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System Level ESD Analysis - A Comprehensive Review I on ESD Generator Modeling

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Abstract – This study presents, for the first time, state-of-the art review of the various techniques for the modeling of the electrostatic discharge (ESD) generators for the ESD analysis and testing. After a brief overview of the ESD generator, the study provides an in-depth review of ESD generator modeling (analytical, circuit and numerical modeling) techniques for the contact discharge mode. The proposed techniques for each modeling approach are compared to illustrates their differences and limitations.

Keywords: Electrostatic Discharge(ESD), System level ESD testing, IEC 61000-4-2, ESD generator, ESD source modeling, Circuit modeling, 3D modeling, *S*-Parameters, Frequency domain.

1. Introduction

Electrostatic discharge (ESD) is a phenomena whereby the discharge occurs between the two objects. The occurrence of an ESD event results in the discharge of high amplitude current with sharp rise time, to the product. A system level ESD event occurs when an electrical system experiences discharge of ESD noise [1-3]. The main sources of system level ESD events are charged humans holding a metallic object, such as a charger, a headset, or a USB etc., and charged metallic objects and products [2, 4-6].

The main purpose of an ESD generator is the reproduction of a typical human-metal ESD scenario. The International Electrotechnical Commission (IEC) 61000-4-2 [7] has defined the characteristics of a desired ESD stressing waveform. The basic components of an ESD simulator are a high voltage direct current (DC) source, a high voltage relay to perform switching operations, a RC discharge network, a lossy metallic discharge tip, connecting coils, an inner ground plate, a polyethylene disk, and a two meter ground strap [1, 2, 4, 8, 9].

A wide range of ESD simulators are available to generate the desired ESD waveform to perform actual system level ESD testing [10]. The major suppliers of ESD generators are NoiseKen [11], Teseq [12], EM Test [13], Thermo Fisher Scientific [14], EMC Partner [15], 3ctest [16], Electro-tech Systems [17], and Haefely Hipotronics [18]. Fig. 1 lists the different products of these suppliers as of the time this manuscript was written. The ESD generators are available with 8 kV to 30 kV discharge voltage specifications. Among the depicted models in Fig. 1, the Teseq NSG 434 and NSG 435, Haefely ONYX, Thermo Keytek Minizap MZ-15, EM Test Dito, 3ctest EDS 20H and EMC Partner ESD 3000 are handheld devices that are battery powered. The other models consist of a separate ESD simulator unit and an interconnecting gun pistol.

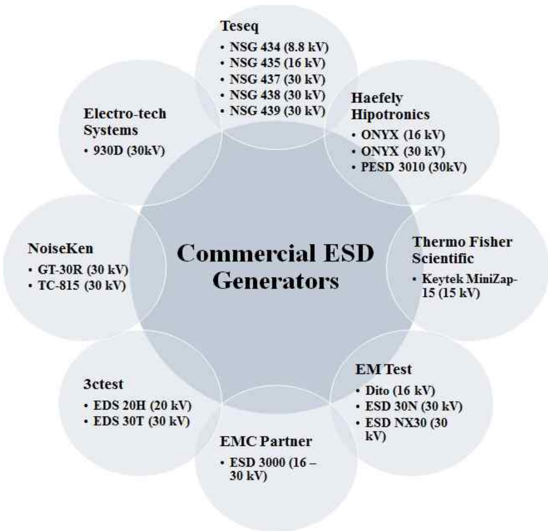

Fig. 1. Major ESD generator suppliers and their products as of 2018

Handheld generators, such as EM Test Dito [19] and Keytek MiniZap-15 [14], contains a rechargeable battery unit. In handled simulators, the gun body contains a selection panel and an LCD block showing the selectable options and the selected discharge voltage levels configurations. However, in other units, such as the NoiseKen TC-815 [11] and GT-30R [11] guns, a discharge pistol is connected to the separate ESD simulators. The selection of the desired voltage type and test mode (air or contact) is done on the ESD simulator or on the selection panel, and the waveform is injected via the connected pistol.

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Most ESD generators have replaceable gun tips, as different tips are used for the air, contact, and automotive ESD discharge testing [7, 20]. Commercial generators also have the options of replaceable discharge RC units if the user wants to perform testing per other standards requirements, such as ISO 10605 [20].

The simulation methodologies for the ESD generator can be categorized into three types: analytical modeling [6, 21-29], circuit modeling for simulation using a SPICE-type circuit simulator [2, 6, 26, 27, 30-46] , and full wave electromagnetic (EM) modeling using various EM tools based on the Finite Element Method (FEM), the Finite-Integration Technique (FIT), and the Finite-Difference Time-domain (FDTD) algorithms [2, 6, 8, 32, 35, 46-48]. The matching of the four parts of the generated waveform: rise time, first peak current value, and the currents at 30 ns and 60 ns is required with the reference waveform in [7].

The uniqueness of this study lies in extensive and comprehensive review of the various circuits, mathematical and three dimensional (3D) modeling approaches of ESD discharge waveform and their comparison. Each topic has been reviewed thoroughly based on available literature and is presented and described in an attractive manner.

The structure of the study is as follows: Section 2 briefly describes the effect of the change in the ESD generator type on ESD waveform. In Section 3, details and comparison of the various mathematical methods for the ESD source modeling are described. Section 4 reviewed the available circuit modeling techniques for the generation of reference ESD waveform. The review of the numerical modeling approaches for ESD generator is outlined in Section 5. Last Section 6 concludes the study

2. Effect of Generator Model on ESD Waveform

It has been reported in the literature [35, 38, 49-51] that different generator types produce significant variations in the generated ESD waveform properties under the same calibration settings. The change in the waveform characteristics can also affect the immunity of the system in estimating ESD failure [1, 50].

The variation in the waveform properties is validated using measurements in the standard calibration setup of [7]. Fig. 2 shows a comparison of the generated waveforms of the +4 kV discharge voltage level for four different commercial ESD generators. The NoiseKen TC-815 [11] and GT-30R [11], EM Test Dito [19], and Teseq NSG 437 [52] ESD generators are used for the current traces in Fig. 2.

The waveform attributes of the waves in Fig. 2 are within the defined tolerance limits of the IEC standard (I_{peak} = 15 A, rise time (t_r) = 0.8 ns, I_{30ns} = 8 A and I_{60ns} = 4 A), but differences in waveform shape and other characteristics can be noted. The ringing effect around the 30 ns mark is a common characteristics of several commercial generators and this effect is more prominent in

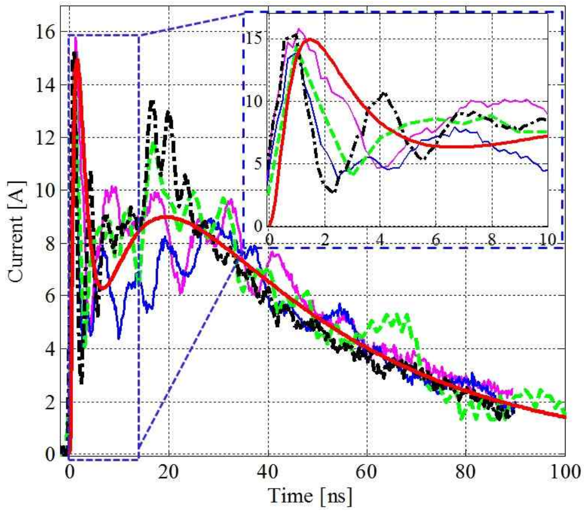

Fig. 2. Comparison of different ESD simulator current waveforms for +4 kV discharge voltage: NoiseKen GT 30R (solid magenta), Teseq NSG 437 (solid blue), NoiseKen TC-815 (dashed green), EM test Dito (dash-dot black), and IEC standard (thick solid red)

waveforms produced by handheld ESD generators (dash-dot black line in Fig. 2), such as the Dito gun, compared to other model's curves. This ringing could be due to the grounding strap position and the physical construction of the commercial ESD simulators [5, 35, 50]. The IEC [7] committee is working on this point to eliminate the difference caused by the ringing of the waveform after the first peak [1, 35] produced by commercial ESD guns in real time measurement environment. A recent study [50] shows that the ringing effect can be reduced by using a longer ground strap (3 m) cable for the gun.

