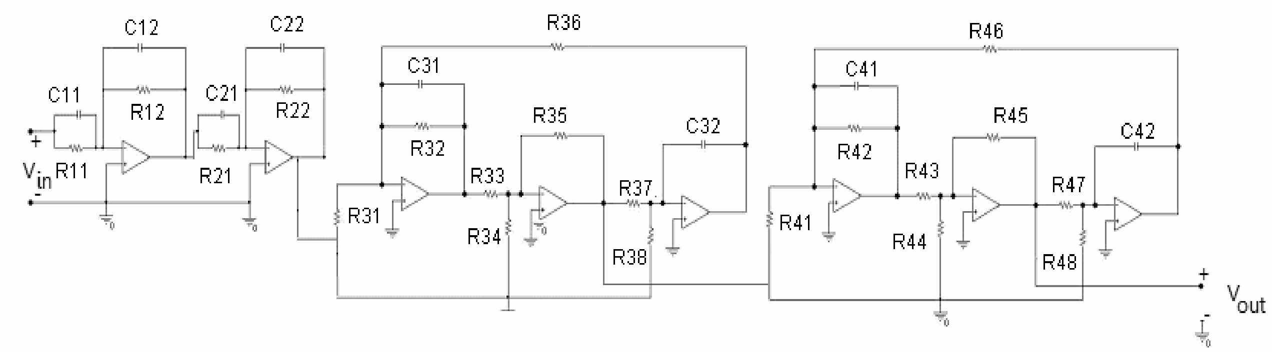

Fig. 8. The circuit that produces the DITTO's ESD current.

Same as before, the circuit is shown in Figure 10, the elements' values in Tab. 3, the crucial parameters' values in Tab.4, and the PSpice output in Figure 10.

Table 3. Elements' values of the circuit in Figure 9, R_{ij}, C_{ij}

j \ i	1	2	3
1	R=9.26Ω C=10pF	R=∞ C=1nF	R=117.55Ω C=10pF
2	R=595.59Ω C=10pF	R=58.85Ω C=1nF	R=95.8773Ω C=10pF
3	x	x	R=10Ω
4	x	x	R=10Ω
5	x	x	R=10Ω
6	x	x	R=10Ω
7	x	x	R=1670.30Ω
8	x	X	R=18601.20Ω

Table 4. Parameters' values of DITTO's equivalent circuit current wave shape

	I_{max} [A]	Rise time [ns]	I_{30} [A]	I_{60} [A]
Specifications [1]	15±10%	0.7÷1	8±30%	4±30%
Recorded	16.10	0.72	8.30	4.38
Simulation	15.73	0.88	8.56	5.21

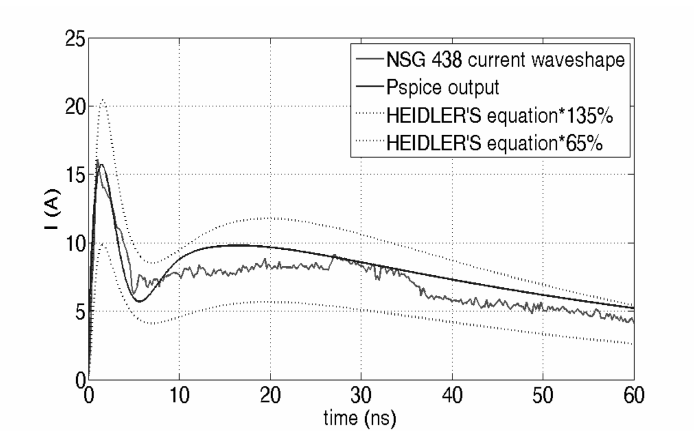

Fig. 11. Plot of the simulation of the circuit, along with the Heidler's equation, as defined in [6]

