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A Severe Human ESD Model for Safety and High Reliability System Qualification Testing

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ABSTRACT

A severe human electrostatic discharge (ESD) equivalent source model has been developed for use in qualification testing of systems that have stringent safety or very high reliability requirements. The model produces the now-acknowledged worst-case waveform, and the values of the constituent components have been selected from measured human body electrical parameters to maximize the peak amplitude and rate of rise of the short-circuit discharge current and energy transfer to the victim system.

Introduction

Many systems have either stringent safety or very high functional reliability requirements. Often these same systems, military ones in particular, are subject to operations and maintenance in field or repair depot environments where there is no guarantee of ESD source control. This combination of requirements implies the need for a capability to demonstrate system tolerance to severe human ESD.

Most of the broadly accepted existing human ESD simulation circuits, for example those in the MIL–STD–883C, International Electrotechnical Commission (IEC), and European Computer Manufacturers Association (ECMA) models, appear to incorporate average values for equivalent body electrical parameters and initial charge voltages. They therefore correspondingly replicate typical, or moderate, ESD events. While these environments adequately address the testing needs for a large variety of commercial and other systems, they are inadequate for qualification of systems of the type mentioned above.

In the present effort, a database of the better documented measurements of human body electrical parameters—capacitance, resistance, and inductance—and the distribution of acquirable body voltages was assembled from the literature. The data were found to be surprisingly sparse, especially with respect to body voltage. A severe human ESD source model was developed with component values selected from the available data to yield short-circuit discharge parameters with reasonable upper-bound values that could be encountered by a system over its life-cycle under actual conditions.

Elimination of the attachment arc in ESD testing is now widely recognized to enhance both the repeatability of test results and their correlation to failure distributions observed on the same test objects due to actual human ESD.[1,2] Therefore, the present model is intended for direct connection to the test item, and no elements corresponding to an arc are included.

In this paper, the rationale is given for the form of the model and its component values. For brevity hereafter, the term ESD is used to mean human body ESD unless otherwise indicated.

Equivalent Source Model

Output Waveform

The key aspects of pulsed electrical overstress transients in general, and ESD in particular, that influence the nature and level of induced effects are peak amplitude, rise rate, and total energy transferred to the victim object. The correlations between effect and the peak amplitude or total energy deposited by the pulse can be readily appreciated. The extreme sensitivity of victim systems (both electronic and ordnance) to rise rate of the discharge current is perhaps less intuitive, but nonetheless well-documented [e.g., Refs. 1–5]. Effects or failure mechanisms that are sensitive to the derivative of the driving current include radiation from the source current, magnetic field coupling into internal wiring or circuit boards, inductive voltage transients, and others.

ESD events result in a very wide variety of waveshapes. It is now widely accepted, however, that the worst-case waveform is of the type shown in Figure 1, which corresponds to the short-circuit current often observed in discharges from a hand grasping some small metallic object. That this particular shape represents the worst case follows from the presence of the initial narrow spike, which generically reflects the highest peak amplitudes and fastest rise rates observed in the extensive empirical database reported by King, Richman, and others in recent years.[3,6,7] This waveform was therefore adopted as the desired output of the model.

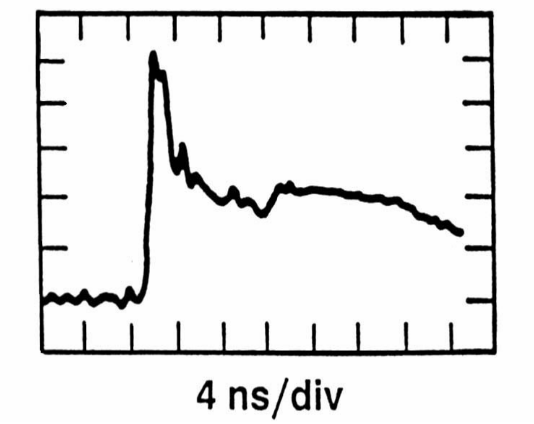

Figure 1. Worst-case human ESD waveform (After Richman[7]).

