Analysis of Cable Discharge Events (CDE)

William D. Greason, Fellow, IEEE

Abstract - A basic model is developed to simulate cable discharge events. Parameters studied are cable characteristics including length, surface charge density due to triboelectrification and mode of termination. Typical results are presented giving peak current and polarity, discharge time constants and energies.

Index Terms - CDE, electrostatic discharge (ESD), model

I. INTRODUCTION

Cable discharge events (CDEs) are a major cause of failures on communications interfaces [1-4]. Cable insulation becomes charged by triboelectrification when it is pulled through conduits during the installation process. Charge, by the induction process, flows when the cable is terminated at the interface to electronic equipment. CDEs are characterized as high current, high energy, extremely fast phenomena which pose a major reliability issue to semiconductor devices.

II. OBJECTIVES

The objective of this work is to develop a basic model to permit simulation of cable discharge events. Preliminary experimental work is done to evaluate the triboelectrification properties of Cat5 Ethernet cable. Results of calculations are presented which assess the effect of surface charge density, cable characteristics, cable length and termination.

III. THREE BODY PROBLEM

A typical Cat5 cable consists of four twisted pairs of conductors with polyolefin insulation enclosed in a polyvinylchloride (PVC) jacket. Nominal electrical characteristics are (i) capacitance: 15 pF/foot (ii) resistance: < 188 Ω/km. Each twisted pair consists of two AWG24 conductors (diameter: 0.020") each with an insulation outside diameter of 0.038". The outside diameter of the jacket varies from 0.020" to 0.025" with a nominal wall thickness of 0.020" In this study, one twisted pair inside the jacket will be modelled as shown in Figure 1. Body 1 is a segment of the charged insulation, body 2 is the ground conductor (when terminated at the equipment) and body 3 is the signal conductor (when terminated at the equipment).

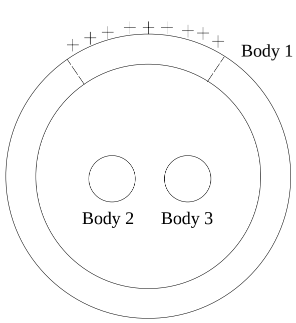

Figure 1: Three body model for CDE

Maxwell's method to formulate multi-body capacitances for a system of conductors [5] can be used to study the model. Body 1, the charged cable jacket acts as an electric flux source; it will be assumed that the flux from this source terminates solely on the two system conductors in the twisted pair with no flux terminating on any external grounds.

The system equations are:

$$Q_1 = c_{11}V_1 + c_{12}V_2 + c_{13}V_3 \quad (1)$$

$$0 = c_{12}V_1 + c_{22}V_2 + c_{23}V_3 \quad (2)$$

$$0 = c_{13}V_1 + c_{23}V_2 + c_{33}V_3 \quad (3)$$

A coefficient of self capacitance is of the form c_{ii} and is defined as the charge on body i when body i is raised to a potential of 1 V with all other conductors in the system grounded. A coefficient of mutual capacitance is of the form c_{ij} and is defined as the charge on body j when body i is raised to a potential of 1 V and all other conductors (including j) are grounded. Thus, c_{ii} is the amount of flux per volt from conductor i with all other conductors grounded while c_{ij} is the amount of flux per volt from body i which terminates on body j. Coefficients of self capacitance are positive; coefficients of mutual capacitance are negative or zero since an induced charge is opposite in polarity to the inducing charge.

Maxwell's method gives a complete solution to the generalized three body ESD problem since it includes the effect of any electric flux coupled to ground planes. A comparison of Maxwell's approach employing capacitance coefficients and the engineering approach using conventional lumped element capacitors has been presented [6]. For clarification purposes, consider a lumped element equivalent circuit for a general two body problem. C_{10} is the capacitance to ground of body1, C_{20} is the capacitance to ground of body2 and C_{12} is the capacitance between the two bodies. More exactly, C_{10} represents that portion of the electric flux associated with the charge on body 1 which terminates on ground, C_{12} represents that portion of the electric flux associated with the charge on body 1 which terminates on body 2, while C_{20} represents that portion of the electric flux associated with body 2 which terminates on ground.

