A New Circuit Approach to Predict Discharge Curents for Air Discharges of ESD Generators

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Abstract. *To predict discharge current waveforms for air discharges of electrostatic discharge (ESD) generators (ESD-guns) used in an IEC immunity test against human ESD, an equivalent circuit modelling for air discharges of ESD-guns is proposed. To simulate spark discharges, two typical spark resistance formulae (Rompe-Weizel's and Toepler's) are applied to the modelling, which consists of a spark voltage source derived from a spark resistance formula, the output impedance of an ESD-gun, and an injecting-point impedance of equipment under test (EUT). For validation, discharge current waveforms for air discharges onto an IEC calibration target in lieu of EUT are calculated to compare with measured waveforms. As a result, it is found that the calculated discharge current waveforms derived from both spark resistance formulae approximately agree with the measured ones, and that Rompe-Weuzel's and Toepler's formulae can better predict their rising slopes and tails, respectively.*

Keywords: Air Discharge, Discharge Current Waveform, ESD-Gun, Equivalent Circuit Modelling, Spark Resistance Formulae

1. Introduction

The transient electromagnetic (EM) fields due to electrostatic discharge (ESD) events have broadband frequency spectra reached in GHz region, which cause serious EMC problems [1-2]. From this perspective, an immunity test against ESD is being specified by the International Electrotechnical Commission (IEC) as the IEC 61000-4-2 [3]. In the standard, an immunity test against ESD events from a charged human body is being prescribed. To simulate the discharge currents from a charged human body, commercially available ESD generators (ESD-guns) are used. The IEC prescribes two types of discharges, or air and contact discharges of ESD-guns. From the viewpoint of reproducibility of the discharge current waveforms, the IEC recommends contact discharges without sparks, while air discharges accompanying sparks should be more faithful to real ESD phenomenon. To evaluate the severity of the immunity test, the authors previously measured discharge currents for both discharges of an ESD-gun onto an IEC calibration target, and showed that below 1 kV air discharges can provide a severer and reproducible immunity test [4]. Regarding the air discharges, however, the characteristics of discharge current waveforms are not yet fully grasped.

In this study, an equivalent circuit modelling is shown to predict the discharge currents for air discharges of ESD-guns. Two typical spark resistance formulae [5][6] are applied as a voltage source which simulates a spark between the tip electrode of the ESD-gun and the discharge target. For validation, calculated discharge current waveforms are compared with measured ones for air discharges onto an IEC calibration target.

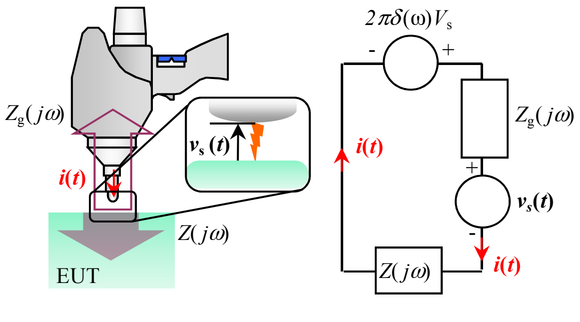

Fig. 1. Schematic diagram (a) and representation of equivalent circuit modeling (b) for air discharges of ESD-gun onto EUT.

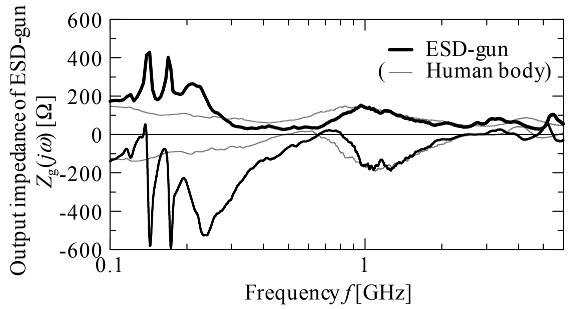

Fig. 2. Measured frequency characteristics of output impedance of ESD-gun.