Source Circuit Model

The traditional human body ESD equivalent source models have been simple series RLC circuits in which the R corresponds to the resistance of that portion of the body in series with the discharge, L is the similar body inductance, and C is the capacitance of the body to its surroundings. The body inductance is often neglected, as, for example, in MIL–STD–883C, in apparent tacit recognition of the fact that zero inductance represents the worst case.

Recent refinements to source models have been suggested to account for various observed features in actual ESD currents, such as multiple-pulse discharges[8] and the important initial narrow spike of Figure 1.[9] Multiple pulses occur only in discharges involving sparks. Since total energy transferred is the sum of that available to the victim in the individual pulses, worst-case stress can be simulated in a single current pulse from an appropriate source. Comparison of the minimum interval between individual pulses (~20 μs[8]) versus the thermal time constants of victim electronics (hundreds of nanoseconds or more) also indicates that the transfer of all available energy from the source in a single pulse represents the worst case.

All ESD source models rely on the Thevenin linear circuit equivalency principle, which guarantees that if the open circuit voltage and short-circuit currents are identical at the output of any two circuits, then the two circuits are completely equivalent electrical sources. The validity of test results obtained with this type or model therefore corresponds in part to the degree to which the ESD event being simulated is linear. In that regard, there are two potential sources of nonlinearity with respect to initial charge voltage to be considered: equivalent body electrical parameters and pre-breakdown corona and other effects in spark discharges. No solid evidence was found in the literature that there is any significant nonlinearity associated with the former, although there appeared to be a hint in one study of decreasing dynamic body resistance with increasing initial voltage.[10] Most of the available data are too sparse and involve too many simultaneous variable changes to allow analysis for that particular effect. Complications with respect to reduction of peak current and rise rate due to corona effects[11] are avoided altogether in the present model, since it is intended for direct connection to the test item prior to discharge.

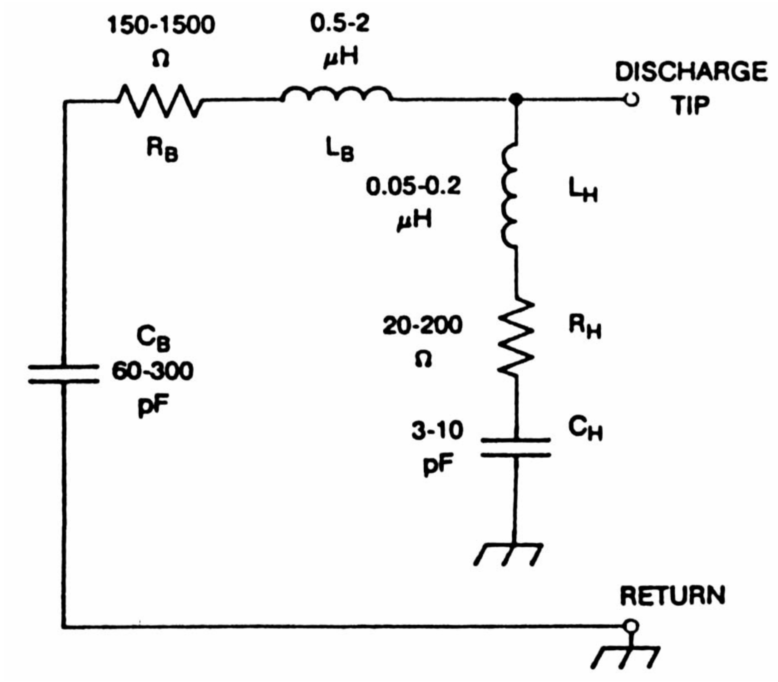

Figure 2. Dual–RLC equivalent human ESD circuit model due to Richman.[9]

The basic form of Richman's 1985 model (Figure 2), shown by him to be capable of reproducing the important early spike,[9] was adopted as the preferred baseline. Here, the components labeled C_H, R_H, and L_H are intended to correspond physically to the capacitance and other electrical parameters of the arm and hand as they reach out towards the victim. From this viewpoint, Figure 1 can be interpreted as a composite of a very fast and narrow initial pulse of limited energy content, corresponding to the rapid discharge of the hand capacitance, superimposed on the slower, broader discharge associated with the bulk body capacitance.