The transformation between the system of capacitance coefficients and the lumped element capacitors can be expanded for the general three body problem. The following relations apply for capacitance coefficients and the lumped element capacitors. $c_{11} = C_{10} + C_{12} + C_{13}$; $c_{22} = C_{20} + C_{12} + C_{23}$; $c_{33} = C_{30} + C_{13} + C_{23}$; $C_{12} = -c_{12}$; $C_{13} = -c_{13}$; $C_{23} = -c_{23}$; $C_{10} = c_{11} + c_{12} + c_{13}$; $C_{20} = c_{22} + c_{12} + c_{23}$, $C_{30} = c_{33} + c_{13} + c_{23}$.

If conductor 2 is grounded, the induced charge Q_2 can be calculated. The system equations become:

$$Q_1 = c_{11}V_1 + c_{13}V_3 \tag{4}$$

$$Q_2 = c_{12}V_1 + c_{23}V_3 \tag{5}$$

$$0 = c_{13}V_1 + c_{33}V_3 \tag{6}$$

From (6),

$$V_3 = -\frac{c_{13}}{c_{33}} V_1 \tag{7}$$

Substituting into (4) yields:

$$V_1 = \frac{Q_1}{[c_{11} - c_{13}^2/c_{33}]} \tag{8}$$

Solving for Q_2 yields:

$$Q_2 = Q_1 \frac{[c_{12}c_{33} - c_{13}c_{23}]}{[c_{33}c_{11} - c_{13}^2]} \tag{9}$$

Let the electric flux from body 1 be linked equally to body 2 and body 3. Then:

$c_{11} = C_{12} + C_{13}$; $c_{22} = C_{12} + C_{23}$; $c_{33} = C_{13} + C_{23}$; $c_{12} = - C_{12}$; $c_{13} = - C_{13}$; $c_{23} = - C_{23}$.

Then:

$$Q_2 = -Q_1 \tag{10}$$

This shows that during the grounding of conductor 2, a charge equal in magnitude and of opposite polarity to the charge Q_1 on the cable jacket is transferred from ground to conductor 2.

If conductor 3 is then grounded, the induced charges Q_2 and Q_3 can be calculated. The system equations become:

$$Q_1 = c_{11}V_1 \tag{11}$$

$$Q_2 = c_{12}V_1 \tag{12}$$

$$Q_3 = c_{13}V_1 \tag{13}$$

It follows that:

$$Q_2 = Q_1 \frac{c_{12}}{c_{11}} \tag{14}$$

$$Q_3 = Q_1 \frac{c_{13}}{c_{11}} \tag{15}$$

After transformation to the lumped element model,

$$Q_2 = - Q_1 \frac{C_{12}}{C_{12} + C_{13}} \tag{16}$$

$$Q_3 = - Q_1 \frac{C_{13}}{C_{12} + C_{13}} \tag{17}$$

The assumption will be made for the symmetrical geometry under consideration that $C_{13} = C_{12}$; then:

$$Q_2 = Q_3 = - \frac{Q_1}{2} \tag{18}$$

This shows that during the grounding of conductor 3, a charge of magnitude - $Q_1/2$ is transferred from ground to conductor 2 and a charge of magnitude - $Q_1/2$ is transferred from ground to conductor 3.

IV. EXPERIMENT

In order to evaluate the triboelectrification properties of Cat5 cables, a basic charging experiment was conducted; the experimental setup is shown in Figure 2. A short length of cable was charged by pulling it mechanically through an inline triboelectrification charger which consisted of a cylinder of material which provided a friction fit against the cable jacket. Sleeves fabricated from polytetrafluoroethylene (PTFE) and aluminum were used in two series of tests. After charging, the cable was pulled through an inline Faraday cage where the total surface charge was measured using a Keithley Instruments model 602 electrometer. The average surface charge density was calculated using the length of the cable in the sensing element of the Faraday cage and the outside diameter of the cable jacket. Five measurements were done for each charger sleeve and the results averaged. Measurements were done in laboratory conditions with T = 25˚C, RH = 35%. The following results were obtained for the average surface charge densities σ developed on the cable jacket.

