THE CHARACTERISTICS OF LOW-VOLTAGE ESD AND ITS THREAT

Masamitsu Honda

Nihon Unisys, Ltd.
Fujigaoka Laboratory
2-39-4 Fujigaoka
Midori-ku, Yokohama 227, Japan
81-45-973-9911

Abstract

The experimental studies of the impact which low-voltage (nearly 3 kv or less) ESD has on electronics in operation have revealed, as opposed to what has commonly been known, the electromagnetic inteference caused by more than 10 kv high-voltage ESD is most likely to provide a greater threat than that low-voltage ESD does. The reason is the rise time in the low-voltage ESD environment indicates a very fast, sharp curve, in addition the unipolar impulse field is generated.

1. Introduction

The human being's coexistence with static electricity started at least some 2600 years ago, and the level of electrostatic discharge (ESD), to which the human body is immune in modern times, has reached up to about 3000 volts [1]. Therefore, bodily charging in this range so rarely stimulate human bodies that no one recognizes these phenomena in most cases.

On the other hand, it is comparatively only a little time ago we first noticed the coexistence of electronic systems consisting of semiconductor devices with static electricity, and such system's immunity to ESD can safely be considered to be still short of the human being at the very present time.

In the particular sphere of computer systems, this is clearly evidenced by the fact that they react more sensitively to ESD at less than 3 kv (causing machine trouble) than to high-voltage ESD (i.e. at 10 kv or more). [2]

The author's thought is the contribution of low-voltage ESD to computer systems entirely disagrees with the conventional concept related to the ESD immunity test — "High-voltage ESD means a high-level threat", and besides serves to be an originator of a fresh fundamental problem to be newly solved. In addition, it is already known the indirect ESD [3] generated between such metal objects as office furniture items located in the vicinity of a computer system gives rise to more powerful electromagnetic interference at low voltage, casting a new serious question on the concept resulting from electromagnetics "the higher energy, the stronger the effect".

Based on the analysis of ESD problems found at actual computer installation sites and the results out of a series of related comparative experiments, this paper is intended to make clear the characteristics of low-voltage ESD and its threat.

2. Computer Malfunctions Caused by Low-voltage ESD

Discharging as generated by less than 3 kv static electricity is not felt by the human being is reffered to "low-voltage ESD" (LVESD) in this report. Likewise, discharging generated by more than 10 kv static electricity is refferd to "high-voltage ESD" (HVESD).

The analysis of a large number of actual ESD-caused computer malfunctions at user sites and the result obtained from the field recurrence tests has produced three different findings that are as follows:

1)Regardless of direct and indirect ESD, the occurrence of malfunctions is infinitely more frequent in LVESD than HVESD. The study of a trouble cause for an engineering workstation required an ESD immunity test based on the factory standards (at the immunity level of more than 10 kv at $C = 120$ pf $R = 250\ \Omega$). The fact is the same trouble took place again in the range of 1 to 3 kv ESD in contrast to initially expected. Meanwhile, no errors were detected ESD with other voltages including 10 kv, thus making it impossible for both the designer and the manufacturer to recognize the existence of this fact.

2) In the case of indirect ESD generated between metal objects in the vicinity of a computer system, the presence or absence of their movement (collision) has much to do with the occurrence of computer malfunctions. Also another fact was discovered the lower voltage on metal objects, the stronger the impact caused by movement becomes.
Considerably higher rates of ESD-caused trouble occurrence were seen on the terminals in use for retrieval of patients' records at the reception desk at a certain hospital, around which human traffic is usually heavy, than on other terminals installed loosely in a spacious room. The cause turned out to be the LVESD generated not only by the mutual collision of steel pipe chairs but also by metal stationery such as scissors, binders and writing utensils.

3) When indirect ESD encounters a computer system, it is LVESD that tends to have a more serious impact on the central processing unit (CPU) while it is HVESD that is more likely to work on the input/output control unit. There was a large-scale main-frame computer whose clock system (ECL circuit) came to a halt by the LVESD generated in the neighborhood (with in one meter or less) of the system's CPU cabinet. However, HVESD exposed to the same cabinet caused no fatal failures, but produced recoverable errors on the control logic (ASTTL circuit) for hard disk drives and on the low speed communications control.

The problem is the LVESD threat seen at computer installation sites has not been recorded nor communicated to hardware designers and plant quality managers up to date. One of the reasons is a decisive difference between human sensitivity and system's susceptibility in their "recognition" of ESD phenomena. Another reason is a deletion of such data (or the fact like this) because individual engineers engaged in field support or equipment testing jobs are so obstinate as to hold to traditional ways of thinking and explaining instead of trying to make changes.

