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Jayong Koo

Qing Cai

Kai Wang

J. Maas

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/ele_comeng_facwork/945

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Correlation Between EUT Failure Levels and ESD Generator Parameters

Jayong Koo, *Student Member, IEEE*, Qing Cai, Kai Wang, *Member, IEEE*, John Maas, *Senior Member, IEEE*, Takehiro Takahashi, Andrew Martwick, and David Pommerenke, *Senior Member, IEEE*

***Abstract*—Some system-level electrostatic discharge (ESD) tests repeat badly if different ESD generators are used. For improving repeatability, ESD generator specifications have been changed, and modified generators have been compared in a worldwide round robin test. The test showed up to 1 : 3 variations of failure levels. Multiple parameters that characterize ESD generators have been measured. This paper correlates the parameters to test result variations trying to distinguish between important and nonrelevant parameters. The transient fields show large variations among different ESD generators. A correlation has been observed in many equipment under tests (EUTs) between failure levels and the spectral content of the voltage induced in a semicircular loop. EUT resonance enhances the field coupling, and is the dominate failure mechanism. The regulation on the transient field is expected to improve the test repeatability.**

***Index Terms*—Correlations, electrostatic discharge (ESD), failure levels, round robin test.**

I. Introduction

THE OBJECTIVE of system-level electrostatic discharge (ESD) testing is twofold: ensuring adequate robustness of electronic systems against real-world ESD and passing a standardized test, as this is often a legal or company internal requirement for selling a product. When passing a legal requirement, an unambiguous pass/fail determination is required. However, it is well known that all electromagnetic compatibility (EMC) tests suffer from reproducibility problems. This is especially true for ESD testing [1]–[4]. When measuring emissions, a test result uncertainty can be calculated; however, standardization groups have only attempted to determine a calibration uncertainty for ESD testing, and have shied away from attempting to establish methods for test result uncertainties for ESD testing.

Owing to the large variable nature of natural ESD phenomena, a reference ESD event has been introduced in the standard IEC 61000-4-2 [5]. This document describes the discharge current waveform. In the early 1990s, testing has been moved from air discharge to contact-mode testing to avoid the effect of arc length variations in air discharge [6] and improve reproducibility. In spite of this and other steps taken to improve the reproducibility of test results, variations as much as a factor of 2 in passing test voltage are common. Thus, the site-to-site variation of test results often leads to regulatory problems, and may cause redesigns for improving product immunity if an equipment under test (EUT) turns out to be especially sensitive to a specific model of ESD generator used at that test site.

A standard needs to regulate the parameters that determine the severity of the tests. However, there has been and still is considerable confusion about which parameters determine the severity of ESD testing. Traditionally, the effort to improve the test repeatability has been focused on defining the right discharge current [7], [8]. This thought guided the standard formulation in its early stage, resulting in the four parameters that define the discharge current specification [5]: rise time, peak current, current at 30 ns, and current at 60 ns. Two reasons may have turned the focus to the current while paying little attention to the fields. The current can be measured with high precision [9], and the belief that the rise time is directly related to the probability of system failure [10]–[12].

Questioning the parameters that determine the severity of system-level ESD led to multiple studies having inconsistent and even partially contradicting results. It was shown in [11] and [12] that the coupled energy is related to the rise time. The authors of [3] concluded that the high-frequency components or the current derivatives dominate simulator severity, while our own previous study claimed that the voltage induced in a small loop predicts the severity level for upset-type failures [13]. Many studies have indicated that the transient fields of ESD strongly influence the EUT response. However, an often met misunderstanding is that the transient fields of the ESD generator are determined by the discharge current. If this is the case, a well-written specification of the discharge current would define the transient fields.

A simple dipole model [14], [15] often assumes a short line current that carries the current of a human–metal ESD. According to this model, it can be used to calculate the transient fields. The limitations of the model have been shown to originate from omitting the field contributions from the complete geometry, and not taking into account that within the ESD generator, much shorter rise time currents are present [16].

However, an ESD event by an ESD generator has the following critically different characteristics from the human ESD model.

1) The ESD energy is stored in a small discrete capacitor.
2) A ground strap is used for the current return path.
3) The pulse shaping network is used to smooth the discharge current.

It is true that the transient field variation is partially due to the discharge current variation; however, the differences listed

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J. Koo and D. Pommerenke are with the Electromagnetic Compatibility Laboratory, Missouri University of Science and Technology, Rolla, MO 65409 USA (e-mail: jkhy6@mst.edu; davidjp@mst.edu).

Q. Cai is with Sprint Nextel Corporation, Overland Park, KS 66251 USA (e-mail: qing.cai@sprint.com).

K. Wang and A. Martwick are with Intel Corporation, Hillsboro, OR 97124 USA (e-mail: kai.a.wang@intel.com; andy.martwick@intel.com).

J. Maas is with IBM, Rochester, MN 55901 USA (e-mail: johnmaas@us.ibm.com).

T. Takahashi is with the Department of Computer Science, Takushoku University, Tokyo 193-0985, Japan (e-mail: take@cs.takushoku-u.ac.jp).