For PTFE charging sleeve, $\sigma = +0.1\text{x}10^{-8}$ C.cm^{-2}
For aluminum charging sleeve, $\sigma = -0.15\text{x}10^{-8}$ C.cm^{-2}

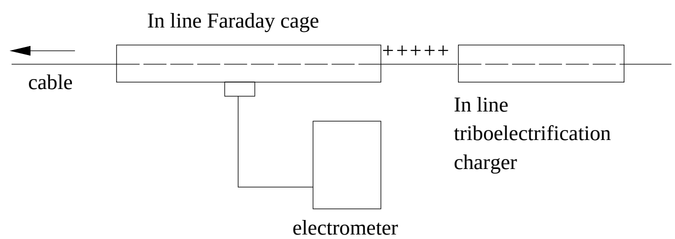

Figure 2: Measurement of cable triboelectrification

The maximum surface charge density due to triboelectrification can be estimated using the electrostatic model shown in Figure 3 and the application of Gauss's law. Assume a surface charge density σ on one surface of the dielectric layer. A Gaussian surface is drawn to enclose the dielectric. Then:

$$\int \mathbf{D} \cdot d\mathbf{A} = Q$$

$$\varepsilon_0 E = \sigma \tag{19}$$

For an air breakdown strength $E = 30\text{kV} \cdot \text{cm}^{-1}$, the maximum surface charge density is $\sigma_M = 2.65\text{x}10^{-9}\text{C} \cdot \text{cm}^{-2}$

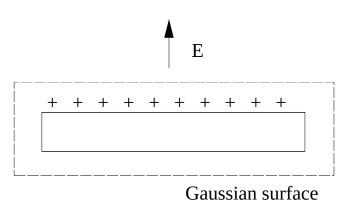

Figure 3: Charged dielectric layer

V. RC CHARGE/DISCHARGE CIRCUITS

A. Fundamentals

The basic RC circuit shown in Figure 4 can be used to model the CDE. The capacitor C has an initial charge Q_0; the switch S is closed at time t=0. The resulting current is given by:

$$i = \frac{Q_0}{RC} e^{-t/RC} \tag{26}$$

The energy of the event is given by:

$$W = \frac{1}{2} \frac{Q^2}{C} \tag{27}$$

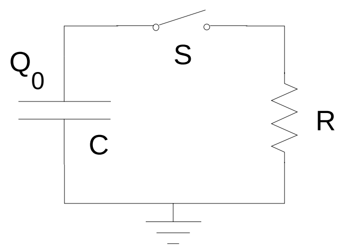

Figure 4: Cable charge/discharge circuit

B. Cable Application

Consider the model of the cable shown in Figure 5. The cable jacket with diameter d_0 and length l is charged by triboelectrification; the surface charge density is σ. When the cable is terminated, it will be assumed that the ground conductor l_1 is connected first, followed immediately by the signal conductor l_2. The input impedance seen by l_2 will be assumed to be R_i.

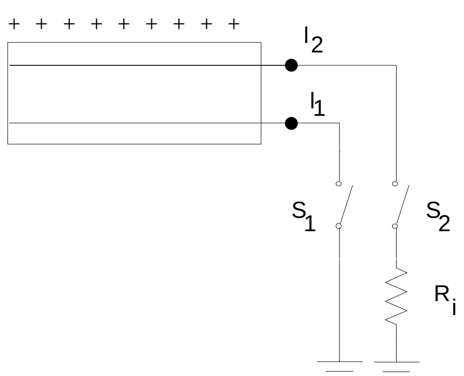

Figure 5: Sequence for CDE

Let the cable capacitance per unit length be C_0 and the resistance per unit length be R_0. For conductor l_1,

$$i_1 = \frac{\sigma \pi d_0 l}{R_0 C_0 l^2} e^{-t/\tau_1}$$

$$= k_1 \frac{\sigma}{l} e^{-t/\tau_1} \tag{28}$$

where $k_1 = \frac{\pi d}{R_0 C_0}$ and $\tau_1 = R_0 C_0 l^2$.