The present model (Figure 3) represents a slight modification of the form of Richman's circuit, in that the resistance and inductance associated with the hand and arm have been moved from a parallel branch into series with the discharge path to improve correspondence with physical reality. In the following, the database on equivalent body electrical parameters is reviewed, and the basis for selection of the specific element values reflected in Figure 3 is given.

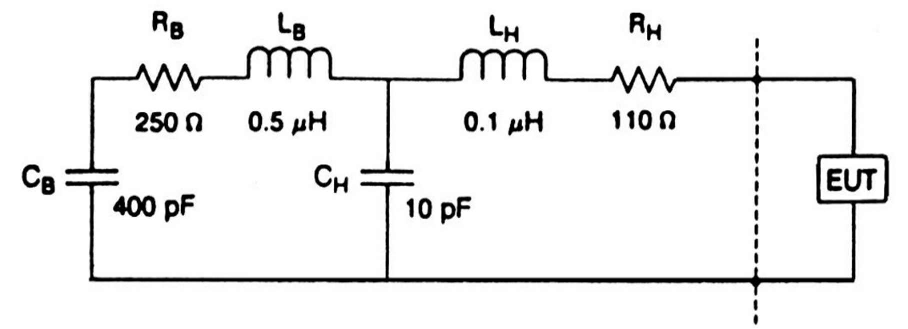

Figure 3. Modified human ESD source model for severe ESD simulation.

Electrical Parameters of the Human Body

Although values for body parameters are widely asserted in numerous ESD handbooks and papers, references in the literature actually describing either the data themselves or the methodology under which they were obtained are surprisingly meager. On the other hand, in the few better documented cases that were found, there is a rather comforting degree of agreement among data that were independently acquired using a considerable range of techniques.[5,l0,12–l4] Among these were the direct use of commercial capacitance bridges and various schemes for extracting body R and C from recorded discharges from volunteers charged to controlled initial voltages. Capacitance data are reported for subjects of differing physical characteristics (height, weight, shoe size, etc.) and for various shoe sole and flooring material combinations. Table 1 summarizes these results. The extreme upper and lower values noted were 105 and 1100 pF, respectively, although several other authors alluded to body capacitances as low as a few tens of picofarads without description of the source of data. Sullivan and Underwood[13] provide fitted normal distributions for their data (Figure 4). The low-end skirts of these curves indicate values of this order, although nothing that low appeared explicitly in their tabulated results. Of more practical import, however, is the fact that, according to their distributions, nothing over 400 to 450 pF would be expected, even *in situ* in an automobile environment, which intuitively might be expected to yield the highest capacitance due to the increase in body surface area in close proximity to its surroundings.

Table 1. Mean Measured Body Capacitance.

Investigator	Standing (pF)	Sitting (pF)
Tucker[5]	121	—
Tucker[12]	250	—
Cleves and Sumner[10]	~250	—
Sullivan and Underwood[13]	~120	280
Sperber and Blink[14]	130	300
Calvin et al.[15]	115	—
Mean/σ	164/67	290