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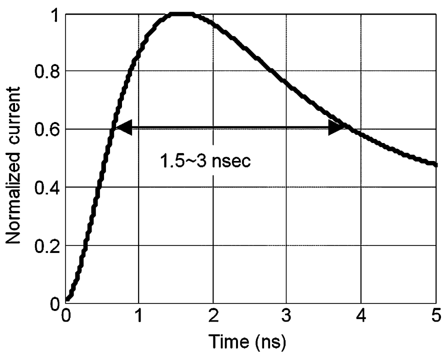


Fig. 1. New specification suggested for discharge current waveform. The width measured at 60% of the first discharge current peak should be 1.5–3 ns.

before also cause other uncertainties in the transient field. Therefore, even if all ESD generators could have identical discharge current, the transient fields may be significantly different. Then, what would be the correct way to represent the field radiation?

It has been known that the transient fields are different among ESD generators from different manufacturers [2], [6]. The voltage induced in a small loop was used as a simple indicator of the transient field, and a correlation to the failure levels was found in some limited conditions [17], [18]. However, if the field distribution is not uniform over the revolution angle [3], [19], [20], then the transient field coupling to the EUT depends not only on the manufacturing, but also on the revolution angle that faces the EUT, which leads to a clear failure level variation with respect to the revolution angle (see Section II).

In spite of numerous factors that would possibly affect the severity of ESD generators, TC77B, the technical group in charge of IEC 64000-4-2, investigated adding another discharge current specification, as can be seen in Fig. 1. The specification states that the width is measured at 60% of the first discharge current peak and should be 1.5–3.5 ns.

A round robin test was initiated to test the effect of this change on different EUTs at three locations (Europe Homologation Center (EHC) Tokushima Laboratory, Japan, Missouri University of Science and Technology, Rolla, and IBM, Minnesota), using the same ESD generators. Various EUTs, such as desktop computers, laptop computers, printers, wireless routers, and projectors, were used. The measurements were performed in accordance with the standards [5]. The contact mode using direct discharge was used to minimize test uncertainty. The detailed test methods are described in [4].

The results of the round robin test demonstrated that the regulation proposed in Fig. 1 hardly improved the test repeatability [21]. Consequently, the IEC 77b MT12 ESD standard setting working group decided not to include this specification in the IEC 61000-4-2 standard. In addition to the test repeatability evaluation, we characterized the ESD generators with respect to their discharge current and fields. These parameters can be used to study the correlation of the failure levels to the ESD parameters.

Section II introduces the failure levels and the variations of various EUTs. Section III presents the measured ESD parameters, including the discharge currents and voltages induced in a semicircular loop. Section IV discusses the frequency selective immunity of the EUTs, and the general correlation between the ESD parameters and the failure levels over all EUTs, and Section V compares the modified and unmodified ESD generators.

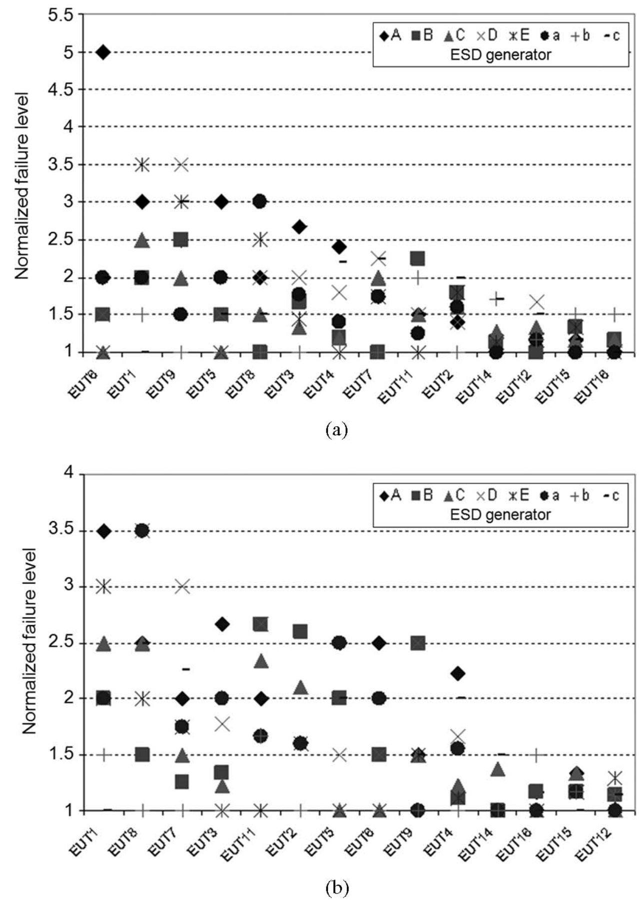


Fig. 2. Normalized failure levels for 14 EUTs while (a) positive voltage discharges and (b) negative voltage discharges were performed using eight ESD generators. The lowest failure level for each EUT was used for normalization. EUT10 (rarely failed up to 10 kV) and EUT13 (indirect discharge) were excluded.

II. EUT Failure Levels

The failure levels of desktop and laptop computers, servers, routers, etc., were determined using the contact mode.

Analyzing a complex set of partially imperfect data requires a set of assumptions that are discussed in this section. We have tested the stability of our results and conclusions against these and other reasonable assumptions, and found them to be consistent with our assumptions.

Some EUTs had multiple test points spaced far from each other. In this case, we assumed that the coupling path and failure cause were different, allowing us to regard each new test point as an independent EUT. A charge voltage of 10 kV was the maximum for most ESD generators. A few EUTs did not fail up to 10 kV. In this case, we assumed a failure level of 12 kV.

