Causes of the ESD immunity testing problems in the IEC 61000-4-2 standard

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Abstract. To resolve the poor reproducibility of the electrostatic discharge (ESD) immunity test platform which is specified in the standard IEC 61000-4-2, using a newly designed ESD testing system, the effects of the switch action of ESD generator, the discharge current and its derivative, the radiation field and the imperfect specification of the test method on the testing results were studied. It was found that the effect of the switch action of ESD generator on the testing results was very distinct, and the radiation field caused by the switch action was one of the main cause of the different testing results; different discharge current and current derivative were caused by different ESD generators, which would cause different testing results; the imperfect specification of the test method in the standard was the other reason.

1. Introduction
The objective of electrostatic discharge (ESD) immunity testing is two fold [1]: ensuring adequate robustness of the electronic systems against the real world ESD and passing a standardized test as this is often a legal or company’s 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 EMC tests suffer from reproducibility problems. This is especially true for ESD immunity testing [2-4]. Owing to the large variation nature of the natural ESD phenomena, in the early 1990’s testing has been moved from air discharge to contact mode testing to avoid the effect of arc length variations in air discharge [5] and to improve reproducibility. In 2008, a reference ESD event has been introduced in the standard, IEC 61000-4-2 [6]. This document describes the discharge current waveform. However, many users have reported many problems about the IEC 61000-4-2 standard [7-11]:

1) ESD test results depend on the manufacturer of the simulator;
2) Even with the same simulator, the repeatability is also bad;
3) Testing for immunity against ESD of human does not guarantee immunity against furniture ESD;
4) The contact discharge method is specified in detail in the standard, but the air discharge mode is not.

Therefore, many efforts have been done to improve the repeatability. Lutz and Calcavecchio [12]-[13] have focused on defining the right discharge current. Lin [4] concluded that the high frequency components or the current derivatives dominate simulator severity. In [14], it was shown that the transient fields of ESD strongly influence the equipment under test (EUT) response. In order to reduce

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the variation of the test results of the ESD test depending on the ESD generator, in 2006, the additional restriction for ESD current waveform was proposed and considered in IEC SC77B/MT12. The specification states that the width is measured at 60% of the first discharge current peak and should be 1.5 to 3.5 ns. In [15], it was shown that the restriction was effective to reduce the variation; however, the much severe restriction is needed to reduce the dependency of the ESD generator.

In this paper, the switch action of ESD generator, the discharge current and its derivative, the radiation field and the imperfect specification of the test method on the testing results are studied, the reasons which cause the problems about the IEC 61000-4-2 standard are analyzed, and some suggestions are proposed to revise and/or perfect the standard.

2. Measurement Setup
The newly designed ESD testing system includes three parts: the parameter measurement system, the electrode approach speed control system, and the ESD simulator. The measurement setup is depicted in figure 1.

![Figure 1. Measurement setup for air discharge.](image)

2.1. Parameter measurement system
The sub-system can capture the discharge current, transient field, and the voltage induced in a semi-circular loop. The wall of a shielded room is used as a ground plane having a current target and field sensors placed upon it while the instrumentation is placed inside. The sub-system includes the current target (Its frequency response is within ±0.3 dB up to 1 GHz and ±1.1 dB up to 6 GHz.), a semi-circular loop (28 mm diameter, 0.7 mm wire diameter) or monopole antenna, a Tektronix TDS 7404B oscilloscope (four channels, 4 GHz, 20 GS s⁻¹, and a Faraday cage.