3. Analytical Modeling Techniques

Analytical models or mathematical descriptions have been developed for generating the standard ESD waveform, as described in [7]. A variety of mathematical descriptions have been proposed in the literature, and a review of the major reported analytical models is given here.

Analytical models have used the exponential or polynomials to fit pulse waveforms to the standard requirements [6, 21, 24, 34, 53]. In addition to the matching of the waveform of the mathematical model with the outline characteristics of the ESD waveform outlined in [7], its current value should be zero at t = 0, because the transient current does not change abruptly during the ESD process [1, 6, 7, 24, 34]. Also, the radiated field generated during the ESD process is not only dependent on the current waveform but also on its time derivative [1, 51]. As the generated current, the transient radiated fields at the discharge moment also do not change abruptly, which means that the current derivative at t = 0 should also be

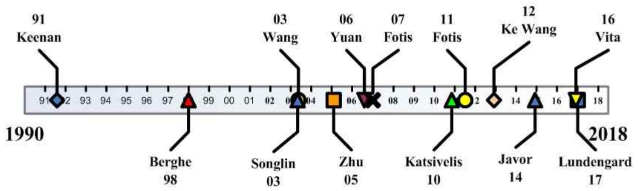

Fig. 3. Timeline of the major proposed analytical models of commercial ESD generators

zero [6, 7, 24]. The mathematical description of the ESD waveform must conform to the current and current derivative requirements [1, 6, 7, 24, 34].

3.1 Review of analytical models

A review of the major reported analytical models from 1991 to 2017 is described in this section. The time line of the major proposed mathematical models for the generation of an ESD current waveform is depicted in Fig. 3.

The initial work for the mathematical modeling of the lighting stroke waveform, which is similar to an ESD waveform, was done in [54, 55]. For the first time, in 1991, Keenan [21] proposed a four exponential mathematical model (1) for the fitting to the ESD waveform parameters with the detailed description of model parameters. Each group of two exponents in (1) corresponds to fast and low ESD and the output wave is the sum of both exponential groups. Eq. (1) parameters for the + 15 kV discharge level outlined in [21] are: I_0 = 1943 A, I_1 = 857 A, t_1 = 2.2 ns, t_2 = 2.0 ns, t_3 = 22 ns, and t_4 = 20 ns. The wave obtained using (1) can be scaled for any discharge voltage level. In [55], Cerri proposed an approximate double exponential representation of an ESD discharge current. However, no additional details about the parameter values of the proposed model were reported in [55].

Berghe [22] proposed a Gaussian function based ESD analytical model (2) in 1998. The parameter values of (2) for +4 kV discharge are: A = 13 A, B = 0.4 GA/s, t_1 =5 ns, t_2 = 10 ns, σ_1 = 1.414 ns, and σ_2 = 35.35 ns [22]. The binomial of the pulse function was used to construct the ESD waveform in [23]. The introduced pulse function based model of (3) by [23] is time-integrable but the value of current derivative is not zero at t = 0. Following are the parameters of (3): I_0 = 106.5 A, I_1 = 60.5 A, t_1 = 0.62 ns, t_2 = 1.1 ns, t_3 = 55 ns, t_4 = 26 ns, and n = 8 for the +4 kV voltage level [23].

In 2003, Wang *et al.* [6] developed a complex mathematical formulation based on the previously developed lightning stroke model of the Heidler equation [54]. The mathematical formulas of [6] consist of exponential functions (4) and re-produce the IEC reference waveform very well per [7] requirements, with a finite derivative of the physical current. The values of (4) parameters for the +5 kV discharge voltage outlined by [6] are: I_1 = 21.9 A, I_2 = 10.1 A, τ_1 = 1.3 ns, τ_2= 1.7 ns, τ_3= 6 ns,

Table 1. Parameters of Yuan trinomial model [24]

Amplitude (A)	Time Constant (ns)	Time Constant (ns)	Exponential Order
I_o = 53.52	τ_1 = 0.606	τ_2 = 1.759	p = 5
I_1 = 27.89	τ_3 = 5.000	τ_4 = 14.220	q = 5
I_2 = 19.19	τ_5 = 18.170	τ_6 = 38.260	r = 3

Keenan model [21]:

$$i(t) = I_0(e^{-t/t_1} - e^{-t/t_2}) + I_1(e^{-t/t_3} - e^{-t/t_4}) \quad (1)$$

Berghe model [22]:

$$i(t) = Ae^{\left[-((t-t_1)/\sigma_1)^2\right]} + B.t.e^{\left[-((t-t_2)/\sigma_2)^2\right]} \quad (2)$$

Songlin model [23]:

$$i(t) = I_0\left[1-e^{(-t/t_1)}\right]^n e^{-t/t_2} + I_1\left[1-e^{(-t/t_3)}\right]e^{-t/t_4} \quad (3)$$

Wang model [6]:

$$\begin{aligned} i(t) = {} & \frac{I_1}{e^{\left[-\frac{\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{1/n}\right]}} \cdot \frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n} . e^{-\left(\frac{t}{\tau_2}\right)} \\ & + \frac{I_2}{e^{\left[-\frac{\tau_3}{\tau_4}\left(\frac{n\tau_4}{\tau_3}\right)^{1/n}\right]}} \cdot \frac{\left(\frac{t}{\tau_3}\right)^n}{1+\left(\frac{t}{\tau_3}\right)^n} . e^{-\left(\frac{t}{\tau_4}\right)} \end{aligned} \quad (4)$$

Yuan trinomial model [24]:

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

Katsivelis modified [6] model [25]:

$$i(t) = I_1 \cdot \frac{\left(t/\tau_1\right)^n}{1+\left(t/\tau_1\right)^n} . e^{-\left(\frac{t}{\tau_2}\right)} + I_2 \cdot \frac{\left(t/\tau_3\right)^n}{1+\left(t/\tau_3\right)^n} . e^{-\left(\frac{t}{\tau_4}\right)} \quad (6)$$

τ_4 = 58 ns, and n = 3. In [34], Zhu modified the parameters of (1) [21], (2) [22] and (4) [6] for a superior fitting of waveforms with [7] characteristics of the +4 kV discharge voltage level. Yuan [24] used the concept of pulse function proposed by [23] to construct two trinomial and quadnomial mathematical descriptions for ESD waveforms. Yuan's model [24] (trinomial model (5) with the parameters values in Table 1) fulfills the continuity requirements of the current and its first derivative, and the proposed model waveform matched exactly with the waveform in [7].

Fotis' group [53, 56] applied a genetic algorithm (GA) to the measured data of the ESD current to fit the waveform to the other previously reported mathematical Eqs. (1) [21], (2) [22], and (4) [6]. In [25], the authors modified the objective function of [56] to better fit the waveform using GA to match the real human discharge event with the revised analytical model (6) of [6] as reference. The parameter values of (6) are shown in Table 3. Another study related to the optimization of the parameter values of (1), (2), and (4) was done by [53] for better matching. The studies of [25, 53, 56] found that the best results of GA fitting and other optimization models with minimum error were obtained for the mathematical model of (4) [6].

