Derivation of Spark Transients from Finger Touch

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***Abstract*— Electrostatic discharges (ESDs) due to finger touch from a charged human with low charge voltages below 1000 V cause a fatal EM malfunction in high-tech information equipment. To investigate a mechanism of such human ESDs, using a 12-GHz digital oscilloscope, we previously measured discharge currents through a hand-held metal bar or a fingertip with/without an aluminum foil attachment from a human body electrified at a charge voltage of 600V. The results demonstrated that the hand-held metal bar and aluminum foil attachment produce a one-shot discharge current with steeply rising time shorter than a hundred picoseconds, while the fingertip causes multiple-shot discharge currents with significantly low amplitudes. In this study, to model the above spark transients, we derived the discharge currents and the corresponding discharge voltages, which were compared with the measurement to reveal that one-shot discharge currents can approximately be calculated from a stepwise change of the discharge voltages, and each of multi-shot discharge currents can roughly be obtained also as a stepwise response to the corresponding discharge voltage.**

Key words: Human ESD, finger touch, spark transients, derivation.

I. Introduction

Human electrostatic discharges (ESD) are known as one of major EM noises since they produce transient EM fields with broadband frequency spectra. The ESD of this kind is also known to give EM failures to electronic information equipment [1-2], while its mechanism remains unknown.

In this context, an ESD-immunity test is being prescribed by the International Electro-technical Commission (IEC). Based on the ESD events from charged human bodies, a detailed discharge current is being specified in the IEC 61000-4-2 [3], and is injected on electronic equipment under test in contact with an ESD generator or ESD-gun with charge voltages over 2000 V. The ESD gun consists of a lumped resistor and capacitor corresponding to the skin resistance and human-body capacitance, respectively.

In actual human ESD events, however, charges distributed on the body surface are discharged through a spark, whose situation largely differs from that of the ESD-gun. Furthermore, it has widely been accepted that the lower voltage ESD events cause a more serious failure in high-tech information equipment, while its mechanism is not also clarified.

To investigate such human ESD events, with a 6-GHz digital oscilloscope, we previously measured discharge currents through a hand-held metal bar or a fingertip from a charged human body with charge voltages below 1000 V [4][5]. The results indicated that the hand-held metal bar produces discharge currents consisting of the first currents with rapidly rising time shorter than a hundred picoseconds and the second currents with slowly falling time, which are roughly similar to the IEC specified current except its rise time (700-1000ps), and also that the forefinger causes multiple discharge currents with significantly low amplitudes, which are entirely different from the IEC specified current waveform. In order to further understand the above spark transients, using a 12-GHz digital oscilloscope, we also measured discharge currents through a hand-held metal bar or a fingertip with/without an aluminum foil attachment from a human body with a charge voltage of 600V [6]. As a result, it was confirmed that the hand-held metal bar and aluminum foil attachment produce a one-shot discharge current with steeply rising time shorter than a hundred picoseconds, while the fingertip causes multiple-shot discharge currents with significantly low amplitudes.

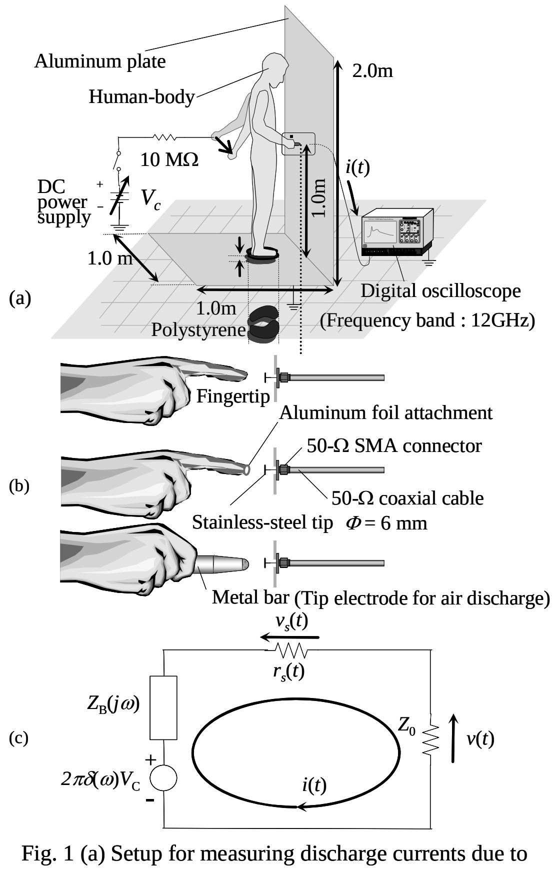

Fig. 1 (a) Setup for measuring discharge currents due to finger touch, (b) detailed description of finger touch and (c) equivalent circuit model for discharge current.

