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Characteristics of Spark Gap Voltage Waveforms for Air Discharges of Electrostatic Discharge Guns

***Abstract**. To grasp the characteristics of air discharges of electrostatic discharge (ESD) guns, time-variant spark gap voltage waveforms at low charge voltages are discussed. Through the application of our proposed circuit approach using measured discharge current waveforms and frequency characteristics of an ESD–gun, the time-variant spark gap voltage waveforms for air discharges of an ESD–gun can be estimated. By comparing them with the ones obtained by applying Rompe–Weizel's spark resistance formula, arc discharges following spark were confirmed.*

***Streszczenie.** W celu zrozumienia charakterystyk wyładowań elektrostatycznych w powietrzu wytwarzanych za pomocą generatorów ESD, w pracy omówiono przebiegi napięcia na przerwie iskrowej przy niskich poziomach napięcia ładowania na generatorze. Przebiegi tego napięcia można wyznaczyć proponowaną przez autorów metodą obwodową, która bazuje na pomiarach kształtu prądu wyładowania oraz charakterystyki częstotliwościowej impedancji generatora ESD. Poprzez porównanie tak wyznaczonych przebiegów napięć z otrzymanymi na podstawie zależności na napięcie przeskoku Rompe-Weizel, potwierdzone zostało wystąpienie, po przeskoku iskry, wyładowań łukowych (**Charakterystyki przebiegów napięcia na przerwie iskrowej podczas wyładowań w powietrzu wytwarzanych za pomocą generatorów wyładowań elektrostatycznych**).*

Keywords: ESD–gun, spark gap voltage waveform, spark–resistance formula, equivalent circuit modeling.
Słowa kluczowe: generator ESD, kształt napięcia na przerwie iskrowej, wzór na wytrzymałość przerwy iskrowej, modelowanie obwodowe.

Introduction

Living in the ubiquitous information society, we have been broadly enjoying the benefit of handy high-tech information equipment. However, the electromagnetic (EM) immunity of such equipment has been continuously impairing. In particular, the transient EM fields caused by electrostatic discharge (ESD) events have broadband frequency spectra reached into the GHz region, which can cause serious failures in high-tech information equipment [1, 2].

From this perspective, an immunity test against ESD has been specified by the International Electrotechnical Commission (IEC), and is referred to as IEC 61000-4-2 [3]. According to this standard, an ESD–gun with charge voltages above 2 kV is used to inject a discharge current onto equipment under test (EUT). The current waveform for contact discharges is prescribed in the IEC standard, but that for air discharges is not specified owing to their poor reproducibility. However, air discharges normally accompanied by sparks is believed to allow severer immunity testing and to be more faithful to real ESD phenomena. Note that even at the same test levels, the severity of the above two discharges are not necessarily equivalent.

Furthermore, for decades, it is well known that ESD events with low charge voltages below several kV cause serious failure to high-tech equipment, the mechanism of which remains unknown. To understand the severity of these discharges and to clarify decisive factors that determine their severity, for charge voltages that ranged from 200 V to 15 kV, we measured the discharge currents for air and contact discharges for a commercially available ESD–gun onto an IEC calibration target, which was connected through a 50-Ω coaxial cable to a 12-GHz digital oscilloscope. The result showed that the maximum current rising slope (peak current divided by rise time) can be used as a severity evaluation index for ESD immunity testing, and that air discharges at charge voltages below 1 kV can provide a more severe and reproducible test [4]. At the same time, because air discharges are phenomena related to discharges with sparks from electrically charged objects, it is not easy to measure spark gap voltage waveforms.

In this respect, spark gap voltage waveforms for air discharges of ESD–guns cannot be directly measured using our previously proposed measurement setup that observes discharge current waveforms. Therefore, to understand the spark gap characteristics better, we estimated time-variant spark gap voltage waveforms by applying our previously proposed circuit approach. At the same time, in our previous studies, the rise time of discharge current waveforms at charge voltages below several hundred volts exceeded our measurement limit due to the 12-GHz bandwidth limitation of the oscilloscope used. Therefore, in this study, to obtain spark gap voltage waveforms, discharge current waveforms measured by a real-time digital oscilloscope (bandwidth: 18 GHz, sampling: 40 GS/s) and frequency characteristics of a commercially available ESD–gun measured up to 20 GHz are used.

We also discuss the discharge characteristics by comparing the estimated spark gap voltage waveforms with those calculated by the Rompe–Weizel's spark resistance formula.