In [26], the mathematical modeling of an ESD waveform based on a modified Prony algorithm (functional approximation of intended curve using the sum of the exponential) is described. The impulse response of the finite order (ninth order) linear time invariant (LTI) system (7) developed using a modified Prony algorithm is used to generate an approximated signal that matches very well with the ESD waveform of [7]. A fourth order exponential model (8) for ESD current simulation is proposed in [27]

Katsivelis transfer function based model [26]:

$$i(t)=\frac{-0.001}{s+0.0262}\cdot\frac{s+0.4241}{s+0.4117}\cdot\frac{s+0.0875}{s+0.0724}\cdot\frac{s-572.1058}{s+20.0599}\cdot\frac{s+2028.75}{s+1.3352}\cdot\frac{s+14.1242}{s+0.4879}\cdot\frac{s+6.3195}{s+0.1480}\cdot\frac{s^2+0.1516s+0.0337}{s^2+6.8054s+14.7796} \tag{7}$$

Kewang model [27]:

$$i(t)=Ate^{-Ct}+Bte^{-Dt} \tag{8}$$

Javor analytically extended function (AEF) model [28]:

$$i(t)=\begin{cases} I_{m1}(t/t_{m1})^a.e^{a(1-t/t_{m1})}+I_{m2}(t/t_{m2})^c.e^{c(1-t/t_{m2})}+I_{m3}(t/t_{m3})^e.e^{e(1-t/t_{m3})} & 0<t<t_{m1} \\ I_{m1}(t/t_{m1})^b.e^{b(1-t/t_{m1})}+I_{m2}(t/t_{m2})^c.e^{c(1-t/t_{m2})}+I_{m3}(t/t_{m3})^e.e^{e(1-t/t_{m3})} & t_{m1}<t<t_{m2} \\ I_{m1}(t/t_{m1})^b.e^{b(1-t/t_{m1})}+I_{m2}(t/t_{m2})^d.e^{d(1-t/t_{m2})}+I_{m3}(t/t_{m3})^e.e^{e(1-t/t_{m3})} & t_{m2}<t<t_{m3} \\ I_{m1}(t/t_{m1})^b.e^{b(1-t/t_{m1})}+I_{m2}(t/t_{m2})^d.e^{d(1-t/t_{m2})}+I_{m3}(t/t_{m3})^f.e^{f(1-t/t_{m3})} & t_{m3}<t<\infty \end{cases} \tag{9}$$

Lundengard AEF model [29]:

$$i(t)=\begin{cases} \left(\sum_{k=1}^{q-1} I_{m_k}\right)+I_{m_q}\sum_{k=1}^{n_q}\eta_{q,k}x_q(t)^{\beta_{q,k}^2+1} & t_{m_{q-1}}<t<t_{m_q}, 1\le q\le p \\ \left(\sum_{k=1}^{p} I_{m_k}\right)+\sum_{k=1}^{n_{p+1}}\eta_{p+1,k}x_{p+1}(t)^{\beta_{p+1,k}^2} & t_{m_p}\le t \end{cases} \quad where: \Delta t_{m_q}=t_{m_q}-t_{m_{q-1}} \text{ and } x_q(t)=\begin{cases} \dfrac{t-t_{m_{q-1}}}{\Delta t_{m_q}}e^{\frac{t_{m_q}-t}{\Delta t_{m_q}}} & 1\le q\le p \\ \dfrac{t}{t_{m_q}}e^{1-\frac{t}{t_{m_q}}} & q=p+1 \end{cases} \tag{10}$$

with the following parameter values: A = 38.1679 A/ns, B = 1.0526 A/ns, C =1 ns-1, and D = 0.0459 ns-1. In [28], the author proposed an AEF (9) based on the sum of the two or three channel based current functions (CBC). The parameter values of the proposed AFE were determined using the least-squares method (LSQM) and are as follows: I_{m1} = 14 A, I_{m2} = 8.2 A, I_{m3} = 2.2 A, t_{m1} = 1 ns, t_{m2} = 21 ns, t_{m3} = 50 ns, a = 2, b = 0.3, c = 2.5, d = 1.5, e =15, and f = 7. The waveforms of [28] comply with the continuity requirements of the ESD waveform.

Recently, Lundengard' group [29] proposed a complex, multi peaked AEF (10) to generate an ESD current based on the work in [28]. In contrast to [28], the authors in [29] estimated the non-linear parameters of proposed model using the Marquardt least-squares method (MLSM) in [29]. The parameter values of (10) can be found in Table 3 of [29] for various combinations of AEFs to produce a more fitted waveform. The proposed models in [29] are complex compared to earlier proposed models [6, 21-24, 26] [28, 56] and also require the estimation of an increased number of parameters for better fitting. In [57, 58], the authors further optimized the modified parameters of [53, 56] for better fitting of the [6, 21, 22] models for the +4 kV discharge voltage level using different objective functions in GA. However, the difference between the reported modified parameters of [53, 56] and [57, 58] is not very significant.

Table 2 summarizes the strategies of all reviewed mathematical models.

3.2 Comparison of analytical models

A comparison of the current waveforms generated using

Table 2. Analytical modeling strategies for ESD waveform

Author	Year	Mathematical Modeling Approach
Keenan *et al.* [21]	1991	• Sum of four exponential (1) • Does not comply with continuity condition at t = 0
Berghe *et al.* [22]	1998	• Sum of two Gaussian pulses (2) • Does not comply with continuity condition at t = 0
Songlin *et al.* [23]	2003	• Based on binomial of pulse function (3) • Does not comply with continuity derivate condition at t = 0
Wang *et al.* [6]	2003	• Complex exponential formulation (4) • Complies with continuity condition at t = 0 • Benchmark waveform included in [14]
Zhu *et al.* [34]	2005	• Parameter optimization of (1), (2), and (4) for +4 kV • No change in continuity condition of respective model
Yuan *et al.* [24]	2006	• Based on trinomial of pulse function (5) • Complies with continuity condition at t = 0
Fotis *et al.* [53, 56]	2006, 07, 11	• Fitting of measured wave data using GA • Best fitting was obtained for (4)
Katsivelis *et al.* [25]	2010	• Fitting of measured wave data using GA with (6) • Best fitting was obtained for (4)
Katsivelis *et al.* [26]	2010	• Transfer function based on modified Prony algorithm (7) • Impulse response of 9th order LTI system
Kewang *et al.* [27]	2012	• Fourth order exponential function (8) • Does not comply with continuity derivative condition at t = 0
Javor [28]	2014	• Analytically extended function (9) • Complies with continuity condition at t = 0
Lundengard *et al.* [29]	2017	• Multi-peaked complex analytically extended function (9) • Complies with continuity condition at t = 0
Vita *et al.* [57, 58]	2016/ 2017	• Fitting of measured wave data using new objective function in GA • Best fitting was obtained for (4)

the reviewed analytical models is shown in Figs. 4 and 5.

The analytical formulation of (4) [6] has been included in IEC 61000-4-2 [7] and is considered as the most accurate formulation for the generation of a reference ESD waveform [25, 26, 53, 56-58] and is being used as the benchmark for ESD waveform. Numerous authors [7, 25, 34, 53] have modified the earlier reported parameters of (4) by [6] for better matching. A comparison of the change in the parameter values of (4) by different authors is given in Table 3. In Table 3, the reported parameters by [6] are scaled by 1/1.25 for the +4 kV discharge level.

Fig. 6 shows a comparison of (4) waveforms according to the different parameter values in Table 3. The values of the waveform characteristics (current and rise time) of the waveforms in Figs. 4, 5, and 6 are given in Table 4. In Table 4, the complexity of the reviewed mathematical models is rated from 1 (simple) to 5 (complex) based on reported analytical equations. The reproduced current waveform by each respective equation has also been classified on a scale of not good to excellent (not good, fair, good, very good, excellent) based on the degree of matching of the waveform shape and its different

Table 3. Parameter modifications of (4) for better fitting for the +4 kV discharge level

	Wang [6] 2003	Zhu [34] 2005	IEC [7] 2008	Fotis [53] 2011	Vita [58] 2017
I_1(A)	17.52	17.5	16.6	16.3	16.2
I_2 (A)	8.08	10.1	9.3	9.10	9.2
τ_1 (ns)	1.3	1.3	1.1	1.20	1.5
τ_2 (ns)	1.7	1.7	2.0	2.05	2.1
τ_3 (ns)	6.0	8.7	12	11.7	11.5
τ_4 (ns)	58	42	37	37.3	37
n	3	3	1.8	1.82	1.82