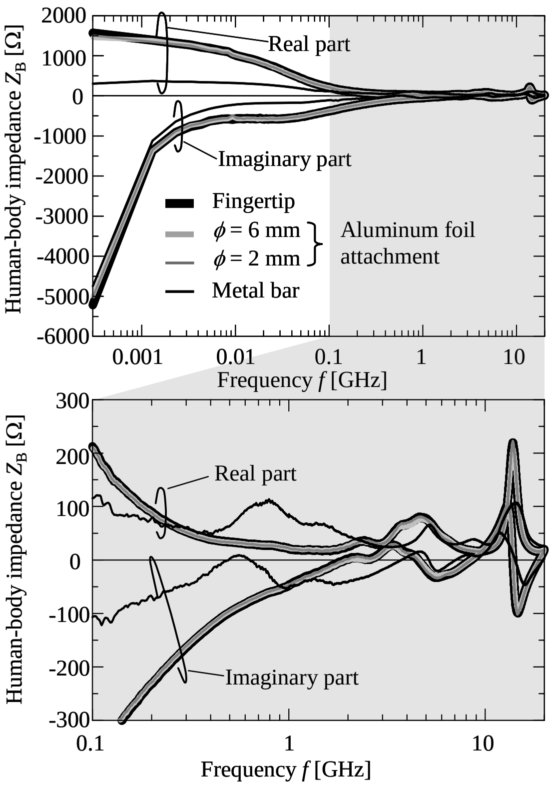

Fig. 2 Frequency characteristics of human-body impedance with/without a hand-held metal bar or fingertip with an aluminum foil attachment.

In this study, to explain the behavior of the above spark transients, we derive the discharge currents and the corresponding discharge voltages from an equivalent circuit we previously proposed for the discharge currents [7].

II. METHOD

Figure 1(a) shows an experimental setup for measuring the discharge current due to the approach of a fingertip with/without aluminum foil attachments or a hand-held metal bar from a charged human body [6], the detailed description of which is shown in Figure 1(b). For the metal bar, we used a stainless tip electrode with a curvature of 4 mm (8 mm in diameter), which is being employed as a current injection electrode of an ESD-gun. An aluminum plate (1m-by-2m) was placed as a ground vertically on a square aluminum plate with a side of 1m. As can be seen in Figure 1(a), a 50-Ω SMA connector was fixed at the center of the vertical aluminum plate, which was connected through a coaxial cable with a characteristic impedance of Z_0 (=50Ω) to a digital oscilloscope with a frequency band of 12 GHz and a sampling frequency of 40 GHz. For easy contact, a small circular metal plate (target) with a diameter of 6mm was attached to the inner conductor of the SMA connector.

After a subject (male, height: 172 cm, weight: 61 kg) standing on form polystyrenes was charged to a voltage of V_C =600 V through a resistor of 10 MΩ from a DC power supply, the forefinger was approached the target from about 6 cm distance. The approaching speed was taken as 2.0 cm/s. When a spark occurs between the fingertip and the target, the resultant discharge current $i(t)$ flows through the SMA connector into the coaxial cable. We measured discharge currents $i(t)$ through a fingertip with /without an aluminum foil attachment or a hand-held metal bar, and examined the effect of the aluminum foil size on discharges through a fingertip in conjunction with the corresponding discharge voltages, which will be described later. Two circular foils with 2mm and 6mm in diameter were used for the fingertip attachment.