Each of the recorded failure levels for an EUT using eight different ESD generators was normalized to the lowest failure level such that the relative failure level variations could be seen. Fig. 2 shows the normalized failure level for the positive and

TABLE I
MEASURED FAILURE LEVELS AT DIFFERENT REVOLUTION ANGLES OF THE ESD GENERATOR

	Failure levels at each revolution-angle of ESD generator (kV)				Variation (max. failure level : min. failure level)
	0 deg.	90 deg.	180 deg.	270 deg.	
Generator a / EUT 3	8	8	8	7	1 : 1.1
	-8	-8	-10	-10	1 : 1.3
Generator a / EUT 4	7	9	7	6	1 : 1.5
	-8	-8	-10	-8	1 : 1.3

negative voltages discharge, respectively. The variations were strongly dependent on the EUT, ranging from 1 : 3 down to 1 : 1.5. The data are sorted such that the EUTs having large variations in the failure level are shown on the left side.

ESD generators are not bodies of revolution. To observe if a nonuniform transient field distribution around the ESD generator causes a failure level variation, the ESD generators were held at four different angles, while the failure levels of the EUT were recorded. Table I shows examples of the variations of failure levels at four different revolution angles of the ESD generator. A failure level variation of 1 : 1.5 was observed for EUT 4 while discharging with "Generator a." Rotation was only performed on a very few number of EUTs and only using few ESD generators, as it was not a part of the round robin test protocol.

The injected current remains unchanged if the generator is rotated; however, the fields will change. The variation indicates the importance of the transient fields, and shows that even when using one generator, there can be repeatability problems.

III. MEASUREMENTS OF ESD PARAMETERS

Five of the ESD generator manufacturers supported the round robin test by providing ESD generators that meet the proposed new current requirement specifying the width of the first discharge current. These generators are denoted by capital letters, "Generator A"–"Generator E," in the measurement results. Three of these manufacturers also provided their old versions, which did not meet the new current requirement, "Generator a"–"Generator c." "Generator D" and "Generator E" do not have corresponding old versions because they have already met the new current specifications. We measured the parameters to characterize the ESD generators and correlate the parameters to failure levels. The general measurement methods and results are introduced in this section. A full-wave ESD generator model for estimation of discharge current and field coupling is demonstrated in [22], and is the topic of ongoing research.

A. Discharge Currents

The discharge current from each ESD generator was measured for 200 ns in accordance with the standards [5]. As shown in Fig. 3, the measured discharge currents meet the four parameters of the discharge current specification in general. However, the current waveforms after the first peak deviate significantly. The spectra differ by more than ±6 dB below 2.5 GHz, as can be seen in [4].

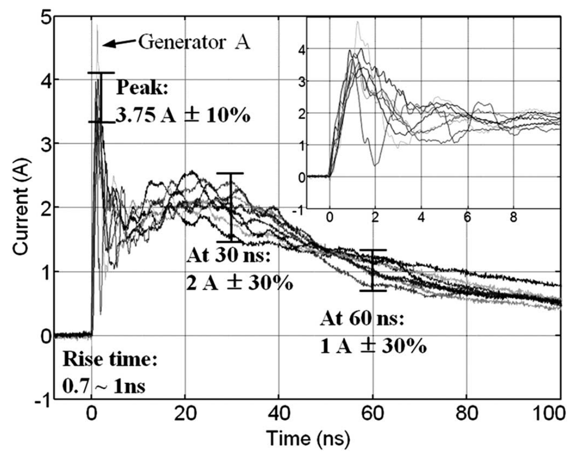


Fig. 3. Discharge currents measured for the round robin test. Eight different ESD generators were used. The four parameters of the discharge current specifications are indicated. The upper right plot shows the first 10 ns.

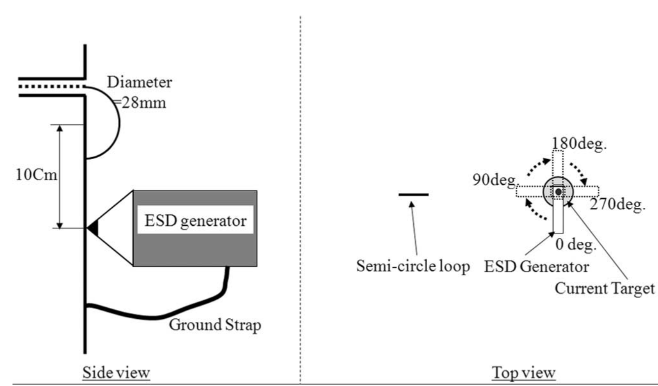


Fig. 4. Measurement setup for the induced voltages in a semicircular loop. The ESD generators that were used were rotated around the discharge tip. The induced loop voltage was measured at four angles.

B. Induced Voltages in a Semicircular Loop

To observe the transient field from the ESD generators during discharge, the induced voltages in a small loop have been measured for 50 ns. The measurement setup is depicted in Fig. 4.

A semicircular loop (28-mm diameter, 0.7-mm wire diameter) was placed on a ground plane (approximately 4 m × 2.5 m) and connected to an oscilloscope (6 GHz, 20 Gs/s). The discharge location is 10 cm from the center of the semicircular loop. A distance of 10 cm was selected as the IEC 61000-4-2 standard requires the same distance for indirect ESD testing. Full-wave simulations of the voltage induced in a semicircular loop by an incident plane wave were conducted. The frequency responses are shown in Fig. 5.