2.2. Electrode Approach Speed Control System
The electrode approach speed is a key factor affecting the air discharge process. This sub-system is composed of a programmable logic controller (PLC), electrode linking device, step-motor and its driver. The operating principle of the system is: firstly, the input control signals e.g. go forward, fall back, stop, approach speed levels are converted into the output signals such as the direction control level and step pulse through the programming of the PLC. Then, these weak signals are amplified by the step-motor driver into the strong current signals which can drive the step-motor to work. At last, different approach speeds will be achieved through the movement of the electrode linking device which drove by the step-motor. The system can provide 15 speed levels from 0.1 ms⁻¹ to 1.5 ms⁻¹ and...
the resolution of speed is better than 0.01 ms\(^{-1}\). During the experiments, the center of the current target and the electrode are in the same axis all the way to ensure that the arc does not initiate at the edge of the target. In addition, when the electrode approaches the target at a high speed of 1 ms\(^{-1}\), the current target or the ESD generator may be damaged, so some measurements are taken to avoid this problem: when the ESD gun reaches the left of the guide track, the position sensor will send PLC a signal to stop the step-motor, the buffer is used for the further protection of the ESD gun or the target.

2.3. ESD simulator

Different ESD simulators can be used in the experiment, e.g., an ESS-200AX simulator (charge voltages range from 0.2 kV to 30 kV) made by Noiseken Company of Japan, a NSG435 simulator (charge voltages range from 0.2 kV to 16.5 kV) made by SCHAFFNER Company of Switzerland, and a NS61000-2A simulator (charge voltages range from 0.2 kV to 28 kV) made by Shanghai Sanji Company of China, these simulators satisfy the qualifications specified in the standard IEC61000-4-2.

3. Analysis of the ESD immunity Testing Problems

3.1. Effect of the switch action of ESD generator on the ESD immunity test

In [16], it was shown that the testing results were varied due to the radiation field in some ESD immunity test. Zhang Xijun [17] also found that the EUT’s failure voltage was very low, but became large after the ESD generator was shielded by the grounded wire netting, this change of failure voltage may be caused by the radiation field from the relay switch of ESD generator. Therefore, the effect of the switch action of ESD generator on testing results was studied using the measurement setup depicted in figure 1.

3.1.1. Comparisons of the current and the field before and after ESD generator shielded.

In the experiment, the ESS-200AX simulator is used; the testing method is contact mode. Figure 2 shows the tested current waveforms before and after ESD generator shielded at 2 kV. As shown in figure 2, the rise times of the current waveforms well overlaps, but the surging part of the current waveforms after first peak-current slightly change.

![Figure 2](image1.png)

**Figure 2.** Comparisons of the current waveforms before and after ESD generator shielded.

![Figure 3](image2.png)

**Figure 3.** Comparisons of the magnetic field waveforms before and after ESD generator shielded.

Figure 3 shows the H-field waveforms before and after ESD generator shielded using a small loop antenna (the distance from the loop antenna to the discharge point is 10 cm). From the figure 2, it was found that the H-field waveforms largely different before and after ESD generator shielded, the value after shielded is lower than that before shielded. This indicated that a part of the radiation field from switch action was shielded by the wire netting, namely, the switch action of the relay inside the ESD.
The simulator could also generate the radiation field, and moreover, the strength of the field can’t be ignored. Therefore, in the ESD immunity test, the electromagnetic interference which EUT suffered was composed of the field radiated from ESD current and the field radiated from the switch action of the relay inside the ESD simulator.

The same results can be gained using the other kinds of ESD simulator, e.g., an NS61000-2A simulator or NSG435 simulator under same testing method. In a word, the electromagnetic field radiated from simulator’s switch action could cause interference to a EUT, consequently affect the reproducibility of the testing results. Therefore, the radiation field of the relay inside the ESD simulator was tested in this paper.

3.1.2. Testing of the radiation field of the relay inside the ESD simulator.
In the experiment, the ESS-200AX ESD simulator was adopted, and it was controlled by a remote switch. The process of charging and discharging was divided into three states: charge the capacitance which inside the simulator (thereinafter, this process was called “CHARGE” for short), connect the discharge circuit and the discharge electrode (thereinafter, this process was called “CONNECT” for short), and an air discharge. The discharge current, the radiation field, and the induced voltage corresponding to those three states were tested by the current target, the wide-band pulse field tester, and the monopole antenna, the results were displayed separately in Channels 1, 2 and 3, the waveforms of the discharge current, the radiation field, and the induced voltage under different conditions were shown in figure 4.