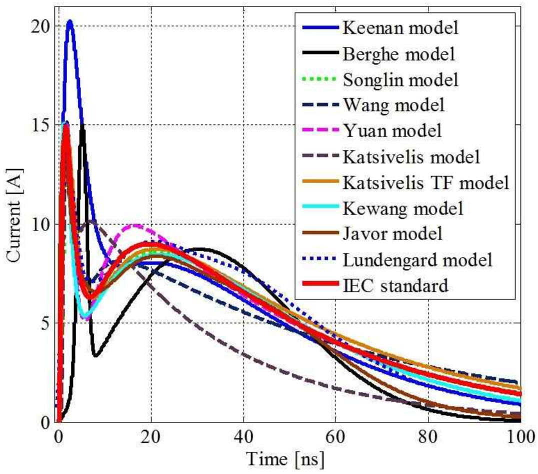

Fig. 4. Comparison of ESD current waveforms of reported analytical models for +4 kV discharge level

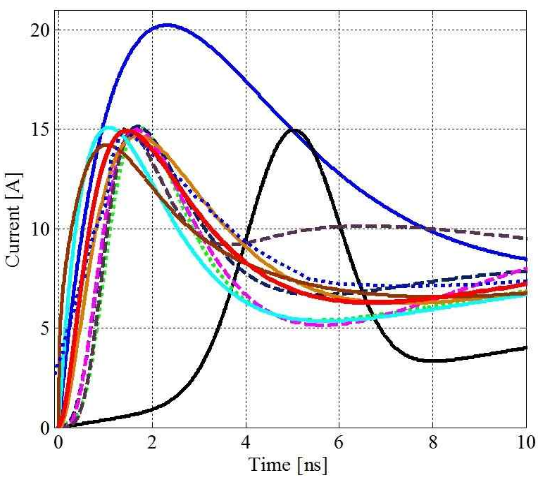

Fig. 5. Elaborated waveforms of Fig. 4 in $0 \leq t \leq 10$ ns

characteristics (current values and rise time) with the specified requirements in [7].

It can be noted from Table 3 that the optimized parameters by [53, 58] closely matched with the described parameters in [7] for the +4 kV voltage level, and so do the respective waveform values in Table 4. These studies suggest that the IEC standard [7] parameters for (4) could be modified for better fitting with reference ESD waveform properties.

Table 4. Comparison of ESD waveform characteristics of different reported analytical models (Figure 3) for the +4 kV discharge level

		I_{peak} (A)	Rising Time *(ns)*	I_{30ns} (A)	I_{60ns} (A)	Mathematical Model (1 = Simple, 5 = Complex)	Reproduced Waveform Shape (Not good-Excellent)
	Standard IEC [7]	15.0 (12.8–17.2)	0.80 (0.60–1.00)	8.0 (5.6–10.4)	4.0 (2.8–5.2)		
	IEC analytical model [7]	14.92	0.80	8.03	4.03		
	Measured	14.62	0.70	9.3	4.9		
Analytical Models	Keenan *et al.* [21]	**20.22**	**1.30**	7.45	3.56	3	Not good
	Berghe *et al.* [22]	14.96	**2.06**	8.71	3.24	3	Not good
	Songlin *et al.* [23]	15.06	0.83	8.02	3.99	3	Very good
	Wang *et al.* [6]	15.11	0.86	6.56	3.94	4	Very good
	Zhu *et al.* [34], for [6] model	14.98	0.86	7.99	3.99	4	Excellent
	Yuan *et al.* [24]	14.97	0.83	7.96	3.99	4	Excellent
	Katsivelis *et al.* [25], for [6] model	14.67	0.72	**4.83**	**1.70**	4	Fair
	Katsivelis *et al.* [26]	14.64	0.92	8.11	4.43	5	Very good
	Fotis *et al.* [53], for [6] model	14.49	0.86	7.86	3.95	4	Excellent
	Kewang *et al.* [27]	15.08	0.60	7.96	4.02	2	Very good
	Javor [28]	14.20	**0.56**	7.67	3.52	5	Fair
	Lundengard *et al.* [29]	14.97	0.7	8.46	4.30	5	Excellent
	Vita *et al.* [58], for [6] model	13.87	0.99	7.91	3.93	4	Good

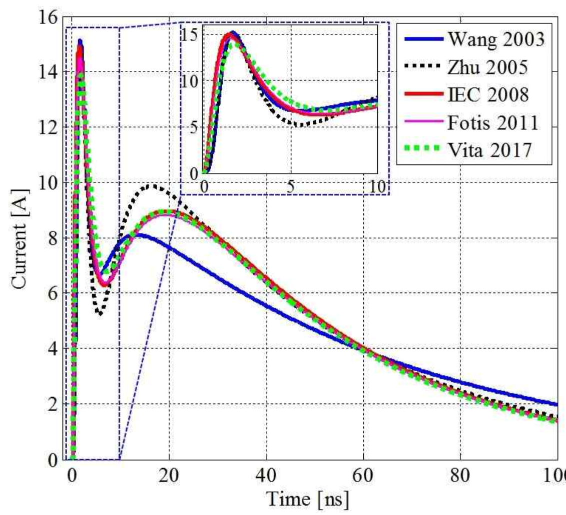

Fig. 6. Comparison of (4) waveforms for different parameters in Table 3 for the +4 kV discharge level

Usually, the waveforms generated using commercial simulators do not match exactly with the waveform in [7] (see Fig. 2). Therefore, if one wants to regenerate the measured waveform with exact matching, then the mapping of the waveform using approximation and curve mapping techniques [25, 26, 53, 56-58] would be more useful because it can help the user to reproduce the waveform with fewer errors compared to the generation of waveforms using analytical models.

The generated ESD current waveform using a mathematical model could be used as an ESD source for the further system level ESD coupling analysis in a circuit simulation or numerical simulation environment to reduce the computational resource requirements. In addition, the reproduced waveform using analytical models can also be used to compare waveforms obtained either by experimental measurements or circuit or full wave EM modeling of the commercial ESD generator.

4. Circuit Modeling Techniques

The circuit modeling of an ESD generator is seen as a powerful and fast tool to characterize the individual components of a gun. System efficient ESD design (SEED) demands circuit simulation for the estimation of EUT robustness [1], which invokes the need for a circuit model of the ESD simulator. The lumped circuit can be easily simulated in any circuit simulator which also offers advantages of saving of computation time and resources required for the complete 3D EM modeling of the ESD gun [1, 5]. The output of the circuit model can also be used for different analysis purposes, such as coupling analysis of the circuit or EM simulator and the SEED.

The literature contains different approaches for the circuit modeling of an ESD generator using behavioral techniques [6, 26, 27, 30-35, 37, 39-43, 59] that are based on frequency domain characterization of the standard ESD waveform calibration setup [2, 36, 44-46]. All reported models can be simulated in any SPICE type circuit simulator. Fig. 7 shows a typical general circuit model of an ESD generator. Efficient circuit modeling requires the effective computation of different circuit components (parasitic coupling between gun material and reference plane and among different gun components, the ground strap, ground impedance and the target object) [2, 6, 35, 40, 46].

The source in the circuit model of an ESD generator can be defined as either a constant DC voltage source with two relay switches for the charge and discharge purposes [31], [33, 35, 39, 42] or a step voltage source [2,

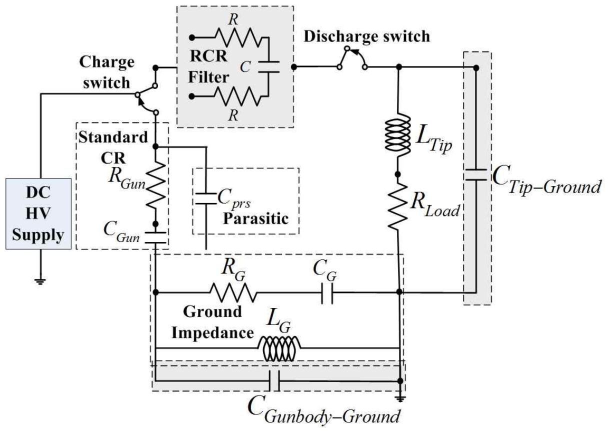

Fig. 7. General circuit model of ESD generator (the requirements for the gray shaded components vary in different reported circuit models in the literature)

6, 32, 36, 40, 46]. In the former, a step function is used to depict the relay switching function that replaces the actual discharging process with the charging of the storage capacitor of the generator [2, 6, 32, 36, 37, 40, 46].