The ground strap, which is approximately 3 m long, was pulled back at its midpoint. The ESD generators that were used were rotated around the discharge tip, as can be seen in the right side of Fig. 4, maintaining the overall shape of the ground strap. The current of the ESD generator is hardly affected by rotating it. However, the transient fields are affected as most ESD generators do not form bodies of revolution. For capturing the effect of these asymmetries, we recorded the induced loop voltage for four orientations of the ESD generators. For example, the

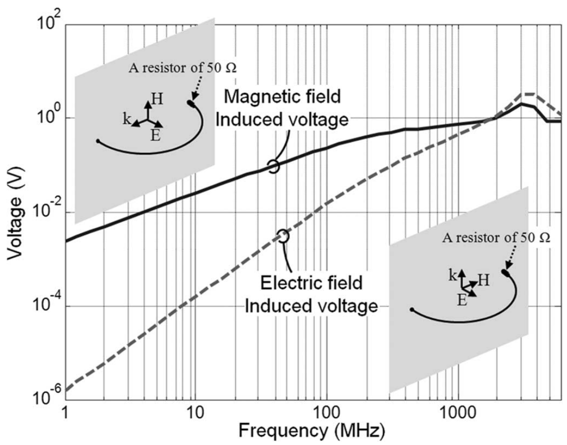
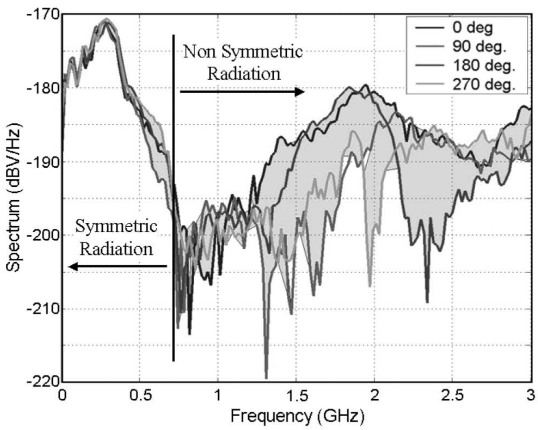
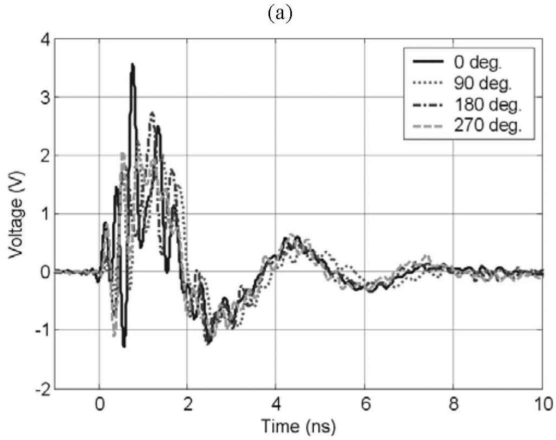


Fig. 5. Frequency responses of the voltage induced in a semicircular loop by an incident plane wave ($E = 377$ V/m, $H = 1$ A/m). Two polarizations were used in each of FW simulations.



(a)



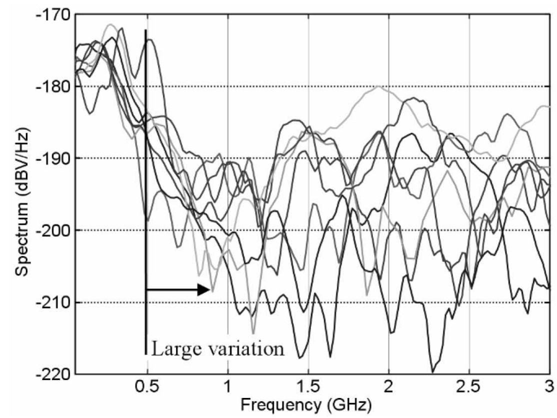
(b)

Fig. 6. Set of (a) spectra and (b) time-domain waveforms of measured induced voltages in a semicircular loop for “Generator a.”

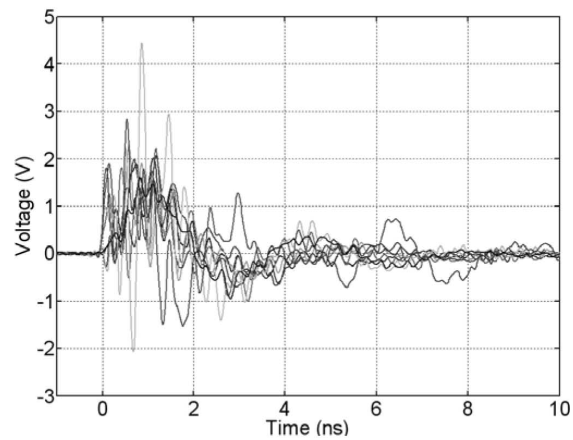
spectra and time-domain waveforms of the measured induced voltages in a semicircular loop for “Generator a” are shown in Fig. 6.

Within the spectrum of the induced voltage in a semicircular loop, one can distinguish two regions. In the lower frequency ranges, the rotation effects are less seen in the spectrum. In the higher frequency ranges, we observe strong variations due to the angle of the rotations. For “Generator a” and a 10-cm loop distance, the transition occurred at about 700 MHz; other generators showed transition frequencies between 250 and 800 MHz.