As shown in figure 4, when the switch actions of ESD simulator were “CHARGE” and “CONNECT”, the ESD radiation field and the induced voltage under those two conditions were very large, though the air discharge was not happened. However, as air discharge happened, the discharge current was very large, the radiation field and the induced voltage were rather lower than that of other conditions. This indicated the electrostatic interference on a EUT was caused by two parts: the fields radiated from ESD current, and the fields radiated from the switch action of the relay inside the ESD simulator.

![Figure 4. Comparisons of the discharge current, the radiation field and the induced voltage under different conditions.](image-url)
3.2. Effect of the discharge currents and its derivatives on the ESD immunity test

Two ESD simulators (NS61000-2A and ESS-200AX) were used in the measurement, Figures 5 and 6 show the waveforms of the measured discharge currents, the current derivatives and its spectrums at 2 kV.

From figure 5, the waveforms and the four parameters of the discharge currents meet the specification in the IEC 61000-4-2 Standard; 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 [15].

From figure 6 when different ESD simulators used, the current derivative waveforms and its spectrum also deviate significantly, this phenomena is more distinct in the high frequency range (>500 MHz).

Figure 5. Comparisons of the discharge current waveforms. Two different ESD simulators were used. The four parameters of the discharge currents specification are indicated. (a) the discharge current waveforms. (b) the first 12 ns current waveforms.

Figure 6. (a) Comparisons of the discharge current derivative waveforms. (b). Comparisons of the current derivative spectrums.

For high-speed, low-voltage digital electronic equipment, which are often designed such that a majority of real world discharges directly go to a grounded part of the system, most coupling is caused
by induction (near field) or by radiation (far field). Because the induction field and the radiation field caused by ESD are correlated closely with the discharge currents and the current derivatives, and the high frequency components or the current derivatives dominate the simulator severity. For such EUTs, they will react differently to different ESD simulators because of different discharge currents and different current derivatives. Therefore, if we want to improve the reproducibility of ESD tests, the current derivatives should be also specified in the standard like the discharge current.

3.3. Effect of the radiation fields on the ESD immunity test

Different ESD simulators would cause different current derivatives; therefore, the radiation field caused by different ESD simulators will vary largely. Because of a well correlation between the induced voltages in a semi-circular loop and EUT

ESD failure levels, Romachandran and Pommerenke [18] used the induced voltage to represent the ESD radiation field. However, if the transient field distribution is non-uniform around the ESD simulator, the induced field coupled into the EUTs is correlated with not only the brand of the ESD simulator, but also the angles of the ESD simulator towards the EUTs. Because ESD simulators are not bodies of revolution, if the transient field distribution around the ESD simulators is non-uniform, this will cause a EUT failure level variation. To observe the variation, the induced voltages in a semi-circular loop have been measured using the measurement setup which shown in figure 1. Figure 7 shows the top view of the measurement setup for the induced voltages in a semi-circular loop (28 mm diameter, 0.7 mm wire diameter). The distance between the discharge tip and the center of the semicircular loop is 10 cm. Table 1 shows the variations of the induced voltage at four different revolution-angles of the ESD simulator at 2 kV. From table 1, one can find that different values gained when different ESD simulators used at different revolution-angles even though the same simulator at different revolution-angles. The variation indicates the importance of the transient fields and shows that even when using one simulator there can be repeatability problems.