2. Equivalent ciruit modeling

Fig. 1 (a) shows a schematic diagram for air discharges of an ESD-gun onto EUT. Here, $i(t)$ is a current injected onto EUT, $v_s(t)$ is a time-dependent spark voltage, $Z_g(j\omega)$ is the output impedance or internal impedance of an ESD-gun with a charge voltage of 0 V seen from tip electrode, and $Z(j\omega)$ is the injecting-point impedance looking into a contact point of EUT. If a spark fully grows due to the charge accumulated in a stray capacitance between the tip electrode and the EUT, a spark voltage can be derived in a closed form from a spark resistance formula. Rompe-Weizel's and Toepler's spark resistance formulae provide the following time-dependent spark voltages at the atmospheric pressure:

$$v_s(t) = \frac{V_s}{\sqrt{1+\exp\left\{\frac{1}{2}\left(\frac{V_s}{\alpha\delta}\right)^2 (t-t_0)\right\}}} \quad (1)$$

and

$$v_s(t) = \frac{V_s}{1+\exp\left\{\frac{V_s}{\beta\delta}(t-t_0)\right\}} \quad , \quad (2)$$

respectively. Here, V_s [V] is a charge voltage of the ESD-gun, α and β are the spark constant ($\alpha \approx 67$ [V·s$^{0.5}$/m], $\beta \approx 3.7\times10^{-3}$ [V·s/m]), δ [m] is a spark gap length between the tip electrode of an ESD-gun and EUT [6].

Fig.1 (b) shows an equivalent circuit modelling for air discharges of ESD-guns. The circuit consists of a time-domain voltage source $v_s(t)$ simulating a spark, a frequency-domain charge voltage source which represents the Fourier transform of charge voltage V_s of an ESD-gun or $2\pi\delta(\omega)V_s$, $Z_g(j\omega)$ and $Z(j\omega)$. The discharge current $i(t)$ is derived from the figure as

$$i(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \frac{2\pi\delta(\omega)V_s - F\left[v_s(t)\right]}{Z_g(j\omega)+Z(j\omega)} e^{j\omega t} d\omega = \frac{V_s}{Z_g(0)+Z(0)} - \frac{1}{2\pi}\int_{-\infty}^{+\infty} \frac{F\left[v_s(t)\right]}{Z_g(j\omega)+Z(j\omega)} e^{j\omega t} d\omega$$

$$= \frac{V_s}{Z_g(0)+Z(0)} - \frac{1}{2\pi}\int_{-\infty}^{t}\int_{-\infty}^{+\infty} \frac{F\left[\frac{dv_s}{dt}\right]}{Z_g(j\omega)+Z(j\omega)} e^{j\omega t} d\omega\, dt. \quad (3)$$

Here, $F[\ ]$ indicates the Fourier transform. $Z_g(j\omega)$ is obtained from measuring the reflection coefficient S_{11} with a network analyzer (an example is shown in Fig. 2 with a human body impedance when a human holds the tip electrode for air dischargers in his hand [7]).

3. Result and discussion

Figs. 3 (a) and 3 (b) show examples of calculated discharge voltage waveforms from Rompe-Weizel's spark resistance formula (Eq. 1) and Toepler's one (Eq. 2), respectively. The charge voltage is 1 kV. In the figures of the discharge current waveforms, the waveforms measured with a 12-GHz digital oscilloscope are also shown with thick solid lines [4]. As a discharge target, we used a commercially available calibration target or a current detector (Schaffner: MD102). The discharge current waveforms injected into the target were observed as voltage waveforms appearing across a 50-Ω termination load of the digital oscilloscope. Thin solid lines indicate discharge current waveforms calculated from Eq. 3. We chose spark gap length δ so that the peak currents match the measured waveforms (δ = 78 [μm] for Rompe-Weizel's,