This can be explained as follows. In the lower frequency ranges, the induced loop voltage is dominated by the fields from the discharge current that is not affected by rotating the ESD generator. The higher frequency components are caused by the relay that initiates the ESD pulse in the contact mode. The voltage collapse time in the relay is less than 100 ps. Thus, a pulse forming network is needed to shape the discharge current into a standard waveform [17]. The currents flowing on this pulse forming network, the relay, and the metallic structures in proximity are not symmetric. Therefore, the currents within the ESD generator will generate nonsymmetric transient fields, while the discharge current flowing through the discharge tip generates the symmetric transient field around the ESD generator. This is valid for the lower frequency range labeled “symmetric radiation” in Fig. 6(a). Fig. 7 shows how strong the spectra and the time-domain waveforms of the induced voltage vary among different ESD generators. As expected, the variation is larger in the high-frequency ranges.



(a)



(b)

Fig. 7. (a) Spectra and (b) time-domain waveforms of measured induced voltages in a semicircular loop for eight ESD generators at 0° of revolution angle.

C. Electric Fields

A broadband electric field sensor [23] was placed on the ground plane at a distance of 0.1 m from the discharge point, and the transient electric fields were measured over 1 ms. The frequency response of the electric field sensor from 3 MHz to 2 GHz is constant within 1 dB. The ESD generators were held at four different angles, the same as was measured for the induced voltage in the semicircular loop. The transient electric fields also show a variation over rotation angles, but the variation is not as strong as that of the voltage induced in a semicircular loop. The electric field sensor has a flat frequency response from about 2 MHz to 2 GHz, while the loop emphasizes the stronger varying high-frequency content. Typical waveforms of the transient electric field are shown in [17].

IV. Correlation Analysis

Multiple parameters describe an ESD event starting from electrostatic parameters like charge up to the gigahertz spectral components. Only the parameters that determine the severity need to be regulated by an ESD standard. However, which parameters should be regulated? During the round robin, we observed the failure levels for a diverse set of EUTs and recorded parameters that characterize the ESD generators. It is a logical step to investigate the correlation between the failure levels and the parameters. We attempted to extract as much general information as possible using a large, but far from perfect dataset.

A. Method

To illustrate the principle, let us assume that an EUT is selectively sensitive to only one ESD parameter and let it be the peak current. If this EUT is tested using a set of ESD generators that differ in their peak current, then we would observe a disproportional relationship between the peak current and the failure level. The correlation analysis searches for a linear relationship between the severity of an ESD generator and the reciprocal failure level. We quantify this using the correlation coefficient ($-1 \leq \rho \leq 1$), where 1 indicates the strongest correlation [24]. See [25] for details about these methods.

In reality, matters are more complex. A weighted combination of these parameters determines the failure level of an EUT. However, the weighting factors are EUT-dependent. For example, one EUT may not react at all to spectral components higher than 100 MHz, but another may have a shield that can only be penetrated by spectral contents higher than 2 GHz. Also, the parameters are not mutually independent. For example, the distributed current derivative over all conducting parts of an ESD generator causes the transient magnetic field. The current derivative at the tip of the generator contains only a fraction of the transient field greater than 1 GHz. But this derivative is certainly a part of those currents that cause the transient field. Thus, both parameters are related. A similar argument is valid for other parameters.

B. Extracting ESD Parameters

The underlying disturbance model assumes that an EUT fails if the peak noise level induced into some circuit exceeds a certain threshold level. The noise is caused by one or a combination of many ESD generator parameters. For the correlation analysis, various peak-to-peak values of ESD parameters were extracted from the measured data: discharge currents, induced voltages in a semicircular loop, and electric fields.

Another simplification is that we assume that there are no cumulative effects. These effects could be of electrical nature, e.g., heating, or from the lack of charge removal from previous pulses or software related, like the accumulation of bit errors.

The transient fields will induce noise in the loop- or monopole-like structures. Based on this and previous publications [17], the standardization committee introduced the voltage in a ground-plane-mounted semicircular loop as a way to characterize the transient fields of ESD generators [5]. Besides the simplicity of the test setup, other arguments for including this specification had been the availability of the data not only on ESD generators, but also on the human–metal ESD event, which forms the event that the standard tries to reproduce. Transient field magnitudes have also been selected as a parameter. However, they do not describe the nature of the induction process as well as the voltage induced in a loop.

The problem of the large variation of ESD test results had been known prior to the round robin, and it initiated the maintenance work on IEC 61000-4-2 that eventually led to the round robin testing. If we assume a linear relationship between parameters and the reciprocal failure levels, it is logical to search for parameters that differ strongly between ESD generators. For example, test result variations of 1 : 3 had been observed previously [4], but the peak currents of different ESD generators that fulfill the standard vary only by $\pm 10\%$. Thus, the peak current is not a suitable parameter to explain the observed variation ratio of 1 : 3.

Immunity problems often occur over very narrow frequency ranges. This is due to resonances that enhance the coupling between the field and the circuits. One might expect that the resonances will increase the sensitivity of the EUTs at specific frequencies. Such behavior is known from radiated immunity testing. Is it possible to see indication of the resonant behavior? At first glance, this does not seem to be easy as pulse testing was performed. However, the following is possible: each generator has different frequency content, and the ranking from strongest to weakest varies with frequency. If, at a selected frequency, the ranking of generator spectral content matches the EUT failure level ranking, then this can be understood as an indication of frequency-selective behavior. It is even better if not only the nonquantified ranking matches, but also the variation trends of parameters and the EUT failure levels correlate with each other.