As a result, more emphasis on those problems in working ESD educational and training programs, so that the efforts can lead to the enhanced ESD immunity of the computer system.

3. Experiments and Findings

3.1 Voltage and the Rise Time of Discharge Current

The report submitted for the 1984 Symposium is already indicative of the relationships between voltage and the rise time of discharge current (4). The detailed testing method is described in this report, with the results shown in Figure 1. As is evident in this figure, according as voltage (v) gets higher, the rise time of discharge current (tr) is on the rapid increase; that is, tr stands at 0.4 ns at a voltage of 500 V while tr shows 10 ns at 10 KV, under the testing conditions that C = 120 pf and R = 250 Ω. This experiment leads to the conclusion that the lower is voltage, or the smaller is the spark gap, the faster the rise time of discharge current becomes.

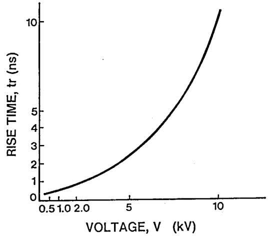
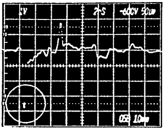


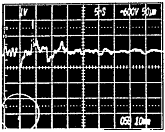
Figure 1. Current Rise Time vs. Voltage

3.2 Voltage and Impulse Waveform

For the purpose of looking into radiated impulse fields, in terms of time domain, produced by ESD in the space in the vicinity of metal objects, made up a discharging apparatus (whose specifications are given below) in an attempt to capture impulse waveforms in the range of 600 V to 2 kV.



v = −600V, g = 50μm, 2 ns/Div.



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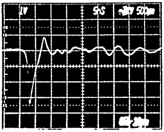

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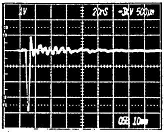
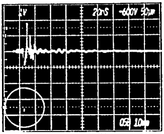
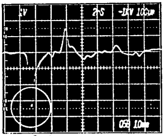


v = −3kV, g = 500μm, 20 ns/Div.



v = −600V, g = 50μm, 20 ns/Div.



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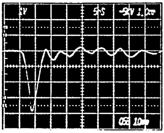
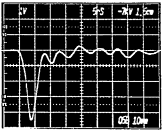
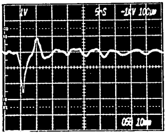


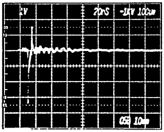
v = −5kV, g = 1.0mm, 5 ns/Div.



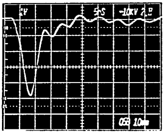
v = −7kV, g = 1.5mm, 5 ns/Div.



v = −1kV, g = 100μm, 5 ns/Div.



v = −1kV, g = 100μm, 20 ns/Div.



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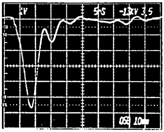
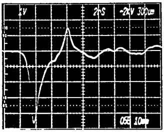
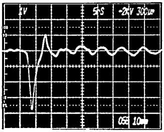


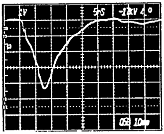
v = −13kV, g = 3.5mm, 5 ns/Div.



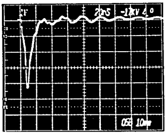
v = −2kV, g = 300μm, 2 ns/Div.



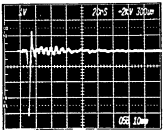
v = −2kV, g = 300μm, 5 ns/Div.



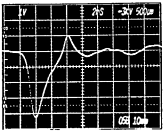
v = −17kV, g = 4.9mm, 5 ns/Div.



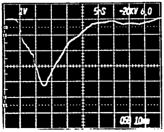
v = −17kV, g = 4.9mm, 20 ns/Div.



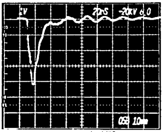
v = −2kV, g = 300μm, 20 ns/Div.



v = −3kV, g = 500μm, 2 ns/Div.



v = −20kV, g = 6.0mm, 5 ns/Div.



v = −20kV, g = 6.0mm, 20 ns/Div.

