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EMI CHARACTERISTICS OF ESD IN A SMALL AIR GAP
--ARP GOVERNS THE EMI--

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Abstract

The EMI (Electromagnetic Interference) with an ESD (Electrostatic Discharge) event is not always proportional to the discharge voltage, but is governed by the ARP (Amplitude-Rate of change of current Product). The present paper clarifies this phenomenon experimentally at various spark gaps with use of a newly developed ESD detector and existing measuring instruments.

Introduction

Recently, the influence of ESD on electronic equipment has become particularly prominent in every scale of system. Even a very simple and small system delivers and accepts signals to and from external units (such as interface, sensor or the like). Naturally, these systems will have overwhelmingly large cross sections susceptible to EMI as compared with the case when a single LSI exists, and will accordingly be easily affected. The electromagnetic energy radiated from an ESD event into the surroundings propagates in two routes, conductor surfaces and space, in the form of the impulsive EMI over an ultra-wide frequency region. The influences of EMI propagating in space can be recognized from the fact that electronic equipment may operate erroneously even when there is no direct passage of the discharge current to it.

Where a computer is in operation, we must clarify the dependency of computer failures on accidental and single-shot ESD events. Particularly, for catching the radiated EMI, we have recently developed an ESD detector.

With use of this detector, we have examined the action of the EMI radiated from the ESD. We have found that, with the ESD at a very low charge voltage (below about 3 kV) at which no electric shock is felt by man, the computer operates erroneously in some cases.

For further verification of this phenomenon, the EMI with the ESD was studied at varying spark gap. In addition, some existing measuring instruments were used to confirm the same with a similar finding that the EMI with the ESD is not always proportional to the discharge voltage.

ESD Detector

Outline of ESD Detector

When a computer fails, many problems are involved in checking for any ESD event in the vicinity of the computer, or in studying the correspondence to the intensity of the ESD. In many cases, combinations of the existing measuring instruments may not be practical at all. One reason for this is that, with an ESD event, the vicinity of it is subjected to strong electromagnetic fields, and naturally, the measuring system is interfered therewith. Especially, in any system which is driven with AC power and delivers and accepts signals directly through a probe or the like to and from the object under measurement, the interference may lead to uncertain results.

From these experiences, we have planned that the ESD detector should be battery-driven, and the problems due to conductive means and grounding loops should be eliminated, so that the EMI radiated from the ESD may be detected through the antenna alone. Of the transient electromagnetic fields of RF frequencies radiated in the air, the induced electric field which will be dominant in the vicinity of the ESD source is received on a mono-pole antenna having a length of 2.5 cm (about 1 in). Even if the ESD event is only one-shot and is sustained only for a period of the order of pico-seconds (10^{-10} to 10^{-12} sec), this detector has the function to hold the display at any of two detection levels, HIGH and LOW, according to the strength of the interference field until it is reset. The HIGH detection level is set to 134 dB which corresponds to the impulsive EMI threshold of the general computers. The LOW detection level is set to 102 dB which is a sensitivity suitable for detecting the presence of an ESD event and/or briskness. The block diagram of the ESD detector is shown in Fig.1.

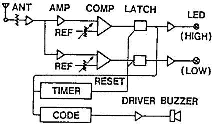


Fig.1 Block diagram of ESD detector

Dimensions and Weight

Detector dimensions 9.6(H) x 6.1(W) x 2.3(D) cm
Weight Approx. 90g

Fig.2 shows the ESD detector as installed in the computer.

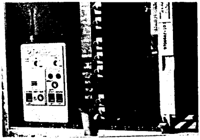


Fig.2 ESD detector installed in a computer

Typical EMI Characteristics Obtained With ESD Detector

An ESD simulator is used to cause an ESD event, and the intensity of the EMI radiated thereby in the neighboring space is examined with the ESD detector.