The charge storage capacitor and discharge resistor (CR units) are modeled with standard element values of 150 pF and 300 Ω [7], along with the stray capacitance of these units. The ground wire is modeled through the self-inductance based on its length, radius and ground loop configuration [2, 31, 33, 35, 46]. The ESD tip inductance is represented using the series inductance values connected with a standard 2 Ω target load. Xiu *et al.* [45] suggested that more accurate modeling of the shunt 2 Ω target with the series inductance can also have an impact on the reproduced waveform. The rise time filter is also designed for the correct formation of the rise time characteristics of the waveform, as done by [6, 36, 38]. For the formulation of the circuit model based on the physical charging and discharging process, the role of the capacitance of the copper ring structure enclosing the main gun body, as in [14, 19], the capacitance between the gun body and the ground plane, the stray capacitance between the reference ground plane (RGP) and the discharge tip, and the copper ring structure are also very important [6, 36, 38].

4.1 Review of circuit models

Fig. 8 depicts the time line of the major reported equivalent circuit models of ESD generators from 1997 to 2017.

To the best of our knowledge, in 1997 Murota [30] reported for the first time the circuit model of a commercial simulator with a detailed procedure for calculating its component values. Tanaka *et al.* [31] proposed an equivalent circuit of a NoiseKen ESD gun in the Laplace domain with calculation formulas to calculate the ESD discharge current into a Pellegrini target. The reported models of [31] have two separate circuits for two modes

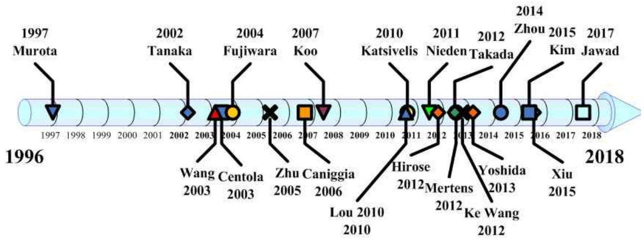

Fig. 8. Time line of major reported ESD circuit models

(first and second peak) of the discharge current. The final discharge current is the sum of the output of two separate circuits. However, the discharge waveform of the circuit in [31] has prominent oscillations after the first peak.

In 2003, Wang [6] proposed an equivalent circuit of the Dito generator based on the illustration of physical charge and discharge processing. The reported model of [6] comprises three parts corresponding to the each part of the discharging waveform. Centola [32] presented a different equivalent SPICE based model of an ESD generator and enclosure that used a 25 Ω step voltage source as excitation. The role of the stray capacitance between the enclosure and the generator body is critical in the presented models of [6, 32] to accurately estimate ESD waveform, which showed good matching with the measurement results.

Fujiwara and Tanaka [33] reported another modified circuit model of [31] for the discharge current into a Pellegrini 2 Ω target and 50 Ω SAM connector [33]. The modified model in [33] removes oscillation after the first peak, as compared to [31]. In [34], the author presented the simple circuit of two resistor inductor capacitor (RLC) branches that can generate the ESD current very well. The parameters values of the circuit elements in [31] were calculated using the Runge Kutta method. The reported circuit model by Caniggia *et al.* [35] consists of two switches for charge and discharge purposes and a loss-less transmission line along with other lumped components for the generation of a reference ESD waveform. Seol *et al.* [59] used the same model in [36] and optimized its component values for the fitting of simulated waveform with the measurements results from a commercial ESD simulator.

The literature also details circuit models based on frequency domain measurements of ESD waveform calibration setup. Koo [36] suggested the circuit modeling using a frequency domain measurement through a modified ESD generator. The time domain ESD waveform was obtained through the step- response of frequency domain data in [36]. The authors in [38] reported a combined impedance measurement technique between the discharge relay and gun tip of the generator by employing a current probe at the relay point to obtain vector network analyzer (VNA) measurements. The impedance data was then converted to a state space representation for time domain analysis using the vector fitting (VF) technique [60]. The utilization of a current transformer at relay point offer advantages of assurance of common VNA reference ground connection at discharge relay as compared to previous available techniques [36, 44], but at the cost of major modification of the ESD generator. Both [36] and [38] modified the proposed circuit model of [6] to compare circuit results with frequency domain measurement results.

In [37], a double RLC network was reported for the generation of an IEC current waveform. However, no information about the circuit component values was provided by [37]. Katsivelis et al. [26] presented a different approach for a circuit model based on the ideal active elements based in (7). Another study based on the calculating the RLC constants of circuit components is done by [39, 42]. The authors of [39, 42] formulated an equivalent circuit based on the RLC components of the first peak, the oscillation point, and the second peak of the measured ESD waveform. Takada *et al.* [40] reported a circuit model comprised of a standard RC unit, different switching components, tip parasitic, and the material of the gun body. Although the circuit in [40] has good agreement with standard characteristics in [7], the discharge waveform shape is not good after the first peak.

The reported circuit model in [41] is composed of two RLC branches corresponding to slow and fast current transients based on the physical components of the gun, as in [37, 39, 42]. The circuit model in [41] is simple and more accurate compared to previous models [6, 35, 36, 40]. In addition, it can be used to reproduce the discharge current for the ISO 10605 standard [20] by changing the values of the RC branch corresponding to slow current transients.

In [27], Kewang *et al.* derived the transfer function of (8) for the step input function, and then calculated the component values of the proposed fourth order passive and active circuit model based on the comparison of (8) and a derived transfer function. Xiu *et al.* [45] modified the model in [41] by incorporating the characteristics of gun tip inductance and customized target load with series

Table 5. Summary of circuit modeling techniques for ESD generator

Author	Year	Proposed Technique
Murota [30]	1997	• Behavioral model • Detailed modeling and circuit element calculations
Tanaka *et al.* [31]	2002	• Two circuits for first and second peaks • Oscillation in waveform after first peak
Wang *et al.* [6]	2003	• Behavioral model • Three parts for three discharge components
Centola *et al.* [32]	2003	• Behavioral model • Rise time issue of reported waveform
Fujiwara *et al.* [34]	2004	• Behavioral model • For 50 Ω SMA not standard 2 Ω ESD load
Zhu *et al.* [34]	2005	• Simplified circuit with two RLC branches • Runge Kutta method for element calculations
Caniggia *et al.* [35]	2006	• Behavioral model • Two switches, lossless transmission line, and lumped components
Koo *et al.* [36]	2007	• Modified model of [82] based on frequency domain measurements • Additional ferrite and resistive component at source point for modified gun
Lou *et al.* [37]	2010	• Simple behavioral circuit of two RLC branches • No information about circuit element values
Katsivelis *et al.* [26]	2010	• Transfer function using approximation method (7) • Ideal active elements (chain of bi-quads) for ninth order LTI
Nieden *et al.* [38]	2011	• Modified model of [82] based on frequency domain measurements • Added additional transformer component for modified generator
Hirose *et al.* [39]	2012	• Calculation of the RLC constants based on measurements • Two parts corresponding to for first and second peaks
Takada *et al.* [40]	2012	• Physics based model • Distorted waveform shape between first and second peaks
Mertens et *al.* [41]	2012	• Simple flexible behavioral model • Two RLC branches for slow and fast transients
Kewang et *al.* [27]	2012	• Fourth order passive RLC network • Circuit derivation based on transfer function of (8)
Yoshida *et al.* [42]	2013	• Calculation of the RLC constants based on measurements • Three parts for first peak, oscillation part, and second peak of waveform
Zhou *et al.* [43]	2014	• Physically self-consistent fourth order circuit model • More matching of reproduced waveform with HMM standard
Kim [44]	2015	• Physics based model based on frequency domain measurements • Rise time issues in generated waveform
Xiu *et al.* [45]	2015	• Modified model of [100] • Modified target load with series inductance
Jawad *et al.* [2, 46]	2017	• Simple model based on frequency domain measurements • Ground component values from impedance data

inductance using the measured single port *S*-parameters data. The authors in [45] measured the *S*-parameters with a mocked gun tip without any modification of the ESD generator, as previously proposed by [36, 38].