Figure 2. Changes in Impulse Waveforms Caused by Different Voltages

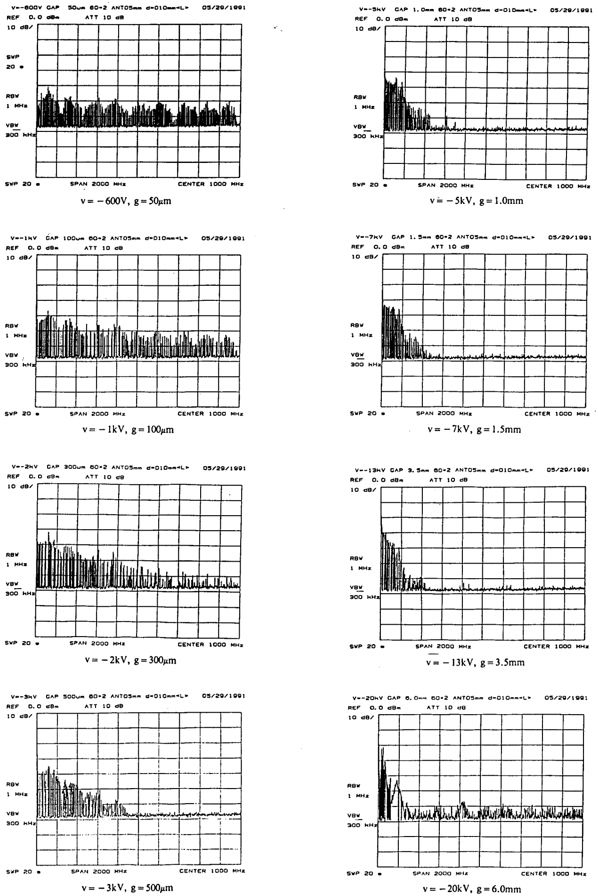


Figure 3. Changes in Spectrum Distribution Caused by Different Voltages

Two 600 mm copper pipes (diameter: 12.7mm and C = 10 pf respectively), A and B, with their tips each having a soldered brass ball of 12.7 mm in diameter, are vertically held and faced to each other with a certain gap width (g) in between, which changes according to each voltage value ranging from 600 V through 20 kV. Then, high voltage is given to the copper pipe A linked with a conductive rubber cable (some 10 MΩ) via a 1000 MΩ current-limiting resistor. The ground level is given to the copper pipe B with the use of a conductive rubber cable having the same characteristics. The reason for the use of the rubber cable is to prevent the emanation of unnecessary electromagnetic fields from other than the copper pipes A and B.

For reception of impulse fields, the element of a 5mm short monopole antenna [5] (with an SMA (F) connector attached) is positioned at a horizontal distance of 10 mm from the lower end of the copper pipe B. This antenna is connected to a 1.0 GHz real time oscilloscope (TEK 7104 with 7A29/7B15) with a 1.5 m-long microwave coaxial calbe (DC-18.5 GHz) in between.

The results from this experiment are shown in Figure 2. Voltage is at 600 V (wih g = 50μm), an impulse rise time is fast and pulse width is as small as less than one ns (*1). The polarity (negative going) of this impulse is due to the fact that the charged polarity of the copper pipe A is negative, signifying that the impulse is isolated and that a unipolar electromagenetic field exists [5] [6]. As the spark gap (g) expands (g: 50μm to 6.0 mm), that is, as voltage increases, the rise time of the impulse gets less fast and the impulse width gets greater. Another noteworthy fact is the anntenna-induced voltage (Vi) hardly changes in spite of some 33-fold increase in the given voltage — namely, Vi = 4.2V when v = 600V and Vi = 4.5V at v = 20 kV.

(*1) Another experiment where a 34 GHz sampling oscilloscope was used indicated a nearly 40-ps impulse width was observed in the case of v = at 550V [5].

3.3 Voltage and Spectrum Distribution

Looking into the distribution of frequency spectrum included in the impulse (on the same experiment apparatus and under the same measuring conditions as stated in item 3.2 above) required the use of a spectrum analyzer (TR 4172) capable of measuring a band width of 10 kHz to 1800 MHz in place of the oscilloscope.

The results from this experiment are shown in Figure 3. Voltage is given at 600 V (with g = 50 μm), a series of spectrum distribution is observed up to the measurable limit (up to 1800 MHz) (*2), and as the voltage increases (with g extending from 50μm to 6.0 mm), the spectrum distribution shrinks into a smaller frequency region and the band becomes narrow in width. Those series of changes in the spectrum distribution are entirely identical with the results obtained from the time domain measurement as mentioned in item 3.2 above.

(*2) Another experiment where a 6.5 GHz spectrum analyzer was used ensured that the spectrum distribution continued up to 6.5 GHz in the case of v = at 1 kV.