The energy is given by:

$$W = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} \frac{(\sigma \pi d_0 l)^2}{C_0 l}$$

$$= k_2 \sigma^2 l \tag{29}$$

where $k_2 = \frac{1}{2} \frac{(\pi d_0)^2}{C_0}$

For the conductor l_2, assume $R_i > R_0 l$. Then,

$$i_2 = \frac{Q_0}{RC} e^{-t/RC}$$

$$= \frac{\sigma \pi d_0 l}{R_i C_0 l} e^{-t/\tau_2}$$

$$= \frac{k_3 \sigma}{R_i} e^{-t/\tau_2} \tag{30}$$

where $k_3 = \frac{(\pi d_0)}{C_0}$ and $\tau_2 = R_i C_0 l$

The energy associated with the l_2 discharge is the same as that for the l_1 event.

VI. RESULTS

Typical results are presented in Figure 6. For this simulation, R_i is set to zero so that both currents have the same time constant. It is assumed that the connection of l_2 to ground occurs approximately 5 time constants after the grounding of l_1. With the initial connection of l_1 to ground, $-Q_1$ is transferred in the connection. With the subsequent connection of l_2 to ground, a charge $Q_1/2$ is transferred in the l_1 connection and a charge $-Q_1/2$ is transferred in the l_2 connection. If l_1 and l_2 were connected instantaneously to ground, a charge $-Q_1/2$ would be transferred in each of the connections l_1 and l_2.

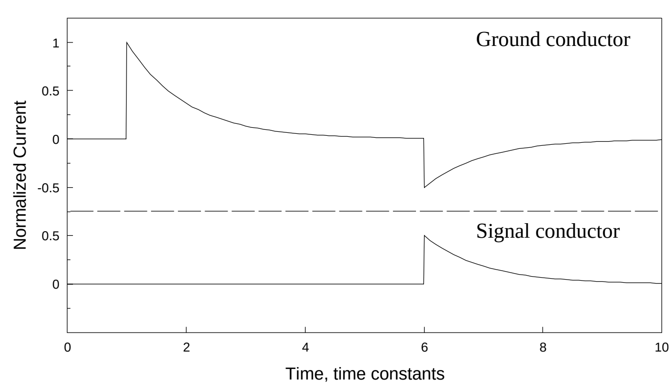

Figure 6: Charge/Discharge currents vs time

Some typical results are presented for a Cat5 cable with the following characteristics: C_0 = 50 pF.m^{-1}, R_0 = 0.2Ω.m^{-1}, d_0 = 5mm.

A. Conductor connected directly to ground (l_1):

$\sigma = 0.1 \times 10^{-4}$ C.m^{-2}

For l = 1 m:
$i_p = 1.57\text{x}10^{4}$ A, $\tau_1 = 1\text{x}10^{-11}$s, W = $2.5\text{x}10^{-4}$ J

For l = 100 m:
$i_p = 1.57\text{x}10^{2}$ A, $\tau_1 = 1\text{x}10^{-7}$s, W = $2.5\text{x}10^{-2}$ J

$\sigma = 0.1 \times 10^{-5}$ C.m^{-2}

For l = 1 m:
$i_p = 1.57\text{x}10^{3}$ A, $\tau_1 = 1\text{x}10^{-11}$s, W = $2.5\text{x}10^{-6}$ J

For l = 100 m:
$i_p = 1.57\text{x}10^{1}$ A, $\tau_1 = 1\text{x}10^{-7}$s, W = $2.5\text{x}10^{-4}$ J

B. Conductor connected through an impedance R_i to ground (l_2):

$R_i = 100\Omega$: $\sigma = 0.1 \times 10^{-4}$ C.m^{-2}

For l = 1 m:
$i_p = 3.14\text{x}10^{1}$ A, $\tau_1 = 5\text{x}10^{-9}$ s, W = $2.5\text{x}10^{-4}$ J