Kim [44] proposed a physics based circuit model based on frequency domain data. The authors in [44] determined the different values of grounding components of the proposed circuit using the impedance measurements of the standard calibration setup in [7] by using a mocked SMA connector instead of modified ESD generators, as proposed in [36, 38]. However, the circuit model in [44] did not satisfy the rise time requirements of the standard waveform.

A physically self-consistent circuit model meeting the requirements of IEC and Human Metal Model (HMM) was proposed in [43] in 2014. The model consists of two RLC networks, as in [27, 34, 37, 39, 41] with the condition of the same initial voltages of both charging capacitor components for physical consistency. Recently, we proposed a relatively simple and efficient circuit model based on frequency domain characterization using a mocked SMA connector [2, 5], [46]. Our proposed model not only produces very good waveform characteristics but also has comparatively fewer circuit components compared to previously proposed models in [6, 26, 31, 33, 35, 36, 38-40, 42].

All equivalent circuits proposed by different authors can be simulated in any SPICE-based circuit simulator. However, the values of lumped components of numerous proposed circuit models depend on the ESD generator type. A summary of the all reviewed state-of-the-art circuit models is shown in Table 5.

4.2 Comparison of circuit models

A comparison of the major reviewed circuit models with the standard reference IEC waveform is shown in Fig. 9 for the +4 kV ESD input voltage level. All waveform characteristics in Fig. 9 are reproduced using the suggested models of the respective authors in the SPICE simulator.

Table 6 elaborates the quantitative comparison of all waveform characteristics of the major reviewed circuit models. In Table 6, circuit simplicity and complexity are determined based on the number of lumped elements of the reported circuit. The assigned attribute of reproduced

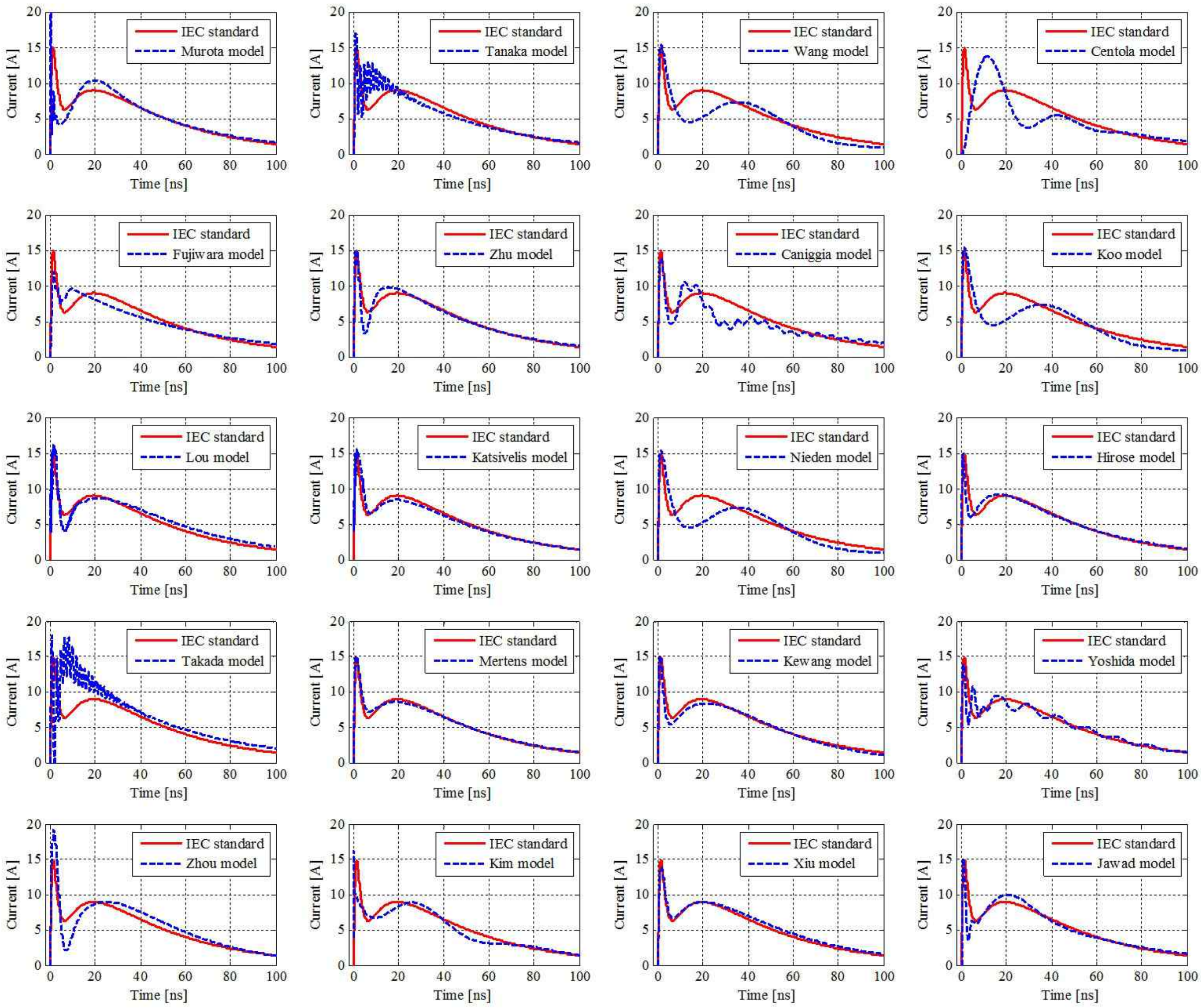

Fig. 9. Comparison of current waveforms of major circuit models of Fig. 8 for the +4 kV discharge voltage level

Table 6. Comparison of the ESD waveform characteristics of different reported ESD circuit models (Fig. 8) for the +4 kV voltage level

		I_{peak} (A)	Rise Time *(ns)*	I_{30ns} (A)	I_{60ns} (A)	Circuit Model (1=Simple, 5=Complex)	Re-produced Waveform Shape (Fair-Excellent)
	Standard IEC [7]	15.0(12.8-17.2)	0.80(0.60-1.00)	8.0(5.6-10.4)	4.0(2.8-5.2)		
	Analytical Model [7]	14.92	0.80	8.03	4.03		
	Measured	14.6	0.70	9.3	4.9		
Circuit Models	Murota [30]	**21.3**	**0.22**	8.7	4.1	4	Fair
	Tanaka *et al.* [31]	16.9	0.70	7.3	3.8	5	Fair
	Wang *et al.* [6]	15.3	0.87	6.9	3.9	4	Very good
	Centola *et al.* [32]	13.8	**6.65**	**3.8**	3.3	4	Fair
	Fujiwara *et al.* [33]	12.0	1.0	6.7	3.8	4	Fair
	Zhu *et al.* [34]	14.9	0.83	8.0	3.9	2	Excellent
	Caniggia *et al.* [35]	13.9	0.98	**4.8**	3.6	4	Good
	Koo *et al.* [36]	15.3	0.86	6.9	3.9	5	Very good
	Lou *et al.* [37]	16.0	0.98	8.0	4.6	2	Very Good
	Katsivelis *et al.* [26]	15.4	0.96	7.5	3.9	5	Very Good
	Nieden *et al.* [38]	15.3	0.87	6.9	3.8	4	Very good
	Hirose *et al.* [39]	14.9	**0.42**	7.8	4.1	2	Fair
	Takada *et al.* [40]	17.9	0.60	8.3	4.2	3	Fair
	Mertens *et al.* [41]	14.9	0.77	7.7	4.0	2	Very good
	Kewang *et al.* [27]	15.0	**0.59**	7.9	4.0	2	Good
	Yoshida *et al.* [42]	13.8	**0.57**	8.3	4.3	4	Fair
	Zhou *et al.* [43]	**19.2**	1.00	8.8	4.7	2	Good
	Kim [44]	16.3	**0.00**	8.7	3.1	3	Fair
	Xiu *et al.* [45]	13.9	0.90	8.3	4.5	3	Good
	Jawad *et al.* [2], [46]	15.1	0.70	8.4	3.9	2	Very good

waveform shape (fair to excellent) is determined based on overall wave shape matching with the standard waveform in [7], rise time, and oscillations between the first peak and the second peak of the ESD current waveform as illustrated in Fig. 9. The measured results in Table 6 are for the Noise Ken TC-815 model from our own experiment (dashed green waveform in Fig. 2).