3.4 Collision of Metal Objects and Unipolar Impulse

It has already been release the strength of the electromagnetic field generated by two metal objects (steel-pipe chairs) and its spectrum distribution are completely different when those two come close to each other and collide from those obtained when they are held in the fixed position. [2] [7] Figures 4 (a) and 4 (b) show how the former spectrum distribution differs from the latter. The antenna used for this experiment was a log-periodic antenna (Anritsu MP636A) capable of measuring band width of 300 MHz to 1700 MHz.

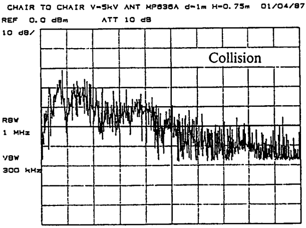


Figure 4(a). Collision of Chairs and Resultant Spectrum Distribution

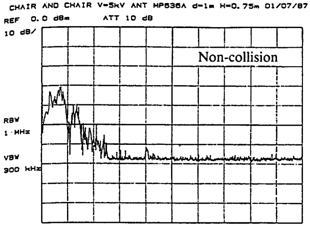
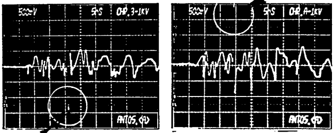


Figure 4(b). Collision of Chairs and Resultant Spectrum Distribution

The experiment conducted this time, a 5 mm short monopole antenna (with an SMA (F) connector attached) is used in place of a log-periodic antenna, is to look into the ESD-caused impulse field generated when two steel-pipe chairs, A and B, approach and collide with each other, with the use of a 1.0 GHz real time oscilloscope (TEK 7104). -1 kV is given to the chair A (or B) linked with a conductive rubber cable (some 10 MΩ) via a 1000 MΩ current-limiting resistor. The ground level is given to the chair B (or A) with the use of a conductive rubber cable having the same characteristics.

As indicated in Figures 5 (a) 5 (b), an isolated unipolar impulse, which is very narrow in width and whose amplitude is as large as 1.5 to 2.0 V, is observed in the ringing waveform. It has turned out the polarity of this unipolar impulse is dependent on (1) the position of the antenna (on A's side or on B's side), (2) charged polarity of the chair A (or B) and (3) the direction of movement (A toward B or B toward A). In this relation, the unipolar impulse is not always observed every time the test is conducted, with the result that there is only a ringing waveform as shown in Figure 6.



5(a) (negative-going) 5(b) (positive-going) (scaled out)

Figure 5. Unipolar Impulse Caused by the Collision of Chairs (with the use of a 5 mm-long short monopole antenna)

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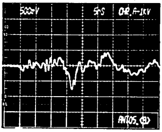

Figure 6. Ringing Waveform Caused by the Collision of Chairs

Figure 7 indicates the unipolar impulse is generated through the collision of two pairs of scissors (18 cm long each), which are placed in a plastic tray (23 cm wide, 30 cm long and 4 cm deep). In this experiment, a 25 mm short monopole antenna (with an SMA (F) connector attached) is positioned at a distance (d) of some 10 cm from the scissors. The finding is the amplitude of the impulse changes high and low; some are in excess of 4 V. There are some cases where there is only a ringing waveform seen with no impulse coming out at all.

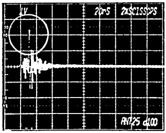

Figure 7. Unipolar Impulse Caused by the Collision of Scissors (with the use of a 25 mm-long short monopole antenna)

4. Discussion

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4.1 Momentary Changes in ESD Phenomena

The experimental results mentioned in items 3.1 to 3.3 above and in the paper [8] all show the same tendency: that is, the lower ESD becomes in voltage, the faster is the rise time of the impulse electromagnetic field emanated into the space in the vicinity of metal objects, and further the smaller (shorter) is the impulse width. In other words, ESD phenomena give rise to even faster changes and finish in a much shorter time in the low-voltage envrionment than in the high-voltage one.

The reasons for such a great rapidness in low-voltage ESD phenomena are considered to include:

1)The air gap existing between two metal objects in the case of 1 kV-ESD is about 100μm, and it is nearly 6 mm in the case of 20 kV-ESD, as defined in Passien's law. In discharging, since the current flows only in a single direction (from an electron-rich object to an electron-poor object all the time) throughout the air gap, low-voltage ESD whose moving distance is small naturally takes a shorter time to travel in the gap. In addition, the static field strength immediately prior to discharging which takes place in the gap becomes greater according as the voltage get lower [2] [4]. The values, for example, stand at about 3 kV/mm in the case of 20 kV and some 12 kV/mm when the voltage is 600. This fact means that traveling electrons are accelerated in a sufficient degree and that their traveling speed is built up.