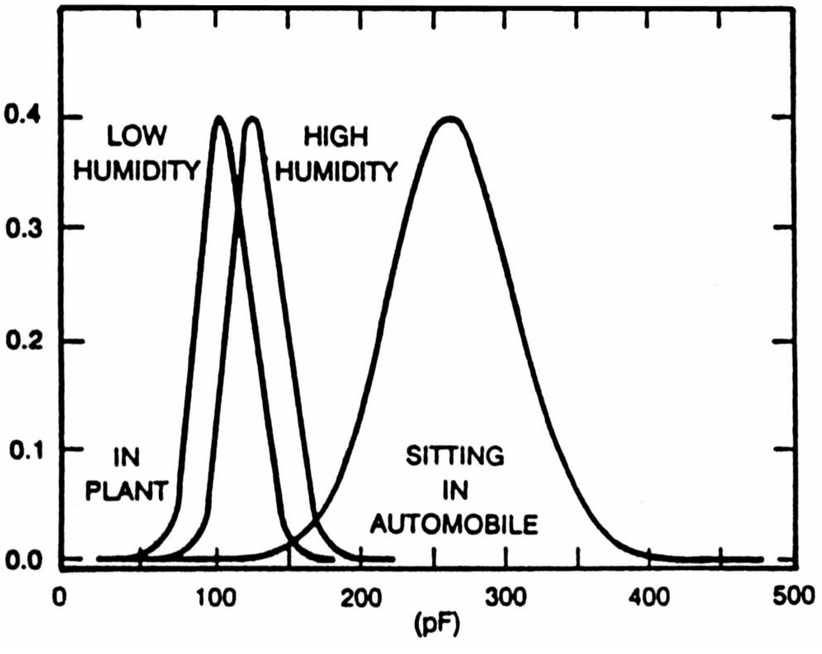

Figure 4. Measured body capacitance distributions for individuals under in-plant and automobile environments (After Sullivan and Underwood[13]).

Body resistance apparently exhibits a much broader range of values, as is suggested by the data in Table 2. It is most dependent on skin moisture, the particular portion of the body involved in the discharge path, and the contact area and degree of pressure applied in grasping a metal object when some hand-held article is included. A distinction is made in Table 2 between the two main types of discharges from the hand, namely, those with and without the involvement of a metal object. Qualitatively, all of the data reviewed indicate that the latter case implies the highest effective resistance. Other values appearing in the literature without discussion of their origin range from 100 to 2500 ohms. The only values for body inductance found were between 0.1 and 2 μH. From this database, values for the various circuit elements were selected according to the following rationale.

Table 2. Measured Effective Human Body Resistance.

Investigator	Fingertip (ohms)	Metallic Object (ohms)
Tucker[5]	1330	357
Sullivan and Underwood [13]	1600	–700
Sperber and Blink[14]	2000	—
Calvin et al.[15]	1920	550
Mean/σ	1713/308	535/172

First, in order to maximize the available discharge energy, the highest reasonable bulk body capacitance was selected. While the single highest value reported in any of the better documented studies reviewed was 1100 pF,[14] this value was a factor of 3.5 higher than the next lower one (314 pF). Furthermore, from Figure 4, it is seen that a value of 400 pF represents something like the 4σ point of the Sullivan and Underwood data. Hence, in the spirit of a practical extreme, a value of 400 pF was selected for the main body capacitance C_B of the present model.

Total body resistance is the sum of that associated with the main trunk and that due to the arm and hand. In order to maximize both peak current and energy transfer to the victim, source resistance was minimized by selecting the lowest reasonable value of total body resistance found during the review. This is Tucker's 357 ohms (Table 2), which was rounded up to 360 ohms. This total was allocated between the main body (R_B) and the arm and hand (R_H), 250 ohms to the former and 110 to the latter.

Hand capacitance C_H was chosen to be the upper limit of Richman's range[9] to maximize the amplitude and energy in the initial spike. Hand inductance L_H was then selected to be 0.1 μH to provide a 10–90% risetime for the initial peak of just under a nanosecond, corresponding to the faster risetimes evidenced in the data of King and Reynolds and Richman. Finally, a value of 0.5 μH for the less critical main body inductance L_B was adopted, also from the range of values reported by Richman.

It should be noted that both the severe waveshape definition and its equivalent model are based on actual short-circuit currents produced in configurations with very low return path inductance.[3,6,7] Although other discharge scenarios could, in fact, involve substantial return path inductance, which would significantly affect the discharge current, this will not necessarily be the case. Hence, once again in the spirit of conservatism, no extraneous inductance is incorporated into the source model itself.

Initial Charge Voltage

Very few well-documented data were found regarding the ranges of electrostatic voltages acquirable by personnel under various environmental circumstances. In principle, the absolute upper limit on the voltage that can be sustained is set by the point at which charge leakage mechanisms, primarily corona, provide equilibrium with respect to further charge accumulation. This implies a practical upper limit on a person in normal proximity to his surroundings, variously stated to be in excess of 25 kV[3,5] and 30 to 39 kV.[16,17]

Table 3. Body Voltages and Capacitances after Exiting from an Automobile.[14]