Figure 1(c) shows an equivalent circuit model for the discharge currents, which was previously developed by our group [7]. In the figure, $i(t)$ is the discharge current, $r_s(t)$ is the time-varying spark resistance, and $v_s(t)$ is the discharge voltage appearing between the fingertip/metal bar and the target just before contact. $\delta(\omega)$ and $2\pi\delta(\omega)V_C$ are the delta function and the Fourier transform of a charge voltage V_C, respectively. $Z_B(j\omega)$ is the impedance of a human body seen from the fingertip/hand-held metal bar. From the equivalent circuit, the discharge current $i(t)$ can be expressed as

$$\left.\begin{aligned} i(t) &= \frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\frac{V_c - v_s(\varsigma)}{Z_0 + Z_B(j\omega)}\cdot e^{j\omega(t-\varsigma)}d\omega d\varsigma \\ &= \frac{1}{2\pi}\int_{-\infty}^{+\infty}\frac{2\pi\delta(\omega)V_c}{Z_0 + Z_B(j\omega)}\cdot e^{j\omega t}d\omega \\ &\quad - \frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\frac{v_s(\varsigma)}{Z_0 + Z_B(j\omega)}\cdot e^{j\omega(t-\varsigma)}d\omega d\varsigma \\ &\simeq -\frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\frac{v_s(\varsigma)}{Z_0 + Z_B(j\omega)}\cdot e^{j\omega(t-\varsigma)}d\omega d\varsigma. \end{aligned}\right\} \quad (1)$$

If the fingertip/hand-held metal bar could touch the target without any discharges just like an ideal switch, the discharge voltage $v_s(t)$ should change stepwise from V_C to zero, which yields from Equation (1)

$$\begin{aligned} i(t) &\simeq -\frac{1}{2\pi}\int_{-\infty}^{+\infty}\frac{\pi\delta(\omega)V_c - \dfrac{V_c}{j\omega}}{Z_0 + Z_B(j\omega)}\cdot e^{j\omega t}d\omega \\ &= \frac{1}{2\pi}\int_{-\infty}^{+\infty}\frac{1}{Z_0 + Z_B(j\omega)}\cdot\frac{V_c}{j\omega}\cdot e^{j\omega t}d\omega. \end{aligned} \quad (2)$$

In this case, the discharge current can be predicted from the measured frequency characteristics of human-body impedance $Z_B(j\omega)$.

Concerning the discharge voltage $v_s(t)$, which is basically unable to be measured, from the equivalent circuit shown in Figure 1(c), we can estimate it from the measurement of a discharge current and a human body impedance [7], which can be given by

$$\left.\begin{aligned} v_s(t) &= r_s(t)\cdot i(t) \\ &= V_C - Z_0 \cdot i(t) \\ &\quad - \frac{1}{2\pi}\int_0^t \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} j\omega \cdot Z_B(j\omega)\cdot i(\xi) \\ &\quad \times e^{j\omega(t-\xi)} d\xi d\omega dt. \end{aligned}\right\} \quad (3).$$

III. RESULTS AND DISCUSSION

Figure 2 shows the frequency characteristics of human body impedance, which were obtained from scattering parameters S_{11} from 300 kHz to 20 GHz with a network analyzer. Also shown in the lower figure is an enlargement of the frequency characteristics from 100 MHz to 20 GHz. The results show that the human body impedance through a fingertip well agrees with those through aluminum foil attachments with 2 mm and 6 mm in diameter, while it does not agree with the human body impedance through a hand-held metal bar.

Figure 3(a) shows a discharge current through a hand-held metal bar with a charge voltage of 600 V. Also shown in the lower figure is an enlargement of the rising part of the current waveform. Solid line represents the measured waveform. Gray and dotted lines represent calculated waveforms from Equation (2) with V_C =600 V and V_C =600-175=425 V, respectively, which will be described later. Figure 3(b) shows the discharge voltage estimated from Equation (3). These figures show that the hand-held metal bar produces a one-shot discharge current with steeply rising time shorter than a hundred picoseconds, and the corresponding discharge voltage abruptly changes from the charge voltage (600 V) to a certain voltage and then reaches an almost constant voltage (80 V), which may be other types of discharges like glows or arcs. It is also shown that the gray line is larger than the measured discharge current, while the dotted lines approximately agree with the measured one. It should be noted that there are some discrepancies between the falling parts of the measured and calculated results, which may be due to the other types of discharges following a spark.