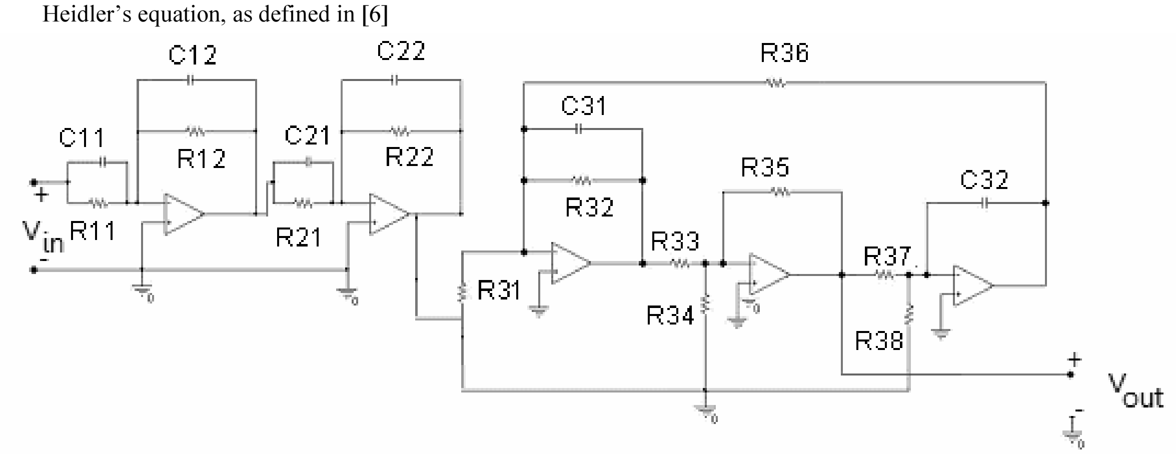

Fig. 10. The circuit that produces the NSG 438 ESD current

6. Conclusions

The remaining problem of the aberration between the circuit proposed by the IEC 61000-4-2 [1] and the typical ESD current waveform included in the new version of Standard [6] is approached in this paper. Commercial ESD generators, in general, seem to meet the specifications set for the parameters' values of the ESD current.

In this work two commercial ESD generators, are been used, EM TEST's DITTO and TESSEQ's NSG 438. Their behavior is guaranteed to be correct from the manufacturers as well as from the calibrating laboratories.

The method employed here, in order to design circuits which will produce the expected ESD current wave shape is a network composition, considering the output of the circuit to be a known wave shape, obtained by the application of the presented approximation method.

This wave shape is the result of the application, of the approximation method presented in the paper, on the ESD current wave shape of each generator.

The approximation method is based on the Prony method, but modified to deal with such sophisticated wave shapes. The approximation is given under the form of sum of fractions. The length of this sum is a matter of the precision desired.

This is a way to design accurate circuits directly (not by trial and error). This kind of circuit can be suitable for simulations. These circuits are good to be used not only for the simulation of these two ESD generators but also as references ESD current circuits.

7. Acknowledgement

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8. References

1. *IEC 61000-4-2 Electromagnetic Compatibility (EMC), Part 4: Testing and measurement techniques, Section 2: Electrostatic discharge immunity test* – Basic EMC Publication", 1995.

2. Fotis, G.P.; Gonos, I.F.; Stathopulos, I.A.2006. Determination of discharge current equation parameters of ESD using genetic algorithms, *IEE, Electronics Letters* 42(14): 797-799.

3. Katsivelis, P.K.; Fotis, G.P.; Gonos, I.F.; Stathopulos, I.A. 2007. A New Method to Design a Circuit for the Electrostatic Dishcarge Current, in *Proceedings of the XVII International Conference on Electromagnetic Disturbances (EMD 2007)*, Bialystok, Poland, September 19-21, 2007: 1.2-1 - 1.2-6.

4. Li Qi; Lewei Qian; David Cartes; Stephen Woodruff. 2006. Initial Results in Prony Analysis for Harmonic Selective Active Filters, in *Proceedings of IEEE Power Engineering Society General Meeting*, Montreal, Canada , P. 6.

5. Tawfik, M.M.; Morcos, M.M. 1999. A Fault Locator for Transmission Lines Based on Prony Method, in *Proceedings of IEEE Power Engineering Society Summer Meeting*, Edmonton, Alta., Canada, 2: 943-947

6. *IEC 61000-4-2: "Electromagnetic compatibility (EMC) DRAFT - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test* – DRAFT version", 2005.

7. Heidler H. 1985. Analytische Blitzstromfunktion zur LEMP-Berechnung, presented at *18th ICLP (International Conference on Lightning Protection*), Munich, Germany.