In the experiment, the discharge probe of the ESD simulator is held by the hand, and the discharge electrode at the probe tip end is brought into contact with an alligator clip at the tip end of the grounding lead, and the range of the EMI radiated by the resulting spark is measured. The results indicate that at a discharge voltage up to about 6 kV, the EMI range extends proportionally to the discharge voltage, but when the discharge voltage exceeds about 10 kV, the EMI range tend conversely to decrease. The EMI range at about 15 kV corresponds to that at 2 to 3 kV. Refer to Fig.3.

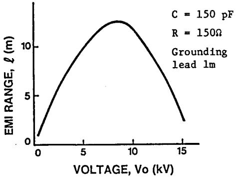


Fig.3 EMI range vs. discharge voltage

Outline of Experiment

The ESD behavior with varying spark gap is analyzed in two respects, ① rise time/frequency spectrum and ② radiated EMI intensity. This analysis is especially in detail at smaller spark gaps.

First, a model ESD source is made, and the discharge current therefrom, the electric field in the vicinity of the spark gap, and the electric field at a distance of 2m from the spark gap, are measured in the time domain and in the frequency domain. The spark gap (or discharge voltage) is used as a parameter.

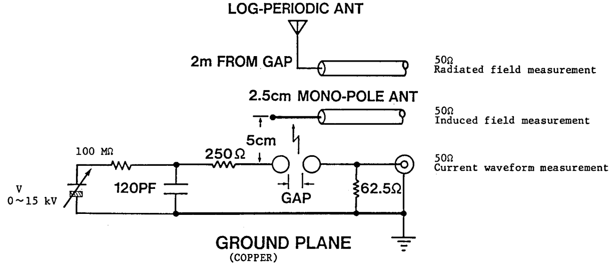


Fig.4 ESD experiment circuit

The most simplified circuit of ESD source is shown in Fig.4. It is constructed with care to minimize the inductance which may cause errors in the measurement along the entire route of discharge current. An approximate value of the inductance is 20 nano-henries. The spark electrode is a brass sphere of 1/2" diameter, and the spark gap (d) is finely micrometer adjustable.

d is 0 to 5000 μm.
Resolution is 10 μm.

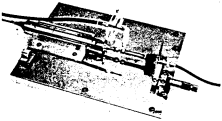


Fig.5 ESD source

Major Measuring Instruments

1) Oscilloscope
   Type 7104 Main frame DC to 1 GHz
   7A29 V-amplifier Rise time 0.4 ns
   7B15 Time base

2) Spectrum analyzer
   Type 7704A Main frame
   7L13 Spectrum analyzer $f_{max.}$ 1.8 GHz

3) Log-periodic antenna
   Type MP63A 300 MHz to 1.7 GHz

Results of The Measurements

Discharge Voltage vs. Spark Gap. Fig.6 shows the results of the measurements with the experiment circuit on the discharge voltage vs. spark gap correspondence. The calculated field (voltage gradient) in the spark gap is also shown. The smaller the spark gap, the larger the field is.

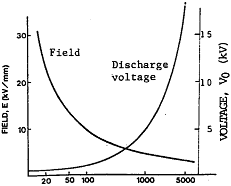


Fig.6 Discharge voltage vs. spark gap, with field in the spark gap

Current Rise time. The discharge current rise time tends to increase clearly with increasing spark gap. The discharge voltage vs. spark gap correspondence is already shown above. Fig.7 shows the results of the measurements on the current rise time vs. discharge voltage relation.

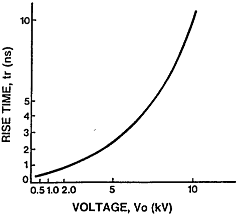
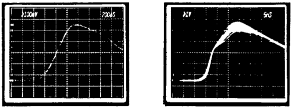


Fig.7 Current rise time vs. discharge voltage

The oscilloscope used in this measurement contains the V-amplifier whose rise time is 0.4 ns. Therefore, when the measured value is near 0.4 ns, it is considered that the true value will be much smaller.