Calculation method

Fig. 1 (a) shows a schematic diagram of air discharges for a commercially available ESD–gun onto an IEC calibration target. Here, $i(t)$ is the current injected onto the target, $v_S(t)$ is the time-variant spark voltage, $Z_G(j\omega)$ is the output impedance or internal impedance of the ESD–gun with a charge voltage of 0 V, as seen from the tip electrode of the gun, and $Z_T(j\omega)$ is the injecting-point impedance looking into a contact point of the IEC calibration target.

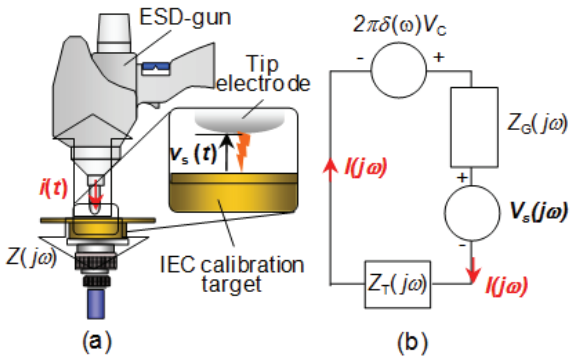

Fig. 1. Schematic diagram (a) and representation of equivalent circuit modeling (b) for air discharge of ESD gun onto IEC calibration target

Fig. 1 (b) shows an equivalent circuit model of air discharges of an ESD–gun in the frequency domain. The circuit consists of a voltage source $V_s(j\omega)$, which simulates a spark; a charge voltage source $2\pi\delta(\omega)V_C$, which represents the Fourier transform of the charge voltage V_C of an ESD–gun, the frequency characteristics of the ESD–gun $Z_G(j\omega)$ and that of the IEC calibration target $Z_T(j\omega)$. When a discharge current waveform $i(t)$ and frequency characteristics of the output impedance of an ESD–gun $Z_G(j\omega)$ are obtained in the time and frequency domain, respectively, the time variant spark gap voltage waveform $v_s(t)$ in the time domain can be estimated as follows:

$$
\begin{aligned}
v_s(t) &= V_C - \frac{1}{2\pi}\int_{-\infty}^{\infty}\{Z_G(j\omega)+Z_T(j\omega)\}\cdot I(j\omega)e^{j\omega t}d\omega \\
&\cong V_C - \frac{1}{2\pi}\int_{-\infty}^{\infty} Z_G(j\omega)\cdot I(j\omega)e^{j\omega t}d\omega \\
&= V_C - \frac{1}{2\pi}\int_{0}^{t}\int_{-\infty}^{\infty} j\omega Z_G(j\omega)\cdot I(j\omega)e^{j\omega\xi}d\omega d\xi.
\end{aligned}
\tag{1}
$$

Here, because $|Z_T(j\omega)|$ is much smaller than $|Z_G(j\omega)|$, the term can be ignored in the calculation. Note that because the output impedance of an ESD–gun contains a DC component, $v_s(t)$ is calculated as shown in the third line of Eq. (1) [5, 6].

Result and discussion

Discharge current waveforms for air discharges of an ESD–gun onto an IEC calibration target are measured by a real-time digital oscilloscope (bandwidth: 18 GHz, sampling: 40 GS/s). In this study, we used a commercially available ESD–gun with the 2m-long earth-return cable (NoiseKen TCP-815P) and its equipped ESD generator, which is a high voltage generator (ESS-2001) [7]. A detailed explanation of the measurement setup can be found in Ref. [7].

Fig. 2 shows an example of the frequency characteristics or the output impedance of a commercially available ESD–gun, as seen from the point edge of the discharge tip electrode of the ESD–gun (measured frequency range: 10 MHz–20 GHz, point: 16001), which was obtained by measuring the reflection coefficient S_{11} with a network analyzer. As a reference, the IEC specification of the ESD–gun at low frequencies (R = 330 [Ω], C = 150 [pF]) are also plotted.

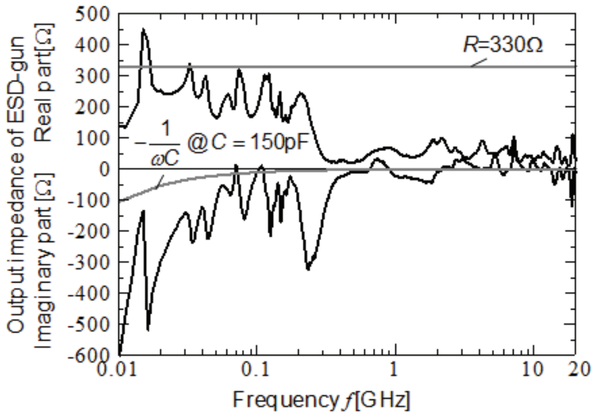

Fig. 2. Frequency characteristics of an ESD-gun (from 10 MHz to 20 GHz)

Fig. 3 shows an example of the estimated spark gap voltage waveforms and typical measured discharge current waveforms for air discharges of an ESD–gun of charge voltage V_C = 1 kV. The upper figures indicate spark gap voltage waveforms and the lower figures represent the measured discharge current waveforms, respectively. The center figures show a magnified section of the top and bottom figures from −2 ns to 3 ns. The thick, solid lines indicate the estimated spark gap voltage waveforms and measured discharge current waveforms. The upper figures show that when a discharge occurs, spark gap voltages do not directly drop to 0 V. There exist residual voltages of approximately 400–500 V for a 1 kV waveform.