2)The time period required for the generation of an low-voltage ESD phenomenon through its termination often stands below the nano-second level, and actually some 40 ps level has been measured [5]. In contrast, high-voltage ESD at 10 kV requires at least 10 ns, and some data indicates that this value reaches as much as 50 ns when there is higher voltage [8].

On the understanding that the length (ℓ) over which electrons on a metal object move at the light velocity (c: 3 x 10^8 m/s) is proportinate to the time (t) when discharging continues, ℓ or ct is equal to 12 mm where t is 40 ps, and ℓ or ct stands at 30 m where t is 10 ns. Accordingly, it can be said that the reaction of inductance existing along the current-moving path is outstandingly small (about one-ten thousandth); to be brief, low-voltage ESD is possessed of a far slighter factor in the blocking of current momentum and causes faster ESD phenomena.

4.2 Unipolar Electromagnetic Field and Oscillating Fields

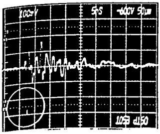
It is already a known fact that, in the low-voltage ESD environment, the electromagnetic field emanated into the space in the vicinity of metal objects is in the form of unipolarity [7] [9]. On the other hand, the fields emitted by high-voltage ESD are in the form of oscillation. (See Figure 2 in reference [8] and Figure 1 (the picture on the right side) in reference [10].)

There have been frequent experiences where the existence of the unipolar impulse (Figure 5 and Figure 7) detected in the experiment as mentioned in item 3.4 has been a great threat to high-speed eclectronic systems. Discussion on the generation of this type of unipolar impulse and its resultant malfunctions on digital circuitry would require further experiments. They should focus on i) the vector distribution of unipolar fields in the vicinity of metal objects, ii) their propagation characteristics in the space, and iii) the impulse attenuation of shielding materials.

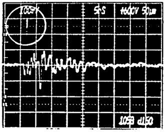
In addition, it is also necessary to have a good look into the reaction of the printed circuit board exposed to the unipolar impulse field [11]. The recent attempt in this connection was to study the voltage waveform induced onto the pattern of a single-layered printed circuit board (a microstrip line 2.5 mm wide and 150 mm long with characteristic impedance being 50 Ω). The wave sources consisted of a) two 60 cm-long copper pipes one of which was given 600 volts and b) a 0.5 W/27 MHz walkie-talkie (with a 1.2 m-long rod antenna). The circuit board was positioned at a distance of 150 mm from each of those wave sources (with one wave source used for one attempt).

As shown in Figure 8, there is a wide difference between the two in terms of their waveforms and amplitudes. The voltage induced on the printed pattern exposed to the oscillating field is as weak as about 10 mv, not strong enough to upset the digital circuit. In contrast, the ESD-exposed printed pattern marks as much as 300 mv, strong enough to drive the ECL circuit easily. In case a greater amplitude is induced on the printed pattern, it may possibly be predicted that the reaction of the ECL circuit (negative-going) and that of the TTL circuit (positive-going) will differ from each other according to the impulse polarity.

All this means no conventional theories can be applied to the reaction of the printed pattern exposed to the ESD electromagnetic field with its impulse width being at less than 100 ps in the very close vicinity of metal objects. The reason is the preconditions (including coordinate systems) all vary from one from another.

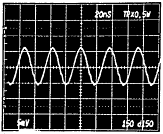


8(a) ESD/negative-going



8(b) ESD/positive-going

Figure 8. Induced Voltage Waveforms on a Printed Pattern (a), (b)



8(c) Walkie-Talkie/continuous waveform

Figure 8. Induced Voltage Waveforms on a Printed Pattern (c)

5. Conclusion

It has been made clear that even such relatively low-voltage ESD cannot be felt by the human have a still greater threat than high-voltage ESD does. It is necessary for us all to newly admit the fundamental facts of ESD physics — "low voltage (low energy) is a strong threat," whereas high-voltage ESD is far from being a threat to electronic systems.

We all know what makes them most sensitive is not the human being but metal objects charged with low voltage, and that their slight movement can bring about a catastrophic situation.

The logical conclusion is that we need to adopt new ways of controlling ESD and conducting ESD immunity tests in place of the methods currently under way.

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