To search for resonance-enhanced correlation, we created a set of parameters by bandpass filtering. Four sets of such parameters were created by sweeping the center frequency and recording the peak-to-peak values at each: $I_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$, $(di/dt)_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$, $V_{\mathrm{LOOP},\ \mathrm{BP}(*),\ \mathrm{p\text{-}p}}$, and $E_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$.

Fig. 8 explains how measured data were processed to obtain the ESD parameters used in the correlation analysis. Also, Table II describes the symbols that describe the ESD parameters and data processing.

Fig. 9 illustrates the dramatic variations of $V_{\mathrm{LOOP},\ \mathrm{BP}(*),\ \mathrm{p\text{-}p}}$, while the center frequency of the bandpass filter is sweeping.

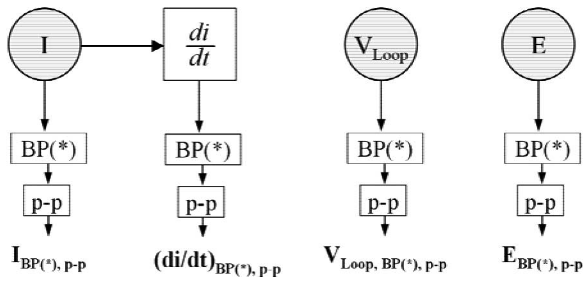


Fig. 8. ESD parameter trees. The shaded circles indicate unfiltered raw data and the rectangles indicate the data processing introduced in Table II.

TABLE II
GLOSSARY FOR ESD PARAMETERS USED IN CORRELATION ANALYSIS

ESD parameter symbols	
I	Discharge current
(di/dt)	Discharge current derivative
V_{Loop}	Induced voltage in a semi-circular loop
E	Transient electric field
Data processing symbols (subscripts after ESD parameter symbols)	
p-p	Peak to peak detection
BP(*)	Band-pass filtering at sweeping center frequency from 50 MHz to 3 GHz with a Q factor of 5 %. A 3rd order Butterworth filter was used.
BP(*freq.*)	Band-pass filtering at center frequency of *freq.* with Q factor of 5 %. Butterworth filter of order of 3 was used

Examples (also seeFig. 8)
$I_{BP(500MHz), p-p}$: A column vector of peak-to-peak values of bandpass-filtered discharge currents at the center frequency of 500 MHz wit Q factor of 5%. Each row corresponds to a specific ESD generator. Butterworth filter of third-order was used.
$I_{BP(*), p-p}$: A matrix whose columns indicate peak-to-peak values of bandpass-filtered discharge currents with a Q factor of 5% at a certain center frequency between 50 MHz and 3 GHz. Each column corresponds to a center frequency. Each row corresponds to a specific ESD generator. Third-order Butter worth filter was used.

At first glance, it may look surprising because the values for most ESD generators are higher in the high-frequency ranges (>1.5 GHz) than in the low frequency. Owing to the strong high-frequency oscillations for the first few nanoseconds of discharging, the high-frequency peak becomes significant after bandpass filtering.

C. Frequency-Selective Immunity of EUTs

The correlation between the reciprocal failure levels and the four sets of bandpass-filtered parameters, $I_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$, $(di/dt)_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$, $V_{\mathrm{LOOP},\ \mathrm{BP}(*),\ \mathrm{p\text{-}p}}$, and $E_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ was investigated for each EUT. To illustrate the results, the two datasets were compared and are shown in Fig. 10. The correlation between the failure levels and $V_{\mathrm{LOOP},\ \mathrm{BP}(630\ \mathrm{MHz})}$ is shown in Fig. 10(a), while Fig. 10(b) shows the noncorrelation between the failure levels and $V_{\mathrm{LOOP},\ \mathrm{BP}(80\ \mathrm{MHz}),\ \mathrm{p\text{-}p}}$ for EUT2. The positive voltage discharges were performed for both cases. At 630 MHz, a strong correlation is visible, while there is no correlation at 80 MHz between the failure level and the induced loop voltage. This indicates that a resonance within EUT2 strongly influences the robustness of the EUT.

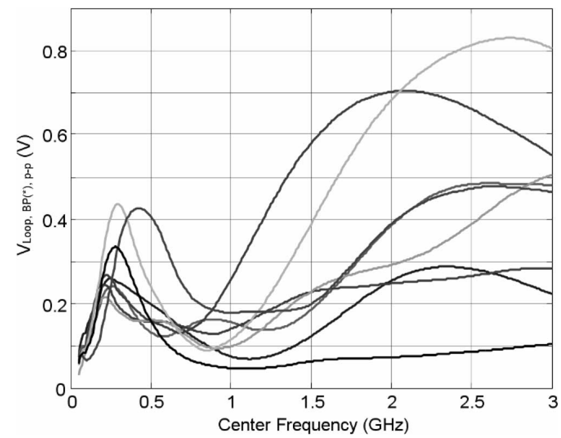


Fig. 9. Peak-to-peak values of bandpass-filtered induced voltage in a semi-circular loop $V_{\mathrm{LOOP},\ \mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ using eight different ESD generators. See Table II for ESD parameter symbols.