For l = 100 m:
$i_p = 3.14\text{x}10^{1}$ A, $\tau_1 = 5\text{x}10^{-7}$ s, W = $2.5\text{x}10^{-2}$ J

$R_i = 100\Omega$: $\sigma = 0.1 \times 10^{-5}$ C.m^{-2}

For l = 1 m:
$i_p = 3.14$ A, $\tau_1 = 5\text{x}10^{-9}$ s, W = $2.5\text{x}10^{-6}$ J

For l = 100 m:
$i_p = 3.14$ A, $\tau_1 = 5\text{x}10^{-7}$ s, W = $2.5\text{x}10^{-4}$ J

$R_i = 1000\Omega$: $\sigma = 0.1 \times 10^{-4}$ C.m^{-2}

For l = 1 m:
$i_p = 3.14$ A, $\tau_1 = 5\text{x}10^{-8}$ s, W = $2.5\text{x}10^{-4}$ J

For l = 100 m:
$i_p = 3.14$ A, $\tau_1 = 5\text{x}10^{-6}$ s, W = $2.5\text{x}10^{-2}$ J

$R_i = 1000\Omega$: $\sigma = 0.1 \times 10^{-5}$ C.m^{-2}

For l = 1 m:
$i_p = 3.14\text{x}10^{-1}$ A, $\tau_1 = 5\text{x}10^{-8}$ s, W = $2.5\text{x}10^{-6}$ J

For l = 100 m:
$i_p = 3.14\text{x}10^{-1}$ A, $\tau_1 = 5\text{x}10^{-6}$ s, W = $2.5\text{x}10^{-4}$ J

VII. SUMMARY

A basic model has been presented to permit simulation of cable discharge events. Parameters included are cable characteristics, length, surface charge density due to triboelectrification and mode of termination.

For conductors connected directly to ground, the peak discharge current is proportional to the cable jacket surface charge density and inversely proportional to the cable length; the time constant for this discharge is proportional to the square of the cable length. The energy associated with this discharge event increases in proportion to the cable length and the square of the surface charge density.

For conductors connected through an input impedance to ground, the peak discharge current is proportional to the cable jacket surface charge density and inversely proportional to the input impedance; the time constant for this discharge is proportional to the cable length. The energy associated with this discharge event is the same as for conductors connected directly to ground.

REFERENCES

[1] Y.-Y. Lin, J. Park, O. Isachar, S. Chaikin, R. Chundru, C. Duvvury, S. Marum and T. Diep, "The challenges of on-chip protection for system level cable discharge events (CDE)", Proceedings EOS/ESD Symposium, EOS-30, Tucson, AZ, USA, September 7-12, 2008, pp. 125-131.

[2] M.-D. Ker and T.-H. Lai, "Investigation on robustness of CMOS devices against cable discharge event (CDE) under different layout parameters in a deep-submicrometer CMOS technology", IEEE Transactions of Electromagnetic Compatibility, Vol. 50, N0. 4, November 2008, pp. 810-821.

[3] C.J. Brennan, K. Chatty, J. Sloan, P. Dunn, M. Muhammad and R. Gauthier, "Design automation to suppress cable discharge event (CDE) induced latchup in 90nm CMOS ASICs", Proceedings EOS/ESD Symposium, EOS-27, Anaheim, CA, USA, September 11-15, 2005, pp. 126-130.

[4] W. Stadler, T. Brodbeck, R. Gartner, H. Gobner, "Cable discharges into communication interfaces", Proceedings EOS/ESD Symposium, EOS-28, Tucson, AZ, USA, September 10-14, 2006, pp. 144-151.

[5] J.C. Maxwell, A Treatise on Electricity and Magnetism, Vol. 1, 3rd Edition, Dover, New York, 1974.

[6] J.R. Huntsman, "Triboelectric charge: Its ESD ability and measuring its propensity on packaging materials", Proceedings EOS/ESD Symposium, EOS-6, Philadelphia, PA, 1984, pp. 64-77.