Figure 7. Measurement setup for the induced voltages in a semi-circular loop (top view). The ESD simulators were rotated around the discharge tip. The induced voltage was measured at four angles.

| Table 1. Values of the induced voltages in a semi-circular loop at different revolution-angles of the ESD simulators. |
|---------------------------------------------------------------|
| ESD simulators | Induced voltages at each revolution-angles of ESD simulator (V) |
|----------------|---------------------------------------------------------------|
| ESS-200AX | 0 deg. | 90 deg. | 180 deg. | 270 deg. |
| NS61000-2A | 2.38 | 2.15 | 3.54 | 3.51 |

Figure 8 shows the spectra of the induced voltages in a semi-circular loop for ESS-200AX simulator at different revolution-angles. Figure 9 shows the spectra of the induced voltages for ESS-200AX simulator and NS610000-2A simulator at 0 degree.
From figure 8, one can distinguish two regions within the spectrum of the induced voltage in a semi-circular loop (the transition occurred at about 500 MHz). In the lower frequency ranges (lower than 500 MHz), the rotation effects are less seen in the spectrum, but strong variations can be observed due to the angle of the rotations in the higher frequency ranges (higher than 500 MHz). This can be explained as follows [14]: in the lower frequency ranges, the induced voltage in a semi-circular loop is dominated by the fields from the discharge current which is not affected by rotating the ESD simulator. The higher frequency components are caused by the relay that initiates the ESD pulse. 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 [18]. 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 simulator will generate non-symmetric transient fields, while the discharge current flowing through the discharge tip generates the symmetric transient field around the ESD simulator. From figure 9, one can see that the variation is larger in the high frequency ranges.

In a word, the variation of the induced voltage in a semi-circular loop is dominated by the brands and the revolution-angles of the ESD simulators, this variation indicates the importance of the transient fields. Thus, better test repeatability will only be achieved by properly controlling the transient field during discharge.
3.4. Effect of imperfect specification of air discharge mode testing method on the ESD immunity test

An air discharge relates to the spark channel forming process, the temperature, the humidity, and the electrode approach speed will cause the discharging process varied obviously, therefore, the repeatability of the air discharge is very bad, and difficult to be controlled. 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 and to improve reproducibility [4]. However, the air discharge mode is the most common ESD phenomenon is industry and living environments, and also a main way to damage and/or interfere to electronic equipment. It is one of the most urgent problems needing to be solved for industry. The imperfect specification for the air discharge mode testing method in the standard limits the application of the standard at a certain degree. In addition, the discharge condition for air discharge mode, especially the discharge electrode approach speed is not specified in the standard, which is difficult for the tester to control a relatively consistent testing condition in air mode ESD immunity test, as a result, we can’t get a well repeatable testing result. Therefore, it is very significant to study the related factors which affect the air mode ESD, to establish and specify a suitable stern condition for air mode ESD immunity testing method.

In the paper, the repeatability of air discharge was studied using the experimental setup depicted in figure 1. In the experiment, the ESS-200AX simulator is used; the approach speed is about 0.5-1.0 m s\(^{-1}\), the charge voltage from ±2 kV to 28 kV, the temperature is 26\(\text{°C}\) and the humidity is 33% RH (the fluctuation of temperature and humidity is strictly controlled within ±2 \(\text{°C}\) and ±2% RH). For each combination of approach speed and voltage, 20 successive experiments were performed and the average was calculated (Note: in ESD immunity test, the test result is usually determined by the most serious discharge and not the average value of multiple discharges. Here, the average value is just used to analyze the general rules of the effect of approach speed and voltage on ESD parameters).

The coefficients of variability of discharge current and rise time at different approach speeds and charge voltages are given in tables 2 and 3. Here, the coefficient of variability is defined as the ratio of standard deviation and average of 20 results; it is used to represent the repeatability of test results.