Fig.8 shows the measured waveforms.



(a) (b)

Fig.8 Measured waveforms of current rise time
(a) At discharge voltage 0.58 kV
(b) At discharge voltage 10 kV

Peak Current vs. Discharge Voltage As the spark gap (discharge voltage) varies, the discharge current varies in correspondence to the discharge voltage, but there is no direct proportionality. Fig.9 shows the results of the measurements. At low discharge voltages, the peak current shows a good agreement with the V/R ratio (discharge voltage / discharge circuit resistance), but as the discharge voltage increases, the peak current deviates from the proportionality and, for example, at 5 kV, is only 54% of the V/R ratio.

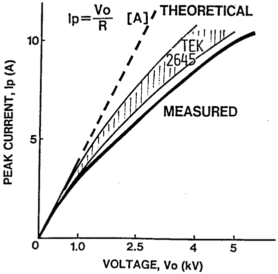
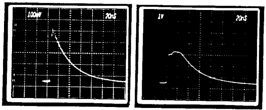


Fig.9 Peak current vs. discharge voltage

In the measurement of the discharge current, there is a problem. That is, as the discharge is repeated at the same discharge voltage, the peak current varies within a range. The variation range is 15 to 20%. In the above figure, the data obtained with the use of TEK 2465 ($f_{max.}$ = 300 MHz) in a separate experiment are shown for reference.



At discharge voltage 0.58 kV　　At discharge voltage 5 kV

Fig.10 Different current waveforms with different discharge voltages

Antenna Induced Voltage in The Vicinity of Spark Gap. At a distance of 5 cm in the space from the spark gap, a mono-pole antenna is fixed and the voltage induced in the antenna is measured with an oscilloscope. The results of the measurements are shown in Fig.11. Fig.12 shows two of the waveforms obtained. It is shown that, as the spark gap increases, the antenna induced voltage decreases while the discharge voltage rises. Moreover, as the spark gap increases, the antenna induced voltage becomes less sharp in the waveform.

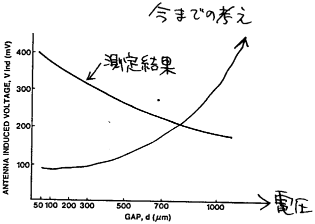
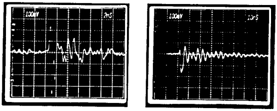


Fig.11 Antenna induced voltage in the vicinity of the spark gap



At spark gap 20 μm　　At spark gap 1000 μm

Fig.12 Antenna induced voltage, difference in the waveform and amplitude

Antenna Induced Voltage at a Distance of 2m from The Spark Gap. At a distance of about 2m from the spark gap, a calibrated log-periodic antenna (300 MHz to 1.7 GHz) is installed and the voltage induced in the antenna is observed with a spectrum analyzer having a bandwidth of 1.8 GHz. As the spark gap increases to increase the discharge voltage, the frequency bandwidth becomes clearly narrow. The results obtained at spark gap 20 μm and spark gap 1000 μm are shown in Fig. 13 and Fig.14, respectively. Taking into consideration the limitations of the measuring instruments used, it will be sure that the true bandwidth is in excess of 2 GHz at spark gap 20 μm.

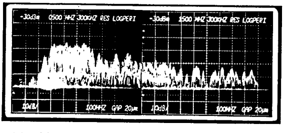


Fig.13 Received power frequency spectrum at spark gap 20 μm

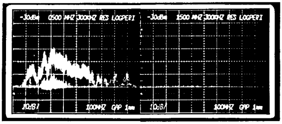


Fig.14 Received power frequency spectrum at spark gap 1000 μm

In both figures, in the low frequency regions below 300 MHz, the power level drops. This is because of the limited effective frequency band of the antenna, and the true level is higher. Especially, at large spark gaps, it is apparent that the power is concentrated in the low frequency regions. Conceptionally, this trend is shown in Fig.15.