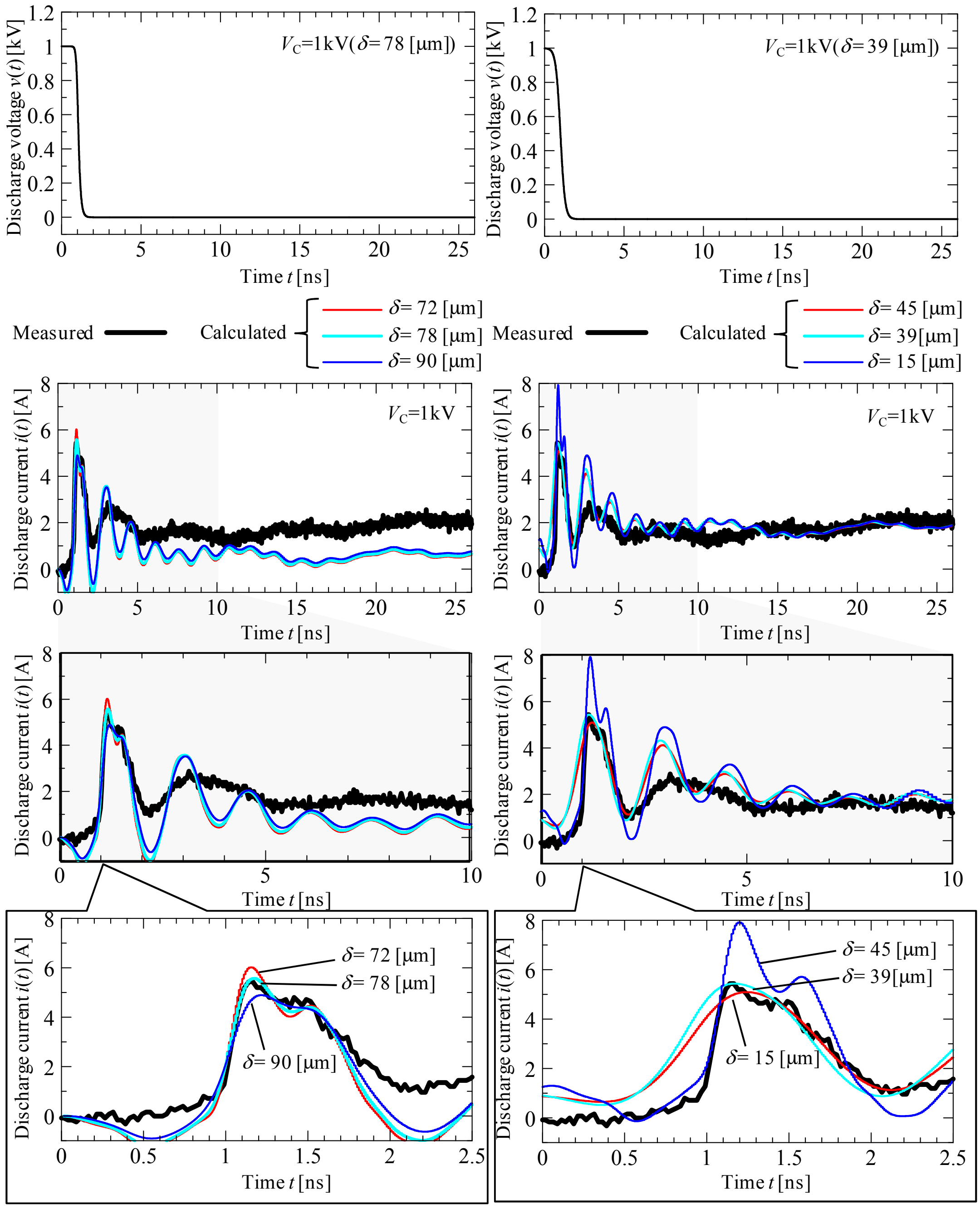

Fig. 3. Examples of discharge voltage and current waveforms calculated by spark resistance formulae, Rompe and Weizel (a) and Toepler (b).

and δ = 39 [μm] for Toepler's, respectively). The lower figure is an enlarged view of the calculated waveforms. In our measurement set-up, the spark gaps δ cannot be measured directly and therefore the values were determined as the calculated waveforms agree with the measured ones.

Regarding Rompe-Weizel's, when the length of 78 [μm] is chosen as the spark gap δ, the calculated waveform agrees well with the measured one especially for its rising slope. As a reference, examples of δ= 72 and 90 [μm] are also plotted. Regarding Toepler's, on the other hand, the length of 39 [μm] chosen as the spark gap δ provides good agreement between the calculated and measured waveforms especially for their tails. As a reference, examples of δ= 15 and 45 μm are also plotted.

4. Conclusion

An equivalent circuit modelling for air discharges of an ESD-gun was proposed, which includes a time-dependent spark voltage source derived from Rompe-Weuzel's formula or Toepler's one. The modelling was validated by comparing the calculated waveforms with the measured ones onto the IEC calibration target. As a result, we found that the calculated discharge current waveforms for air discharges agree with measured ones. It was also found that Rompe-Weuzel's and Toepler's formulae can better predict rising slopes and tails of the waveforms, respectively.

Our future task is to confirm the feasibility of the circuit modelling for air discharges of ESD-gun with different charge voltages especially low charge voltages below 1 kV.

Acknowledgements

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