Near-Field Coupling of Transient Electromagnetic Field by Small Gap Discharge to a Transmission Line

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Summary

Induced output voltages of a transmission line by the transient near-field generated by a small gap discharge are calculated from the discharge current with the parameters of line length and the distance between the source and the line. The calculation is performed by using the coupling theory based on S-parameters which is applicable to microwave frequencies. The measured outputs agree well with the calculated ones.

key words: Electrostatic discharge, Transmission line, EM coupling, Near field

1 Introduction

Electrostatic discharge (ESD) is one of the serious noise sources to electronic equipment. Recently, various studies related to the ESD have been reported(1)–(9). It has been reported that the indirect ESD often interferes with equipment much more than the direct ESD when the indirect ESD occurs at a distance less than 1 meter from electronic equipment (1),(2). The immunity of recent electronic equipment such as a microcomputer to fast transient fields generated by an ESD event tends to be degraded because the equipment runs faster and lower power-consumption than the former. Therefore, studies concerning errors on the equipment owing to the ESD field are needed for the increase in the immunity to the ESD field. As a first step of those studies, transient response of output voltage of a transmission line coupled with near-field by the ESD event should be estimated and measured.

Near-fields radiated by a small gap discharge which simulates an ESD event has been evaluated and measured.(9) In the study, a model is proposed that the real electric and magnetic fields radiated from the discharge instrument may consist of two kinds of radiation. One radiation is generated by the neutralization of the initial static charges on the electrodes. Since the “neutralization” current cannot be measured by the current sensor with the usual structure, it was evaluated from the electromagnetic fields near the electrodes(9). Another radiation is made from a current which flows through a rod electrode. The “electrode” current can be measured by the current sensor.

It has been pointed out that output voltages of a transmission line can be evaluated only from the current measured by the current sensor in the far fields where the line is sufficiently distant from a gap (11). On the other hand, when the transmission line is near the radiation source, the output voltage of the transmission line should be calculated from the two source, the neutralization current and the electrode current, because the near-field terms of the both fields are not negligible at the transmission line.

In this paper, induced output voltages of a transmission line by the near-field due to the small gap discharge are calculated from the two source with the line length and the distance between the electrode and the line as parameters. The calculation is performed by using a coupling theory based on S-parameters which is applicable to microwave frequencies(12). The output voltages are measured using a waveform measuring system. The evaluated and the measured outputs are compared.

2 Electromagnetic fields by small gap discharge

Radiations from the small gap discharge which simulate the ESD event are illustrated in Fig. 1(9),(10).

The radiation due to the neutralization current occurs from the gap at the moment of the discharge. This radiation acts as the short electric-dipole. The field results from the current $i_c(t)$ generated by the neutralization of the initial static charges on the electrodes. However, the current $i_c(t)$ can not be measured by the current sensor with the usual structure because the current $i_c(t)$ does not flow into the resistors of the current sensor.

The radiation due to the electrode current is made from a current $i_e(t)$ which flows through a mostly short-circuit path. These fields contain the term $r^{-1}$ in the electric fields and the term $r^{-2}$ and $r^{-1}$ in the magnetic fields because the field are mainly made from a vector potential(10),(12) caused by the current $i_e(t)$. The current $i_e(t)$ can be measured by the current sensor.
Thus, the electric field \( E(t) \) and the magnetic field \( H(t) \) at the observing point in Fig. 1 may be expressed as \(^{10}\):

\[
E(t) = E_c(t) + E_s(t) \tag{1}
\]

\[
H(t) = H_c(t) + H_s(t) \tag{4}
\]

where \( \mu_0 \) and \( c \) are the vacuum permeability and the speed of light in air, respectively. \( E_c \) and \( H_c \) are the electric and magnetic fields caused by the neutralization of the charges, respectively. \( E_s \) and \( H_s \) are the electric and magnetic fields from the rod electrode, respectively. It is assumed that the short-dipole length \( d_s \) is the sum of the gap length \( d_g \) and the semi-sphere radius (1.15 mm) of the rod electrode. In (3) and (6), the plus and minus sign of \( i_s(t - \frac{r \pm s}{c}) \) correspond to the forward and the reverse current direction with increasing \( z \), respectively.

**3 Measurement of electrode current**

The equipment for measuring electric fields, \( E(t) \), magnetic fields, \( H(t) \), and electrode currents \( i(t) \) mainly consist of a discharge apparatus, a current sensor, a waveform-measuring instrument and field sensors as shown in Fig. 2 \(^{9,10}\). The discharge apparatus, the current sensor and the field sensors (the monopole antenna and the half-loop antenna \(^{10}\)) are set on a 4-square-meters groundplane. The discharge apparatus consists of a DC high-voltage source, a capacitor (150 pF) and a metal-rod electrode whose end is hemisphere in shape. A discharge occurs between the rod-end and a disk electrode of the current sensor whose diameter is 8 mm. The disk electrode is nearly the Rogowski type in shape. The discharge is not a corona but a spark discharge because an impartial electric field is generated between two electrodes. A type of discharge is determined from the size and the shape of electrodes and the gap length.