| Polarity | Approach Speed (m s\(^{-1}\)) | Charge Voltage (kV) | 2  | 4 | 8  | 15 | 24 |
|----------|-----------------------------|---------------------|----|---|----|----|----|
| Positive | 0.5                         | 0.125               | 0.185 | 0.249 | 0.246 | 0.232 |
|          | 0.6                         | 0.105               | 0.196 | 0.241 | 0.340 | 0.223 |
|          | 0.7                         | 0.108               | 0.134 | 0.219 | 0.314 | 0.218 |
|          | 0.8                         | 0.060               | 0.115 | 0.142 | 0.232 | 0.181 |
|          | 0.9                         | 0.059               | 0.132 | 0.144 | 0.249 | 0.183 |
|          | 1.0                         | 0.076               | 0.134 | 0.150 | 0.230 | 0.179 |
| Negative | 0.5                         | 0.145               | 0.128 | 0.128 | 0.123 | 0.121 |
|          | 0.6                         | 0.114               | 0.116 | 0.113 | 0.113 | 0.119 |
|          | 0.7                         | 0.166               | 0.113 | 0.044 | 0.036 | 0.029 |
|          | 0.8                         | 0.072               | 0.117 | 0.025 | 0.027 | 0.025 |
|          | 0.9                         | 0.138               | 0.115 | 0.063 | 0.064 | 0.058 |
|          | 1.0                         | 0.139               | 0.119 | 0.053 | 0.049 | 0.043 |

From tables 2 and 3, one concludes that, for a constant charge voltage, the coefficients of variability of discharge current and its rise time increase with the growth of approach speed, especially at 0.8 ms\(^{-1}\) (this claim is based on many times test results, the same conclusion also get at the humidity of 44% RH and 54% RH). This indicates that the repeatability can be improved by increasing approach speed for the air discharge mode. This important conclusion will provide the foundation of developing a standard method for air ESD immunity tests.
Table 3. The Coefficient of Variation of Rise Time.

| Polarity | Approach Speed (m s\(^{-1}\)) | Charge Voltage (kV) | 2 | 4 | 8 | 15 | 24 |
|----------|-------------------------------|---------------------|---|---|---|----|----|
| Positive | 0.5                           | 0.304               | 0.390 | 0.427 | 0.377 | 0.260 |
|          | 0.6                           | 0.258               | 0.292 | 0.393 | 0.382 | 0.231 |
|          | 0.7                           | 0.230               | 0.300 | 0.321 | 0.380 | 0.204 |
|          | 0.8                           | 0.181               | 0.184 | 0.187 | 0.237 | 0.129 |
|          | 0.9                           | 0.201               | 0.203 | 0.178 | 0.248 | 0.151 |
|          | 1.0                           | 0.197               | 0.201 | 0.206 | 0.238 | 0.133 |
| Negative | 0.5                           | 0.402               | 0.333 | 0.470 | 0.430 | 0.297 |
|          | 0.6                           | 0.363               | 0.312 | 0.395 | 0.440 | 0.283 |
|          | 0.7                           | 0.362               | 0.245 | 0.396 | 0.340 | 0.255 |
|          | 0.8                           | 0.216               | 0.233 | 0.220 | 0.292 | 0.192 |
|          | 0.9                           | 0.221               | 0.240 | 0.232 | 0.248 | 0.225 |
|          | 1.0                           | 0.222               | 0.228 | 0.240 | 0.245 | 0.222 |

Except above discussed factors, the non-flat frequency response of current target, cable loss, and the reflections which caused by the scope, the attenuators, and the target are not perfectly matched to the cable impedance, will affect the discharge current measurement, and further affect the ESD immunity testing results.

4. Conclusion

The mostly widely used system level ESD test standard, IEC61000-4-2, causing irreproducibility results, neither ESD standard specifications nor the methodology used to verify the specifications are presently sufficient restrictive to provide acceptable ESD system test repeatability. Therefore, using the newly designed ESD simulation testing system, we find that the switch action of the ESD simulator is one of the main reasons; variation between different brand ESD simulators is also a major reason for the lack of reproducibility in ESD tests. In addition, the brand of ESD simulator and its revolution angles, and the imperfect specification of the test method in the standard can also affect the reproducibility of the test results.

Acknowledgments

This work was supported by National Natural Science Foundation of China under Grant 61172035, Grant 51177173, and Grant 60971042.

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