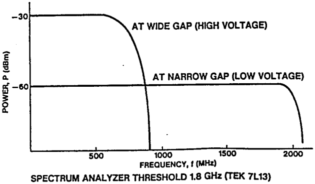


Fig.15 Radiated frequency spectrum vs. spark gap

Summary of The Results of The Experiments

1. The field (voltage gradient) in the spark gap increases rapidly with decreasing spark gap.
2. The rise time of discharge current increases with increasing spark gap.
3. The peak discharge current increases with increasing spark gap, but the rate of increase decreases.
4. The voltage induced in an antenna placed in the vicinity of the spark gap decreases with increasing spark gap.
5. The frequency spectrum observed at some distance from the spark gap concentrates into the low frequency regions with increasing spark gap.

Discussions

Rise Time of Discharge Current

From the results of the measurements, it has been confirmed that the rise time of discharge current increases with increasing discharge voltage.

This rise time is very important to electronic equipments as an EMI characteristic of ESD. Then, the reason why the rise time increases with increasing discharge voltage will be examined.

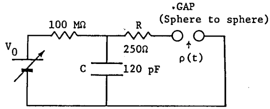


Fig.16 CR circuit for discharge through an air gap

In Fig.16, when the voltage across C reaches the breakdown voltage of air as determined by the length of the air gap, the air confined in this gap is quickly placed in a conducting mode.

Now, the instantaneous event of this breakdown at a definite gap length will be studied in terms of the change of electric conductivity (ρ) of air. First, let us consider that the rise time of discharge current is determined by the rate of increase of electric conductivity. The electric conductivity of air at such an instant should change with time and therefore, it is understood that the electric conductivity ρ(t) shows a different rate of increase with respect to time at a different gap length.

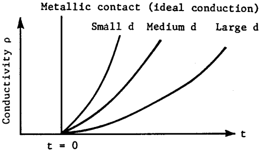


Fig.17 Conceptional diagram showing the rate of increase of electric conductivity vs. gap length

Fig.17 is a conceptional diagram showing the above-mentioned relation. The smaller the spark gap for discharge, the more quickly the electric conductivity increases. According to Hugh Hyatt et al.[1] the resistive phase (τ_R) for the duration of current rise and the formative phase (τ_f) for the subsequent duration of current increase up to the peak are defined regarding the history of discharge current from the insulated to the conducting condition. It is indicated that the formed τ_R increases with increasing discharge voltage, showing a good agreement with the results of the experiments carried out by us.

Peak Limiting and Peak Shifting of Current

During a discharge, the electric conductivity of air in the spark gap is not constant at all times but changes with time. This electric conductivity is governed also by the gap length. With these facts taken into consideration, it will be shown that the rate of peak current does not increase with increasing discharge voltage and moreover, peak shifting takes place.

In Fig.16, assume that the capacitor C is applied with voltage V_0. If the electric conductivity $\rho(t)$ in the spark gap were infinite, that is, the resistive component in this portion were zero, then the peak current I_p should be proportional simply to the voltage. Actually, however, the electric conductivity $\rho(t)$ is finite and varies with time. The peak current I_p is given by the following equation.

$$I_p(t) = \frac{V_0}{R + \frac{1}{\rho(t)}}$$

Further, the electric conductivity increases with a time delay. During this delay, the initial voltage stored on the capacitor C begins to decrease and the peak current further decreases. As a result, the peak current I_p actually measured is determined by the following equation, showing a tendency of peak limiting and also, peak shifting (delay in time for reaching the peak value).

$$I_p(t) = \frac{V_0 - v(t)}{R + \frac{1}{\rho(t)}}$$

where v(t) is the voltage drop across the capacitor.