Figures 4(a) and 4(b) show discharge currents through aluminum foil attachments with a charge voltage of 600 V and the estimated discharge voltages, respectively. The results show that the aluminum foil also produces a one-shot discharge current, whose rising part is roughly similar to the case for the hand-held metal bar. It was also shown that the peaks of discharge currents through a fingertip increase with the foil size, and the fingertip with an attachment of an aluminum foil with a diameter of 6mm gives almost the same discharge currents as the first discharge currents from the hand-held metal bar. Furthermore, it was observed that the discharge voltages abruptly fall from the charge voltage to certain remaining voltages due to the other types of discharges following a spark, which decrease with increasing the foil size. These results imply that the growth of a spark itself can be affected mainly by the amount of charges accumulated in the stray capacitances around the fingertip. It was also shown that the dotted lines calculated from Equation (2) approximately

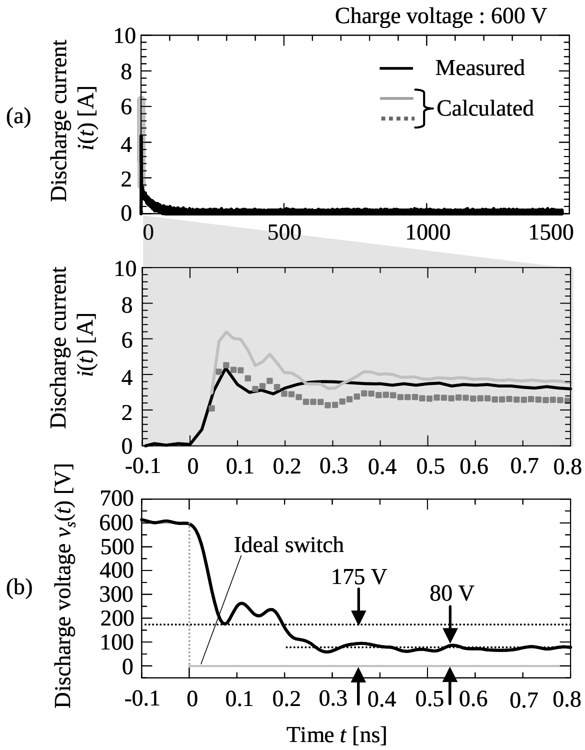

Fig. 3 (a) Measurement of discharge current through a hand-held metal bar, and (b) estimated discharge voltage.

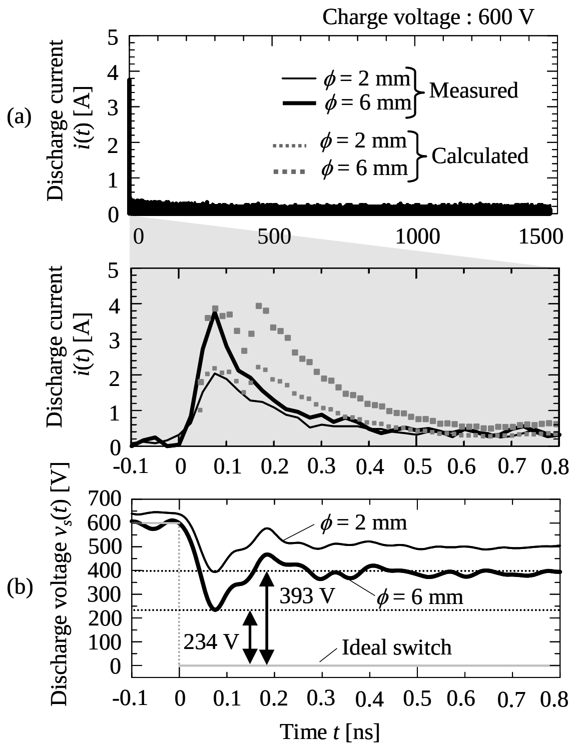

Fig. 4 (a) Measurement of discharge current through a fingertip with an aluminum foil attachment, and (b) estimated discharge voltage.