A comparison of Table 6 and Fig. 9 shows that the better matching between the measured and circuit model results and the smaller deviation from the standard IEC reference waveform is for the circuit models in [2, 6, 36, 38, 40, 41, 45, 46]. Overall, the reported circuit models in [2, 39, 41, 46] are simpler compared to all other models in Fig. 9; however, [39] did not satisfy the rise time requirements of the waveform. The waveform shapes in [39, 42] are good but have been rated as fair because the generated waveforms do not comply with the rise time requirements in [7].

5. 3D EM Modeling Techniques

Circuit modeling of an ESD simulator is good for generating an ESD reference waveform. However, the predication of the field coupling to the EUT for the immunity compliance testing and susceptibility analysis requires the modeling of a full wave electromagnetic model of the generator. Recently, different circuit simulation based techniques have been pro-posed by different authors [2, 5, 42, 46] to estimate induced coupling without the full wave EM modeling of the ESD generator. However, calculating the transient fields generated due to an ESD event and their effect on the coupled noise at the EUT point requires full wave modeling [35, 40, 48]. Field coupling analysis is particularly important for the soft-error analysis of EUT that is mostly caused by the higher frequency (> 1 GHz) components of the transient fields of the ESD generator [8, 48]. The intensity of these higher order field components depends on the details of the constructed full wave EM model [6, 32, 35, 40].

The main components of a numerical model of ESD generators are similar to those of a circuit model except that they include various structural components. Fig. 10 illustrates the different structural elements of a typical EM model of an ESD gun. It requires source modeling using a voltage source or a current source, a high voltage relay, a low pass R-C-R filter, a gun main discharge CR unit, a metallic discharge tip, a ground strap for the gun pistol and different electronic and structural elements of the real time simulator [6, 8, 35, 48]. The numerical modeling of generator can be accomplished using various numerical computation algorithms like FEM, FDTD, FIT and Transmission Line Modeling (TLM). As the generation of an ESD waveform requires the transient analysis, FIT and TLM based coding and commercial software’s [61, 62] are preferred choice of many authors [8, 35, 48]. FIT and TLM based solvers reduce the simulation time with fewer computational resources and memory requirements compared to other FEM based solvers [8, 35, 48].

Accurate source modeling is essential for the correct generation of ESD waveform. The basic approach is to use a DC source with a high voltage relay and a low pass

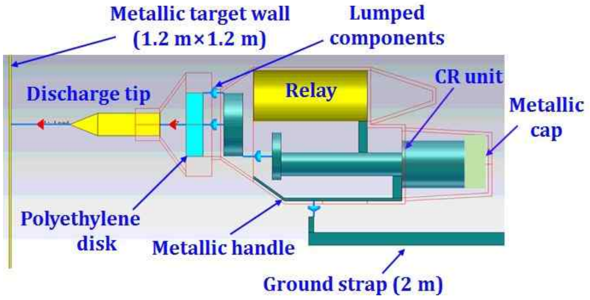

Fig. 10. General typical EM model of ESD generator (requirements of structural/lumped components vary for different numerical models)

filter to provide the switching function, as used in [6]. However, the complex detailed modeling of a high voltage relay to perform switching and modeling of an R-C-R filter to increase the rise time of the relay to around 1 ns can increase the simulation time and computational requirements [8, 48]. Step sourcing (similar to circuit models) with a finite rise time (0.2 ns to 1 ns), as used in [8, 35, 48], has been seen as a good solution for the source modeling, with less calculation time for the model. It is imperative to mention that the step source can give the good transient current results. However, for the correct modeling of high frequency content of the discharge waveform, modeling of the actual pulse forming network in the EM model is essential [32].

The length of the grounding strap in the EM simulation has a major impact on the generated waveform. A greater length (up to 2 m) generates the most accurate second and third peak positions and respective wave values at those (30 ns and 60 ns) positions. The greater length of the ground strap can be modeled by introducing distributed inductance along the short ground strap [8] to minimize the computational resources. In addition, the insertion of a small lumped inductance component between the gun body and the ground strap [2, 32, 35, 46] can mimic the long strap effect with a smaller actual metallic ground strap in the numerical model. Such approaches are used to limit the computational resource and simulation time [2, 8, 32, 35, 46].

The main discharge CR units and other parasitic components are modeled using lumped components [2, 8, 32, 35, 46], depending on the type of generator. Such a modeling approach is referee to as a simple EM modeling. In detailed numerical modeling, these lumped elements can also be modeled using metallic layers and dielectric as done in [6, 48], but at the cost of increased computational time.

The detailed and simplified full wave modeling of the ESD simulator also has an impact on the different analysis parameters. A comparison of the effect of the modeling of ESD generators on different performance parameters in undertaken in [32] and is reproduced in Table 7 with written permission from the authors. The transient field

Table 7. Main characteristics of ESD generator numerical modeling © [32], reproduced with written permission from the authors of [32]

	Fully detailed model	Simplified model	Only enforced current
Injected current	Accurate	Quite Accurate	Accurate
H-field	Accurate	Quite Accurate	Accurate, close to EUT
E-field	Accurate	Only its main characteristics	Not correct
Strap current	Accurate	Quite Accurate	Depends on EUT size
EUT size	Correctly modeled	Moderately correct	Strong effect if EUT is small
Numerical design of simulator	Yes	No	No
'Unwanted' radiation caused by fast switching	Included	Not included	Not included
Calculation time	Long	Short	Short

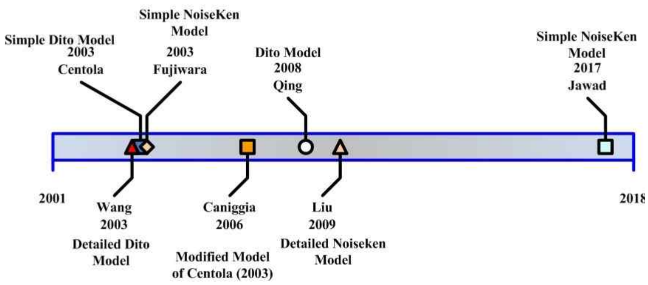

Fig. 11. Time line of major proposed 3D models for an ESD generator

emitted from the generator varied with the change of model. Therefore, for the accurate matching between numerical and measured system level ESD testing results, specific structural details of the model must be considered in the modeled 3D gun [48].

5.1 Review of numerical models

A review of numerous published full wave EM models of ESD generators from 2003 onward, is presented in this section. Fig. 11 illustrates the time line of the major reported 3D models of an ESD generator.

The initial work for the estimation of an injected ESD waveform in a numerical environment is done in [63]. Leuchtmann and Sroka [63] predicted the simulated ESD current waveform by measuring the magnetic field current at a distance of 1 mm, away from the target in a simulation environment. The simulation model of [63] is not the actual numerical model of an ESD generator, but rather a very simple calibration setup.

The first highly detailed numerical modeling an ESD generator consisting of the physical geometry of the simulator, a relay, a low pass filter, a ground strap, and lumped elements using metal and dielectric layers, was presented by Wang *et al.* in 2003 [6]. The authors developed a detailed full wave EM model of a Dito gun using FDTD code specially developed by Zeland software and collaborative coding by the MST EMC laboratory. The developed code helped the authors to emulate the relay breakdown by using time varying material constants.

