Frequency Analysis of Transient Electromagnetic Wave Caused by Low Voltage ESD in Spherical Electrode

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Abstract—Frequency spectra of transient electromagnetic wave caused by electrostatic discharge in spherical electrode were examined by experimental study. The experimental system consists of a pair of spherical electrodes with different diameters, a 1-18 GHz band width horn antenna and a 20 GHz bandwidth digitizing oscilloscope. Discharge voltage is less than 600 V in this experiment. Frequency spectra and waveforms of received voltages caused by ESDs were measured in order to clarify an EM radiation mechanism. As a result, we found that the waveform duration and first peaks of the EM field radiation can be explained from a dipole antenna structure which makes the spark part of spherical electrodes. Furthermore, as the excitation factors of the EM radiation from electrode elements are mentioned the current path length determined by the size of the spherical electrode.

Keywords—ESD (electrostatic discharge), Electromagnetic Radiation; Transient Electromagnetic Wave; Spherical Electrode; Radiation Mechanism

I. INTRODUCTION

Very fast transients of electromagnetic (EM) fields arise from gap discharges of electrostatic discharges (ESDs) and electrical contacts. The transient due to a gap discharge is a very wide band (high frequency) EM noise source. Over the past few years a considerable number of studies have been made on EM noises of ESDs from the viewpoint of electromagnetic compatibility, so-called, EMC. The EM noise characteristics of gap discharges are gradually becoming clearer [1]-[7].

In recent years, on the other hand, digital electronics equipment has a tendency to grow high-density, high-speed processing and low voltages operation so that it is easily affected by ESD events. The main purpose of our study is to clarify the relationships between EM radiation characteristics and discharge phenomena as EMI (electromagnetic interference) sources. The former should be crucial in validating the results of EUT (equipment under test) evaluated by ESD immunity tests. The latter should provide a basic immunity design for planning communication devices and electronic equipment.

Then, at first, we examined the rise time of the transients using distributed-constant transmission lines to observe the transition durations, because the transients due to low voltage gap discharges are very rapid. It was confirmed that transient rise times for the transition duration were 32 ps or less with a 12 GHz experimental system [8]. Voltage gradients of gap breakdown were also investigated to validate the very fast transition durations of about 32 ps. Gap length characteristics were measured and then the voltage gradient was calculated by the gap length. The voltage gradient was found to be about 80 MV/m when the ESD occurred at low voltages below 350 V. It should be noted that in such the low voltage ESD, the voltage gradient level is higher than in normal discharge ESDs [9], [10].

Besides, the relationship between voltage gradients and EM radiation was investigated experimentally [11]. We then confirmed that the antenna received voltages of EM radiation is in proportion to the voltage gradient in the gap of electrodes, although they are affected by surface roughness of the gap electrodes [12]. These are results obtained by using a resonance system of discharge electrodes having a dipole-like configuration [13], [14]. We then attempted to examine the EM radiation in more wideband region using spherical electrodes. The amplitudes of antenna received voltages was found to be linearly in proportion to diameters of the spherical electrodes, while they are not always in proportion linearly to surface areas of the spherical electrodes. This implies that the received voltage of EM waves has an upper limit due to the increase of the electrode surface areas [15]. Furthermore, directivity and polarization of EM field radiation due to low voltage ESDs in a sphere-electrode gap was examined experimentally to reveal that the ratio of the directivity between front and side values was about 18 dB [16]. To clarify the radiation factors and excitation mechanisms for the above-mentioned EM radiation, we investigated experimentally polarization effects due to ESDs from a pair of spherical electrodes. Characteristics of
electromagnetic radiation are similar to a polarization effects of radiation from a dipole antenna model. The antenna efficiency decided by electrode configurations is one of important factors for EM radiation in the ESD [17].

In this paper, we investigated experimentally to clarify the excitation mechanisms for the electromagnetic radiation caused by the low voltage ESDs in a pair of spherical electrodes. The time durations of received voltage waveforms due to electromagnetic radiation caused by discharge were measured by using very wideband experimental system of 18 GHz band width. Furthermore, frequency spectra of transient electromagnetic wave caused by electrostatic discharge in spherical electrode were examined to clarify the relation between electromagnetic radiation and electrode size.

II. EXPERIMENTAL SETUP

Figure 1 shows an experimental system to measure the received voltages due to transient electromagnetic radiation in a pair of spherical electrodes. The system consists of a pair of spherical electrodes, a high voltage D.C. power supply (HAMA-MATSU C3350, ±0-3 kV), high resistance lines, a horn antenna (ETS 3115, 1-18 GHz) and a digital oscilloscope (Tektronix DPO72004B, 20 GHz, 50 GS/s) for wide band measurements. In this experiment, five sizes of electrodes were used. Table 1 shows size of the spherical electrodes of this experiment. Types (a) to (c) were made by brass balls, while types (d) and (e) were aluminum balls. In the experiment, a constant voltage was applied between the electrode gap, and one spherical electrode was approached the other electrode very slowly at about 1 cm/s. In this experiment, the applied source voltage (discharge voltage) was from 400 V to 600 V. The antenna received voltage waveform due to the EM radiation was measured with a 20 GHz bandwidth digitizing oscilloscope when a discharge occurred. The received voltage waveforms may be affected by the antenna factor and wave phase velocity of the double-ridged antenna due to the frequency dependence. In this paper, however, we evaluated the relative relation-ship between discharge parameters and radiation characteristics. For this reason, as long as the same measurement system is used, results obtained for the relative evaluation could be less affected by the antenna factor and the waveguide dispersion effect. The antenna received voltage was expressed as a relative voltage value, which was normalized to the peak-to-peak voltage observed on the oscilloscope. In this study, we did not transform the antenna received voltage to the corresponding accurate value of the electric field intensity.