Theoretically, the peak current at discharge voltage 5 kV should be 18A, while the value experimentally obtained is only 9.7A. This suggests that a current limiting action comparable to that of the impedance actually existing in the discharge circuit has taken place instantaneously. It is to be noted that, during such a high voltage discharge, a peak shifting of as long as 3 ns has been induced. Refer to Fig.7 and Fig.9.

ARP (Amplitude Rate of Change Product)

As is obvious from the experiments, it has been found that the degree to which the interference caused by the ESD affects electronic equipments, that is, the EMI action, is not always proportional to the discharge voltage. In order to investigate why such a phenomenon takes place, it will be reasonable to note the following factors.

1. Increasing with increasing gap
   - o Discharge voltage [V]
   - o Discharge current [I]
   - o Corona loss
2. Increasing with decreasing gap
   - o Field [E]
   - o Rate of change or rate of rise, [di/dt], of current
   - o Frequency spectrum
   - o Instantaneous electric conductivity of air [$\rho(t)$]

In addition, it has also been confirmed that the intensity of the radiated EMI caused by the ESD is governed by the displacement current and does not depend on the discharge energy. Refer to Fig.18 and Fig.19.

Hatched area shows
discharge energy (J)
(heat, light, sound, etc.)

$J = \frac{1}{2} CV^2$ [Joule]

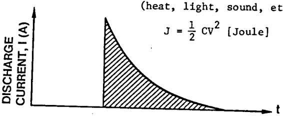


Fig.18 Time dependency of discharge energy

Displacement current (i_d)

$i_d = \varepsilon \frac{dE}{dt}$ [A/m^2]

ε : dielectric constant

$\lambda_d = \frac{\partial D}{\partial t}$ $D = \varepsilon E$

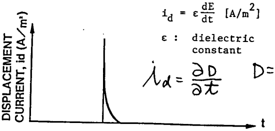


Fig.19 Time dependency of displacement current

When these phenomena, and the data obtained with use of the ESD detector, which shows that the radiated EMI peaks at some discharge voltage, are combined together in a skillful way, quite a new concept can be proposed.

今までの考え

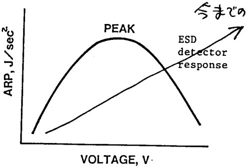


Fig.20 EMI vs. discharge voltage

Ultimately, we have drawn a conclusion that it is reasonable to denote the intensity of the impulsive radiated EMI caused by the ESD by the ARP (Amplitude Rate of change Product), and judge the EMI in terms of this value. Refer to Fig.20.

$$\mathrm{ARP} = V \times \frac{di}{dt}\ [\mathrm{J/sec^2}] \Longrightarrow [\mathrm{W/sec}]\ \text{と同じ}$$

where V : discharge voltage

$\frac{di}{dt}$: rate of change of discharge current

And the influences of the ESD on any actual electronic equipment should also depend on the EMI affected cross section which is determined by the physical dimensions of that electronic equipment, and accordingly, the effective ARP should be rewritten as follows.

$$\mathrm{WARP} = V \times A \times \frac{di}{dt}\ [\mathrm{J/m^2/sec^2}]\ \text{又は}\ [\mathrm{W/sec/m^2}]$$

where WARP: working ARP

A : effective cross section factor

This WARP will have the same dimension as the Poynting's vector which shows the flow of the transient electromagnetic energy caused by the ESD, and the larger its value, the larger the EMI action.

Conclusions

1. EMI caused by ESD is governed by ARP.

2. Radiated EMI caused by ESD is not always proportional to the charged voltage.

3. This has been found for the first time with use of the ESD detector, and, it has also been verified with the existing measuring instruments.

4. The reason why EMI is not always proportional to the voltage is that the rise time of discharge current elongates with increasing spark gap.

5. ESD even at low voltage should not be neglected. And, it is necessary to be aware that there are many chances of being charged at low voltages.

Reference

1. Hugh Hyatt, Hugh Calvin and Hans Mellberg, "A closer look at the human ESD event" 1981 EOS/ESD Symposium Proceedings EOS-3.