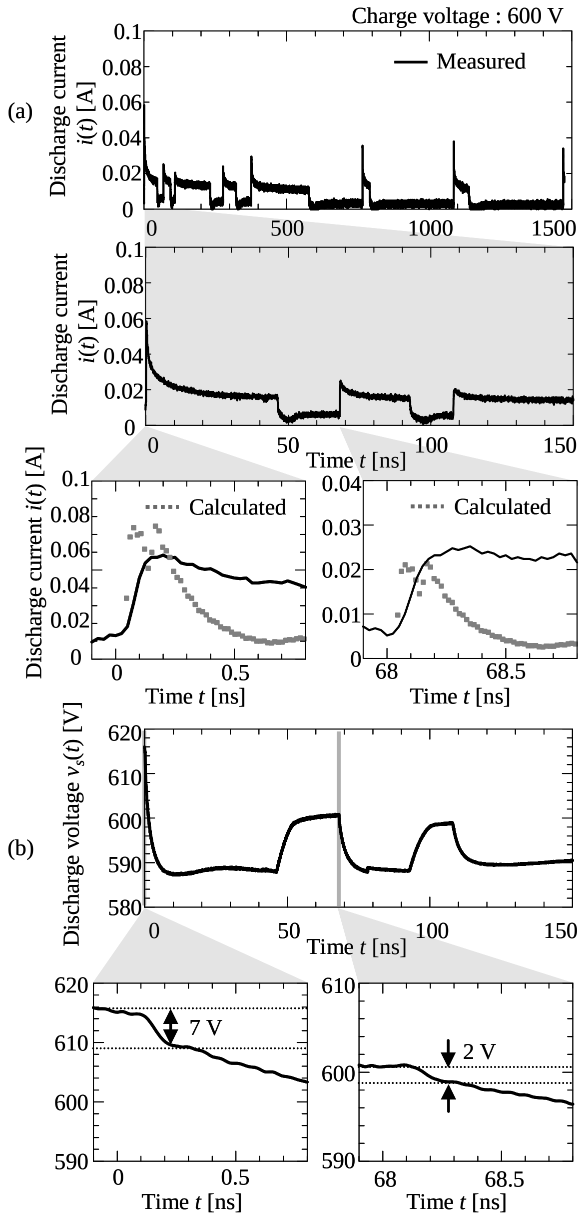

Fig. 5 (a) Measurement of discharge current through a direct fingertip, and (b) estimated discharge voltage.

agree with the measured results, when the charge voltages for the aluminum foil with a diameter of 2 mm and 6 mm substituted V_C =600-234 = 366 V and V_C =600-393 = 207 V, respectively. These results show that the discharge currents through a fingertip with an aluminum foil attachment can also be obtained as a stepwise response from a charge voltage to the remaining voltage resulting from the spark.

Figure 5(a) shows discharge currents through a fingertip with a charge voltage of 600 V. Also shown in the lower figures are enlargements. Figure 5(b) shows the estimated discharge voltages corresponding to the discharge currents. The results show that the fingertip produces multiple-shot discharge currents with fast rising time and significantly low amplitudes, which are entirely different from the cases for the hand-held metal bar and aluminum foil attachments. It is also shown that the corresponding discharge voltage abruptly changes. Dotted lines in the figure for the first and second discharge current waveforms are the calculated results from Equation (2) with V_C = 7 V for the first current and V_C = 2 V for the second current, which shows that there is fair agreement between the calculated and measured results around the first and second current transients, though the falling parts of the dotted lines do not agree with the measured waveforms due to other types of discharges falling gently as shown in the enlargement of Figure 5(b).

IV. Conclusion

To explain the behavior of spark transients due to human ESD events, we have derived the discharge currents and the corresponding discharge voltages through a hand-held metal bar or a fingertip having an aluminum foil attachment from a human body with a charge voltage of 600V, and have estimated the corresponding discharge voltages. In comparison of the measured discharge currents with a 12-GHz digital oscilloscope, we have found that although the hand-held metal bar and aluminum foil attachments produce a one-shot discharge current with steeply rising time shorter than a hundred picoseconds, the discharge currents can be calculated from a stepwise change of the discharge voltages. For the discharge through a fingertip without aluminum foil attachments, on the other hand, the results show that the fingertip produces multiple-shot discharge currents with fast rising time and significantly low amplitudes, while each of the current burst transients can roughly be calculated as a stepwise response to the corresponding discharge voltages.

The future task is to clarify a mechanism of burst spark transients due to finger touch with respect to charge voltages.

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