The waveform-measuring instrument mainly consists of a delay line, a broadband amplifier with a bandwidth of 5.1 GHz and a 4.5 GHz-bandwidth (for sine wave) waveform digitizer (Tektronix SCD5000).

The electrode currents are measured with the gap length of 0.1 mm and with the applied voltage of \( \pm 1 \) kV to the gap.
Fig. 4: Evaluated neutralization current $i_c(t)$.

Fig. 5: Coordinate system for a transmission line and the electrode.

4 Evaluations of neutralization current

Equations (1)-(6) are rewritten using the Fourier transform as

\[
E(\omega) = \frac{\mu_0}{2\pi} \left\{ d_s I_s(\omega) e^{-j\omega t_0/c} \left( \frac{c^2}{j\omega r_0^2} + \frac{c}{r_0} + j\omega \right) + j\omega I_s(\omega) \int_0^d e^{-j\omega r} \frac{1}{r} dr \right\} \quad \cdots (8)
\]

\[
H(\omega) = \frac{1}{2\pi} \left\{ d_s I_s(\omega) e^{-j\omega t_0/c} \left( \frac{1}{r_0} + \frac{j\omega}{c r_0} \right) + J_s(\omega) \int_0^d e^{-j\omega r} \frac{1}{r} \sin \theta dr \right\} \quad \cdots (9)
\]

where

\[
E(\omega) = \mathcal{F}\{E(t)\} \quad \cdots (10)
\]

\[
H(\omega) = \mathcal{F}\{H(t)\} \quad \cdots (11)
\]

and $\mathcal{F}\{}$ denote the Fourier transform.

From (8) and (9), $E(\omega)$ and $H(\omega)$ are the functions of $I_s(\omega)$ and $J_s(\omega)$, respectively. Conversely, $I_s(\omega)$ and $J_s(\omega)$ can be expressed by $E(\omega)$ and $H(\omega)$. If $E(t)$ and $H(t)$ at the same distance $r_0$ are given by the measurement, the neutralization current $i_c(t)$ can be calculated from (8)-(11) as

\[
i_c(t) = \frac{2\pi r_0}{\mu_0 d_s} \mathcal{F}^{-1} \left\{ \frac{j\omega e^{-j\omega t_0}}{h_0 \mathcal{F}\{E(t)\} + \mu_0 \sigma e \mathcal{F}\{H(t)\}} \right\} \quad \cdots (12)
\]

where

\[
e_s = \int_0^d e^{-j\omega r} \frac{1}{r} dr \quad \cdots (13)
\]

The current $i_c(t)$ is calculated by using (12) as shown in Fig.4. A discharge begins at about 1.6ns in this figure. Measured electric field $E(t)$ and magnetic field $H(t)$ are reconstructed from observed sensor outputs by using the complex antenna factors of each sensor (9).

5 Evaluations of output voltage at transmission line terminals

The discharge electrode and the transmission line are located on the coordinates as shown in Fig.5. It is assumed that the transmission line has no loss and sets in the air. Since the electric field and the magnetic field concerned with coupling to transmission line are the $z$-component of the electric field $E_z(t)$ and the $y$-component of the magnetic field $H_y(t)$, respectively (12), $E_z(t)$ and $H_y(t)$ at an arbitrary point of the transmission line are expressed from (1)-(7) as

\[
E_z(t) = -\frac{\mu_0}{2\pi} \left\{ d_s \left( \frac{1}{r_0} \int_0^t \frac{i_c(t)}{r} dt \right) + \frac{c}{r_0} \frac{1}{r} \left( \frac{\partial i_c(t)}{\partial t} \right) + \int_0^d \frac{1}{r} \left( \frac{\partial i_c(t)}{\partial t} \right) dz \right\} \quad (17)
\]

\[
H_y(t) = \cos \phi \left\{ d_s \left( \frac{\partial i_c(t)}{\partial t} \right) + \frac{1}{r_0} \frac{\partial i_c(t)}{\partial t} \right\} + \int_0^d \frac{1}{r} \left( \frac{\partial i_c(t)}{\partial t} \right) \sin \theta dz \right\} \quad \cdots (18)
\]

where

\[
t_c = t - \frac{r_0}{c} \quad \cdots \quad (19)
\]
Matched output voltages at each terminal induced by these fields, \( V_{m1}(t) \) (near the radiator) and \( V_{m2}(t) \) (far the radiator), are given as (12):

\[
v_{m1}(t) = \frac{h}{2} \int_0^l \left( \mu_0 \frac{\partial H_y(t-\frac{z}{c})}{\partial t} - \frac{1}{c} \frac{\partial E_z(t-\frac{z}{c})}{\partial t} \right) dz \tag{21}
\]

\[
v_{m2}(t) = -\frac{h}{2} \int_0^l \left( \mu_0 \frac{\partial H_y(t-\frac{l-z}{c})}{\partial t} + \frac{1}{c} \frac{\partial E_z(t-\frac{l-z}{c})}{\partial t} \right) dz \tag{22}
\]