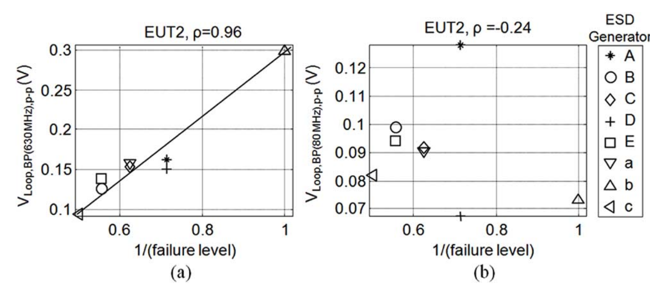


Fig. 10. Example of (a) correlation and (b) noncorrelation between ESD parameter and failure level.

Most EUTs show the similar correlations at different frequencies. Cases of correlation (correlation coefficient > 0.7) are summarized in Table III, where the center frequencies that had the largest correlation coefficient are shown. $I_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ is not shown in the table because it is directly correlated to $(di/dt)_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$. The example just discussed is shown in Fig. 10(a) and is marked by a "$*$" in the Table III.

The rows in the table are sorted such that the center frequencies for $V_{\mathrm{LOOP},\ \mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ are in ascending order. In general, $V_{\mathrm{LOOP},\ \mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ shows the correlations in a wide frequency range, while either $(di/dt)_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ or $E_{\mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ shows correlations around the frequencies where $V_{\mathrm{LOOP},\ \mathrm{BP}(*),\ \mathrm{p\text{-}p}}$ correlates.

The data in Table III point at a frequency-selective behavior of the EUT response. This is further supported by experiences in radiated immunity testing and the plausible argument, where resonances enhance the coupling between the field and the circuit. If we accept that resonances increase the variation of the sensitivity of the EUTs, then we can use this to explain one of the most surprising results of the round robin test: no ESD generator was the most severe on most of the EUTs, nor the least severe. This question is relevant for many reasons, not in the least that members of the standard committee often ask about the

TABLE III
EUTs WHOSE FAILURE LEVELS SHOW CORRELATIONS (CORRELATION COEFFICIENT > 0.7) TO BANDPASSED ESD PARAMETERS AT SPECIFIC CENTER FREQUENCIES

EUT	$V_{LOOP, BP(*), p-p}$	$(di/dt)_{BP(*), p-p}$	$E_{BP(*), p-p}$
EUT12 (+)	70 MHz	X	X
EUT 14 (+)	90 MHz	120 MHz	X
EUT 16 (+)	170 MHz	170 MHz	180 MHz
EUT 16 (-)	170 MHz	170 MHz	180 MHz
EUT 15 (+)	210 MHz	200 MHz	230 MHz
EUT 9 (-)	380 MHz	360 MHz	X
EUT 9 (+)	480 MHz	420 MHz	X
EUT 2 (-)	510 MHz	470 MHz	X
EUT 2 (+)	630 MHz*	540 MHz	X
EUT 3 (+)	750 MHz	1.27 GHz	1.07 GHz
EUT 8 (-)	770 MHz	1.08 GHz	X
EUT 7 (-)	770 MHz	1.14 GHz	X
EUT 7 (+)	790 MHz	990 MHz	X
EUT 4 (-)	880 MHz	1.11 GHz	1.02 GHz
EUT 3 (-)	920 MHz	730 MHz	1.04 GHz
EUT 6 (-)	960 MHz	X	1.09 GHz
EUT 4 (+)	970 MHz	X	1.08 GHz
EUT 6 (+)	990 MHz	X	1.11 GHz
EUT 5 (+)	990 MHz	X	X
EUT 5 (-)	990 MHz	X	X
EUT 11 (-)	1.24 GHz	X	1.28 GHz
EUT 11 (+)	1.48 GHz	X	X
EUT 14 (-)	2.36 GHz	2.29 GHz	850 MHz
EUT 12 (-)	X	50 MHz	X
EUT 8 (+)	X	1.04 GHz	X
EUT 1 (+)	X	X	X
EUT 1 (-)	X	X	X
EUT 15 (-)	X	X	X
# of EUTs	23	17	11

*Corresponds to Fig. 10 (a).
X: No correlation stronger than correlation coefficient of 0.7.
(+): Positive voltage discharge.
(–): negative voltage discharge.

performance of commercial ESD generators. We had observed that the spectral density of, for example, the induced loop voltage varies strongly over frequency. A generator that is strong at some frequencies may show weak fields at other frequencies. The order of severity is a function of frequency and the parameter observed. Thus, one EUT may be very sensitive to one generator, because the resonance and the range of strong fields match. However, it may not react strongly to another generator that has strong fields, but not in the range of the resonance.

Do we have proof? No, a test that uses pulses of ringing narrowband signals while observing the failure level as a function of frequency might provide proof. However, such an investigation was not part of the round robin test. For now, we have to settle for the plausible explanation that it is strongly supported by data.

D. Limit of the Correlation Analysis

Correlation does not prove a cause-and-effect relationship. However, the correlations are supported by a plausible physical model (e.g., resonances), allowing for cautious conclusions regarding the cause-and-effect relationships. Being able to perform experiments that monitor internal voltages and currents, and varying only one parameter may be able to prove the relationships.

V. CONCLUSION

The system-level ESD round robin test, conducted at three laboratories, comparing eight generators, showed test result variations of up to 1 : 3 with 1 : 2 being common. No ESD generator was the most severe over all of the EUTs, and no one generator was the least severe.