III. EXPERIMENTAL RESULTS

A. Received Voltage Waveforms

The waveform durations of the antenna received voltages due to EM radiation to clarify the excitation mechanisms in EM radiation. Here we define the waveform duration as the sum of pulse durations in the first and second half cycles. Figure 2 shows waveforms of the received voltages for different electrode sizes. The waveform of a dark blue line is type (a) of the electrode size, a red line is type (b), a green line is type (c), a purple line is type (d), and a light blue line is type (e). To measure the waveform durations, the enlargement of
Figure 2 is shown in Figure 3. As shown in the figure, the \( t_a \) and \( t_e \) are the waveform durations for 19 mm and 100 mm diameters of the electrodes, respectively. We found that the waveform durations were obviously affected by the electrode size. Table 2 shows relation of the electrode size, minimum lengths of current exciting path, propagation time and the waveform duration. The minimum length of current exciting path was defined as a half circumference of the sphere electrode. The propagation time is the time for the charge to move the entire length of the current path. This propagation time, we can be thought of as a time of excitation current with a single discharge in the spherical electrodes.

In the table, the measured waveform durations are about 197 ps in type (a), about 240 ps in type (b), about 286 ps in type (c), about 377 ps in type (d), and about 469 ps in type (e). The waveform durations are related to the electrode size in the minimum current-path length of the electrodes, which is calculated from a path of half circumference of the spherical electrode surface. Figure 4 shows a relationship between the propagation time of electrodes and the waveform duration. A solid line is the approximate curve by fitting, the dotted line is
obtained by approximating by a linear connection on the type (a), (b), and (c). The waveform duration is proportional logarithmically to the electrode diameter. Coefficient of determination of the logarithmic approximation was 0.989. In the electrode about 30.0 mm of type (c) or less, the waveform duration is in linear proportion to a diameter of the electrode, while in the electrode about 50.0 mm or more, the waveform duration is proportional logarithmically to the diameter. The waveform duration is proportional to the excitation-current path-length in diameters of 30.0 mm or less of the spherical electrodes (Type (a), (b), and (c)). However, the waveform duration does not always increases in proportion to the current-path length in the electrodes with diameters of 50.0 mm or more (Type (d) and (e)). This implies that the relationship of the waveform duration and excitation path length can be influenced by the excitation mechanism of the electrodes caused by ESDs.

B. Analysis of the Frequency Spectra

Frequency spectra of transient electromagnetic wave caused by electrostatic discharge in spherical electrode were examined to clarify a relation between the time duration of received voltage and electrode size. Figure 5 shows the frequency spectra of the received voltage waveforms in figure 3. Figure (a), (b), (c), (d) and (e) in the Fig 5 is frequency spectra of the voltage waveform in Type (a) 19.0 mm, Type (b) 24.5 mm, Type (c) 30.0 mm, Type (d) 50.0 mm and Type (e) 100.0 mm, respectively. The resonance frequency shows in the figures when it is considered to be 1/4 wavelength at the current exciting path on the electrode surface. The resonance frequency is 2.5 GHz in Type (a), 1.9 GHz in Type (b), 1.5 GHz in Type (c), 0.9 GHz in Type (d), and 0.5 GHz in Type (e), respectively.

Figure 5 (a), (b) and (c), in the small electrodes has a high frequency component, but the distribution of the frequency spectrum does not match the resonance frequency. On the other hand, the electrodes relatively large in the figure (d) and (e), the distribution of the frequency spectrum is lower, dominant component of the frequency distribution tend to match the resonance frequency. These results are different from the tendency of the characteristic of transition duration in the time domain measurement. Therefore, the relationship of the resonance frequency of the transient electromagnetic wave and the current path length of the electrode surface is not unambiguous. In order to clarify the excitation mechanism, it is necessary to investigate these relationships.

IV. CONCLUSION

We investigated experimentally to clarify the excitation mechanisms for the electromagnetic radiation caused by the low voltage ESDs in a pair of spherical electrodes.

As a results, the waveform duration is proportional to the excitation-current path-length in diameters of 30.0 mm or less of the spherical electrodes. However, the waveform duration does not always increases in proportion to the current-path length in the electrodes with diameters of 50.0 mm or more. On the other hand, the frequency spectrum does not match the resonance frequency in the small electrodes. However, the electrodes relatively large, the dominant component of the frequency distribution tend to match the resonance frequency. In the future, will be discussed in detail these relationships.

REFERENCES