where \( h \) and \( l \) are the height and the length of the transmission line. The matched output voltages induced by the fields can be calculated from the currents \( i_c(t) \) and \( i_s(t) \) by (17), (18), (21) and (22). The output voltages for arbitrary loads \( R_1 \) and \( R_2 \) are obtained by using the Fourier transform as (12):

\[
v_1(t) = X^{-1} \left[ \frac{(\Gamma_1 + 1)}{1 - \Gamma_1 e^{-2j\beta l}} \cdot \{F\{v_{m1}(t)\} + \Gamma_2 F\{v_{m2}(t)\} e^{-j\beta l}\} \right] \tag{23}
\]

\[
v_2(t) = X^{-1} \left[ \frac{(\Gamma_2 + 1)}{1 - \Gamma_1 e^{-2j\beta l}} \cdot \{F\{v_{m2}(t)\} + \Gamma_1 F\{v_{m1}(t)\} e^{-j\beta l}\} \right] \tag{24}
\]

where \( \Gamma_1 \) and \( \Gamma_2 \) are the reflection coefficients at the loads of the near and the far terminals, respectively. \( \beta \) is the propagation constant in the line.

The output voltages at the near terminal are evaluated in the case that the transmission line and the discharge electrode are set up as shown in Fig.6, where the conditions are:

- characteristic impedance of the line \( Z_0 : 200\Omega \)
- line height \( h : 1.5\text{mm} \)
- line lengths \( l : 25, 50, 100, 200\text{mm} \)
- distances of the line and the electrode \( r_0 : 50, 100, 150\text{mm} \)
- polarity of the electrode : + and –
- load impedance \( Z_l : 50\Omega \)
- short-dipole length \( d_s : 1.25\text{mm} \)
- electrode length \( d : 11.5\text{mm} \).

Typical output waveforms evaluated under the conditions are shown in Fig.7(a)-(d). In each waveform, the first peak has the maximum value and the polarity of the peak is opposite to that of the rod electrode. The second peak exists at 5.5ns after the first peak. The second peak is due to the reflection from the capacitor of the discharge apparatus. Fig.8(a)-(d) shows the output voltages calculated from the neutralization current, \( v_{c1}(t) \) (dotted line), or from the electrode current, \( v_{s1}(t) \) (dashed line), separately. In each case, the risetime of \( v_{c1}(t) \) at the first peak is faster than that of \( v_{s1}(t) \) and the peak width of \( v_{c1}(t) \) is broader than that of \( v_{s1}(t) \). The first peak of \( v_{c1}(t) \) and \( v_{s1}(t) \) are almost equal in value. These results might lead that both ingredients, the output induced by the neutralization current and by the electrode current (\( v_{c1}(t) \) and \( v_{s1}(t) \)), evenly contribute to the first peak value of the total output and that the acuteness of the peak mainly depends on the peak of \( v_{c1}(t) \) in the distances of these calculations (50-150mm).

6 Measurements of output voltage from transmission line

The equipment for measuring output voltages consists of the discharge apparatus, the waveform-measuring instrument and a transmission line as shown in Fig.2. Dimensions of the transmission line are also shown in Fig.2. The output voltages of the transmission line are reconstructed from the observed waveform with the characteristics of the instrument. The conditions in the measurement are the same as those in the evaluations.

Typical measured waveforms are shown in Fig.9 with the evaluated waveform shown in Fig.7 for comparison. The two results agree well in the waveform and in the peak value. However, differences at \( \circ \) in Fig.9 may be due to the reflection of the voltage induced in the vertical line of the near terminal which is not considered in the evaluation.

The first peak values of the evaluated and the measured output voltage with the line length \( l \) are shown in Fig.10(a)-(c). The measurement results roughly agree with those of the evaluation except the case at the plus polarity of \( r_0 = 50\text{mm} \). However, a dispersion of the peak value is not small at the same parameters. One reason for the dispersion may be a poor reproducibility of the discharge. The low reproducibility may be due to the small dust in air and the fluctuation of the atmospheric temperature and humidity.

The peak values do not increase as the increment of the line length, and they approach a constant value at \( l = 50\text{mm} \) over irrespective to the distance \( r_0 \) and the polarity of the electrode. These figures also show that the peak values decrease as the increment of the distance \( r_0 \).

Therefore, these results lead that the evaluations of the
output voltage are appropriate. The output voltages of a transmission line induced by the near-field can be evaluated from the neutralization current and the electrode current.

7 conclusion

Induced output voltages of a transmission line by the near-field produced by the small gap discharge were evaluated from the neutralization current and the electrode current with the line length and the distance between the electrode and the transmission line as parameters. The evaluation was performed by using the coupling theory based on S-parameters which is applicable for microwave frequencies.

The measured outputs of the transmission line were compared with the estimated ones. As the results:

- The peak values of the output do not increase as the increment of the line length. They approach a constant value irrespective of the distance \( r_0 \) and the polarity of the electrode.
- The output voltages of a transmission line induced by the near-field can be evaluated from the neutralization current and the electrode current.
In future work, a direct method for measuring the current caused by the neutralization of the initial charges should be developed.

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References

Near-Field Coupling of Discharge


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