ESD generator parameters have been correlated to upset levels. Correlation between the spectral content of the ESD generator parameters and upset levels indicated resonant behavior: The narrowband spectral content of the voltage induced in a semicircle loop correlated well with upset levels at selected frequencies for many EUTs.

The data indicate that the resonance-enhanced field coupling is the dominate failure mechanism. The transient fields of ESD generators strongly contribute to the repeatability problem of system-level ESD testing. Better test repeatability will only be achieved by properly controlling the transient field during discharge.

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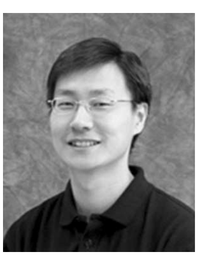
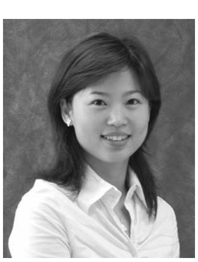


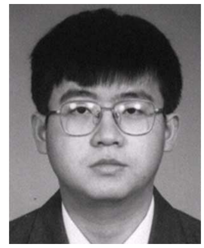
Jayong Koo (S'06) received the B.S.E.E. degree in electrical engineering from Chung-Ang University, Seoul, Korea, in 1996, and the M.S.E.E. degree in electrical engineering from Yonsei University, Seoul, in 1998. He is currently working toward the Ph.D. degree with the Electromagnetic Compatibility Laboratory, Missouri University of Science and Technology, Rolla.

He was with LG Electronics, Korea, for four years, and with Dacom, Korea, for two years. His current research interests include electrostatic discharge, electromagnetic compatibility, and numerical calculation as well as advanced RF measurements.



Qing Cai received the B.S. and M.S. degrees in precision instrument of instrument science and optoelectronic engineering from the Hefei University of Technology, Hefei, China, in 1999 and 2002, respectively, and the second M.S. degree in electrical engineering from the Missouri University of Science and Technology, Rolla, in 2008.

Since 2008, she has been with Sprint Nextel Corporation, Overland Park, KS. Her current research interests include electrostatic discharge, electromagnetic compatibility, and advanced RF measurement.



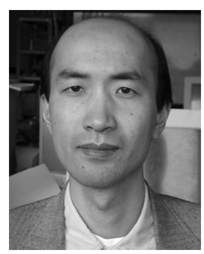
Kai Wang (S'01–M'05) received the B.S. and M.S. degrees in electrical engineering from the Tsinghua University, Beijing, China, in 1998 and 2000, respectively, and the Ph.D. degree in electrical engineering from the University of Missouri at Rolla, Rolla, in 2005.

In 2005, he joined Intel Corporation, Hillsboro, OR. His current research interests include electromagnetic compatibility in high-speed digital and mixed signal designs, electronic packaging, and electrostatic discharge.

John Maas (M'88–SM'96) received the B.Sc. degree in electrical engineering from the Illinois Institute of Technology, Chicago, in 1981.

He joined IBM's Electromagnetic Compatibility (EMC) Laboratory, Rochester, MN, where he has been involved in the field of EMC for over 25 years, and is currently IBM's Corporate Program Manager for EMC.

Mr. Maas is a member of the USA Technical Advisory Groups for International Electrotechnical Commission (IEC) TC77, SC77A, and SC77B for Comite International Special des Perturbations Radioelectriques (CISPR/I). He is the Secretary of IEC SC77B Working Group 10 Maintenance Team 12. He was the Chair or Co-Chair of the Workshops and Tutorials Program for the 2007, 2008, and 2009 IEEE International Symposia on EMC.



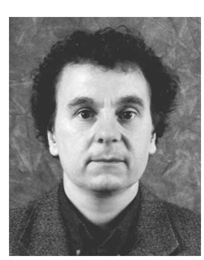
Takehiro Takahashi received the B.E., M.E., and Dr.Eng. degrees in electronics from the Tokyo University of Agriculture and Technology, Tokyo, Japan, in 1985, 1987, and 1997, respectively.

In 1988, he was a Research Assistant in the Department of Computer Science, Takushoku University, Tokyo, where in 1999, he became an Associate Professor, and currently a Professor. His research interests include electromagnetic compatibility (EMC) and design system of electronic circuits with EMC consideration.

Prof. Takahashi is a member of the Institute of Electronics, Information, and Communication Engineers of Japan, Japan Institute of Electronics Packaging, and the Institute of Electrical Engineers of Japan. He is the Chief of the International Electrotechnical Commission SC77B Working Group of Japan.

Andrew Martwick received the M.S. degree in physics from Portland State University, Portland, OR, in 2008.

He is currently a Platform Designer with Intel's Ultra-Mobile Group, Hillsboro, OR, where he is engaged in cell phone architectures. His research interests include surface plasmons and electrostatic discharge propagation in systems.



David Pommerenke (M'98–SM'03) received the Ph.D. degree in transient fields of electrostatic discharge (ESD) from the Technical University Berlin, Berlin, Germany, in 1996.

He was at Hewlett Packard for five years. In 2001, he joined the Electromagnetic Compatibility Laboratory, Missouri University of Science and Technology, Rolla, where he is currently a Tenured Professor. His current research interests include electromagnetic compatibility (EMC), ESD measurement techniques, and electromagnetic interference analysis methods, numerical methods, and instrumentation for EMC and high voltage. He has published more than 100 papers. He is the inventor of seven patents. Besides other professional activities, he is the U.S. representative of the ESD standard setting group within the International Electrotechnical Commission TC77b.