Centola *et al.* [32] reported a simplified numerical model for the Dito generator. It consists of real lumped elements, a perfect electric conductor (PEC), and lossy dielectric physical structural components. The reported model in [32] takes much fewer computational resources compared to the earlier detailed models in [8, 40, 48]. The generated waveform characteristics of the model in [32] model are good, except for the small deviation in the waveform shape around 30 ns due to the non-accurate modeling of high frequency components. Caniggia *et al.* [35] proposed a slightly modified model based on that in [32]. However, as in [32], the reported model in [35] has a waveform matching problem around the 30 ns interval.

Fujiwara *et al.* reported a relatively simple prototype model of a NoiseKen generator [47] using the FDTD method. The authors in [47] compared the simulation and measured results for a discharge into a 50 Ω SMA connector.

Another full wave, Dito like, generator model for system level ESD coupling analysis was proposed in [48]. The authors of [48] used the FIT technique (Computer Simulation Technology Microwave Studio (CST MWS)) for the gun simulation, with the step source having a rise time of 200 ps. The reported model calculation time is within hours, with some mismatching of the discharge current pulse due to the short ground strap. In 2009, Liu *et al.* [8] reported a detailed full wave simulation model for the NoiseKen ESS-2000 (TC- 815) gun. In [8], the authors reported both the separate and combined modeling of different gun components, such as the relay, coil, ferrite rings, capacitor unit, and polyethylene disk, using a FIT based solver. Qing *et al.* [48] obtained a good agreement between the measured and simulated results with a comparatively long simulation time compared to [32, 35]. However, the work in [48] is very good for a basic understanding of the operation of the major components of an ESD gun in a 3D environment. Takada *et al.* [40] modified the earlier model of his group [47] for the hybrid simulation of ESD system level ESD testing. Jawad *et al.* [2, 46] proposed relatively simple, fast, and efficient EM modeling of the NoiseKen ESD generator. The proposed model consists of both structural and lumped generator elements, as in [32, 35]. However, the proposed model in [2, 46] produced very good agreement between the measured, IEC standard and 3D model results.

A summary of the state-of-the art 3D modeling techniques in Fig. 11 is given in Table 8. In Table 8, the ESD gun numerical modeling has been rated on the scale of simplified (=1) to detailed (=5), based on the construction of each reported model. The calculation time for simulation of EM model based on the complexity of the proposed 3D models by each author is estimated and shown in Table 8.

5.2 Comparison of the 3D models

Fig. 12 illustrates a comparison of the numerical models in Fig. 11 with the standard analytical waveform in [7]. The variations in the current values of these waveforms compared with the standard requirements in [7] are shown in Table 9. All the waveforms in Fig. 12 are obtained from

Table 8. 3D EM modeling techniques for an ESD generator

Author	EM Model Characteristics	Modeling (1 = Simple, 5 = Detailed)	Simulation EM Technique/Software	Calculation Time
Wang *et al.* [6]	• Dito based complete numerical model • Structural and lumped elements • Time dependent materials	5	• Customized EZ-FDTD code • Fidelity time domain code	Long
Centola *et al.* [32]	• Dito based model • Structural and lumped elements • Metallic PEC and lossy dielectric components	3	• FIT • CST MWS	Short
Fujiwara *et al.* [47]	• Prototype NoiseKen based model • Physical and lumped elements • Compared induced voltage for 50 Ω SMA	2	• FDTD • Customized coding	Short
Caniggia *et al.* [35]	• Modified [23] Dito based model • Structural and lumped elements • Metallic PEC and lossy dielectric components	3	• FIT • CST MWS	Short
Qing *et al.* [48]	• Dito based model • Full wave numerical model • Structural and lumped elements with short ground strap	4	• TLM • CST Microstripes	Medium
Liu *et al.* [8]	• NoiseKen ESS-2000 model • Detailed 3D model • Structural and lumped elements with both short and long ground straps	5	• FIT • CST MWS	Long
Jawad *et al.* [2, 46]	• NoiseKen TC-815 model • Relatively simple 3D model • Structural and lumped elements with long ground strap	3	• FIT • CST MWS	Short

Table 9. Comparison of ESD waveform characteristics of the reported ESD numerical models detailed in Fig. 11

		I_{peak} (A)	Rising Time *(ns)*	I_{30ns} (A)	I_{60ns} (A)	Reproduced Waveform Shape (Fair– Excellent)
	Standard IEC [7]	15.0 (12.8–17.2)	0.80 (0.60–1.00)	8.0 (5.6–10.4)	4.0 (2.8–5.2)	
	Analytical Model [7]	14.92	0.80	8.03	4.03	
	Measured	14.6	0.70	9.3	4.9	
Numerical Models	Wang *et al.* [6]	15.8	0.80	9.4	4.0	Very good
	Centola *et al.* [32]	16.5	0.85	6.2	3.6	Fair
	Caniggia *et al.* [35]	15.5	0.75	**4.2**	3.4	Good
	Qing *et al.* [48]	13.8	0.72	-	-	Good
	Liu *et al.* [8]	15.0	0.97	8.0	-	Good
	Jawad *et al.* [2], [46]	15.2	0.70	6.8	3.9	Very good

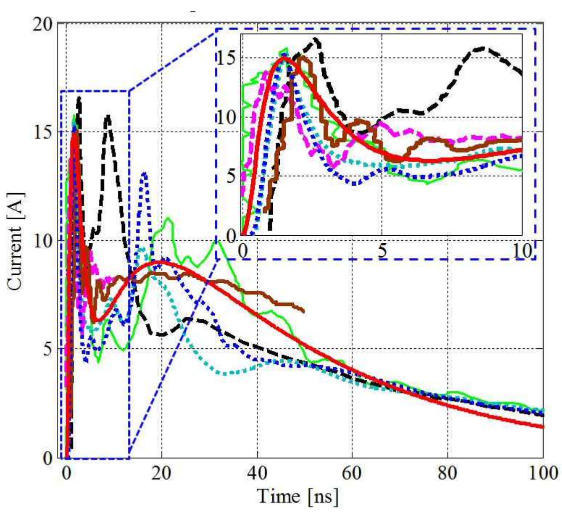

Fig. 12. Comparison of current waveforms of major numerical models detailed in Fig. 11 for +4 kV discharge voltage : Wang [6] (solid green), Centola [32] (dashed black), Caniggia [35] (dotted aquamarine), Qing [48] (dashed magenta), Liu [8] (solid brown), Jawad [2, 46] (dotted blue) and IEC standard [7] (thick solid red)

the reported graphical results in [2, 6, 8, 32, 35, 46, 48] using commercial data digitizer software [64].

The digitized waveforms were scaled for the +4 kV discharge voltage level for comparison with the specifications in [7]. In Table 9, the attribute (fair to excellent) of the reproduced waveform shape are determined based on the graphical results in Fig. 12 and the quantitative matching of waveform data with the standard requirements in [7], as elaborated in Table 9.

It can be noted from Fig. 12 and Table 9 that all suggested models reproduce the ESD waveform quite well, especially in terms of ranges the standard suggests [7]. The model in [6] could be used for the enhanced agreement of different waveform characteristics and current waveform shape with the requirements in [7] due to very detailed modeling of the inner structure of the generator. However, among the simplified models [2, 32, 35, 46, 47] with shorter simulation time, the good results are for the reported for the models in [2, 35, 46]. It can be concluded that the reported 3D model in [2, 8, 35, 46, 48] can be used for the susceptibility testing of products in a numerical environment due to fewer resource requirements and a good ESD waveform shape. For fast simulation with minimum requirements in terms of computational resources, the models [2, 35, 46] might be preferable.

6. Conclusion

In this study, an in-depth review of ESD generators modeling approaches for system level ESD testing is presented. The study covers the detailed quantitative and graphical comparison of the generated current waveforms using analytical, circuit, and full wave modeling of ESD generators.

This study is unique because it provides a comprehensive review of ESD source modeling approaches for system level ESD testing in very attractive manner with and a detailed comparison of numerous reported techniques

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