Capacitance	Voltage	Shoe Type	Vehicle
176	11.0	3/8-inch Plastic	Intermediate Size Station Wagon
176	10.8	3/8-inch Plastic	
172	7.2	3/8-inch Plastic	
174	11.5	3/8-inch Plastic	
176	15.0	3/8-inch Plastic	
172	17.5	3/8-inch Plastic	
314	4.0	Rubbers Over Shoes	
242	6.5	5/8-inch Rubber Sole	
1100	0.5	3/16-inch Leather Sole	
112	20.0	3/4-inch Plastic Sole	
112	21.5	3/4-inch Plastic Sole	
114	15.0	3/4-inch Plastic Sole	
109	17.0	3/4-inch Plastic Sole	

Sullivan and Underwood[13] report measured data from a sample of subjects within laboratory and production plant environments. They give mean values of 5.8 kV and 1.4 kV (no standard deviations) for low and high humidity conditions, respectively, but point out that their data are skewed in the low direction due to limitations of their measuring equipment. Sullivan has privately reported measured personnel voltages in excess of 70 kV within an airplane environment.[18] Sperber and Blink[14] give measured data (Table 3) on a sample of people with varying heights and weights as they exited from automobiles. Their data contain the highest measured personnel voltages reported among the better documented studies. Conspicuously absent from the database appear to be any measurements of personnel voltages acquired under outdoor conditions and activities. If levels of 20 kV or more can be developed under plant-type condition, one can readily envision significantly higher voltages in the case of, say, a soldier or airman operating outdoors in a dry wind. In view or these considerations, a reasonable upper bound for use in the present model was chosen to be 25 kV, although arguments could be entertained for an even higher value.

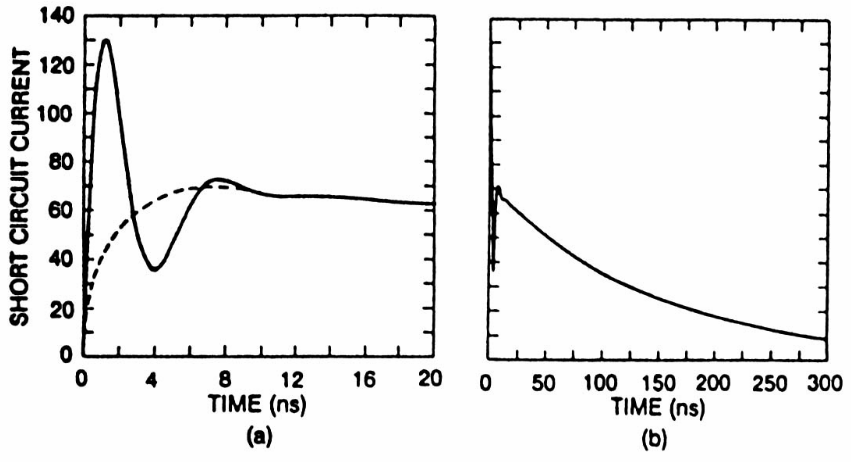

Figure 5. Output of the ESD model of Figure 3 computed for an initial charge voltage of 25 kV; (a) early and (b) longer time base.

Model Output

Figure 5 gives the short-circuit output current computed with the model shown in Figure 3 for an initial voltage of 25 kV. The waveshape compares favorably with the generic worst-case waveform represented in Figure 1. Although the model was specifically developed for use in system-level qualification testing at severe levels, it contains only linear elements; and its output amplitude therefore scales linearly with initial voltage. This allows it to be used at lower voltages while still preserving the desired waveform. The dashed early portion of Figure 5a represents the component or current due to the main body capacitance. Of the three main stress parameters, peak amplitude, rise rate, and total pulse energy, the initial peak accounts for the first two. The energy contained in the first peak, relative to that in the sustained current, is approximately the ratio of the capacitance of the hand to that of the body, which in this case is 0.025.

Conclusion

The ESD model presented herein provides a short-circuit output current corresponding to the acknowledged worst-case waveform evidenced in the available human ESD empirical database. Values of the constituent electrical components were chosen from the ranges of substantiated measurements of human body equivalent electrical parameters and acquired charge voltages reported in the literature. The severity of the resultant output is thought to replicate a reasonable worst-case ESD transient in terms of rise rate, peak amplitude, and total pulse energy available to the victim. The model was developed for specific application as a human ESD standard at Sandia National Laboratories for systems required to tolerate severe ESD. However, since its output is linear with initial voltage, the model can be used at more moderate levels as well.

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