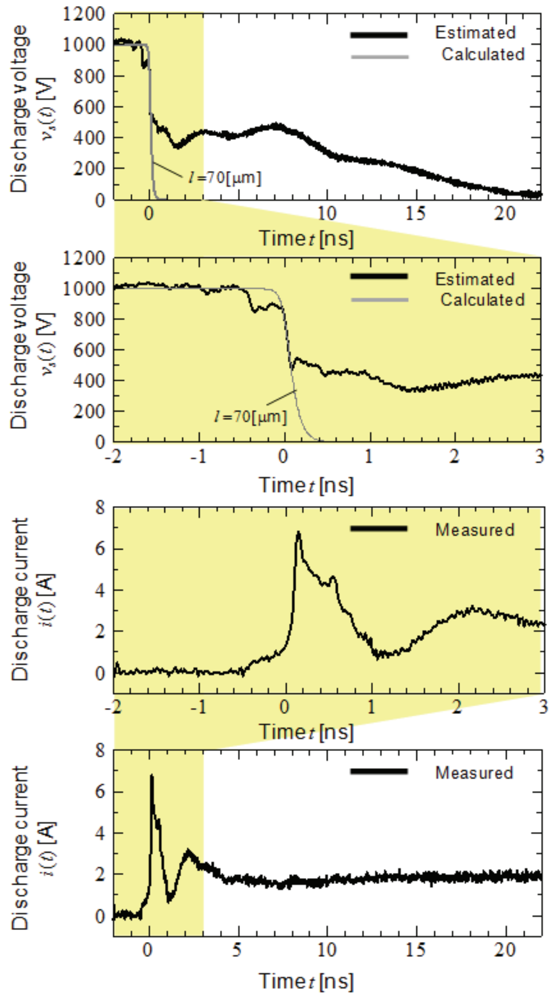

Fig. 3. Examples of estimated and calculated spark gap voltage waveform and typical measured discharge current waveform (V_c = 1 kV)

To determine the discharge characteristics, we calculated spark gap voltage waveforms using the Rompe and Weizel's spark resistance formula, which provides time-dependent spark voltages. With the assumption that the charge accumulated in a stray capacitance between the tip electrode and the target is sufficient to cause a fully grown spark, the time-variant spark gap at atmospheric pressure can be expressed as:

$$
v_s(t) = \frac{V_C}{\sqrt{1+\exp\left\{\frac{1}{2}\left(\frac{V_C}{\alpha l}\right)^2(t-t_0)\right\}}}
\tag{2}
$$

Here, V_C[V] is the charge voltage of the ESD–gun, $\alpha \simeq 67[\mathrm{V\cdot s^{0.5}/m}]$ is the spark constant, l is the spark gap length, and t_0 is the time when the discharge voltage drops from V_C to a specific level [8, 9].

The calculated results for spark gap voltage waveforms using the Rompe–Weizel's formula are shown in Fig. 3 by the thin, gray lines. The spark gap lengths l are chosen so that the falling slopes of the calculated waveforms agree well with those of the estimated ones. For example, they are approximately 70 μm for 1 kV. By comparing the estimated spark gap voltage waveforms with the calculated ones using Rompe–Weizel's spark resistance formula, it was found that after the spark discharges, there exist other types of discharge, which are believed to be arc discharges.

Conclusions

To grasp spark gap voltage waveforms of air discharges for a commercially available ESD–gun, which cannot be directly measured using our previously proposed measurement setup, we estimated the time-variant spark gap voltage waveforms by applying our previously proposed circuit approach. It was found that time-variant spark gap voltage waveforms of air discharges for an ESD–gun can be estimated using our proposed method.

By comparing the estimated spark gap voltage waveforms with those calculated using the Rompe–Weizel's spark resistance formula, it was also found that after the spark there exist arc discharges.

After analyzing and better understanding the discharge mechanism of air discharges of an ESD–gun (especially at low voltages), in future, we aim to evaluate the decisive factors affecting the severity of air discharges of an ESD–gun with low charge voltages, especially of the order of several hundred volts.

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