Travelling-wave fast-transient ESD simulation

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Abstract

Human electrostatic discharge is discussed as a travelling-wave process, with the objective of simulating the initial nanosecond-scale current impulse. The approach presented uses swept-frequency impedance measurements at the "fingertip" to establish equivalence between the human subject and the simulator which is a lossy dielectric strip. The impedance measurements at the fingertip are used for approximate FFT calculation of transient discharge current. Time-domain arc discharge current measurements for the human subject and the simulator are presented for comparison. Also presented are method-of-moments calculations of time-domain discharge currents, using a loaded wire grid representation for the lossy dielectric strip simulator.

1. Introduction

Human electrostatic discharge (ESD) presents a serious threat to electronic systems. High-speed digital logic devices in particular are potentially susceptible to the very fast, nanosecond-scale initial impulse in the current injected from an ESD event, and it is the simulation of this initial impulse that is the subject of this paper. Deficiencies in existing simulators [1-4] have led us to investigate a new approach to simulating human ESD based upon considering the human body as a charged, lossy transmission line which discharges by a travelling-wave process.

As a charged person reaches out to touch a grounded conductor, an arc forms at the fingertip and most of the charge on the human body drains through the arc. This results in a current wave that propagates along the body until charge removal is complete. Based on the assumption that the current wave propagates close to the velocity of light in vacuum, the relevant time scales for two-way propagation would be of the order of a fraction of a nanosecond (finger), a few nanoseconds (arm), and ten to a few tens of nanoseconds (body). Because these time scales are comparable to those of actual measured ESD arc currents [5,6], it is appropriate to consider ESD as a wave process. Moreover, it is equally appropriate to consider the wave process in ESD simulation, which leads to simulators made of continuous, lossy materials rather than lumped circuits.

2. Frequency-domain impedance measurements

The discharge current waveform at the arc is closely related to the impedance characteristics of the human body as measured at the arc site. This relationship is valid to the degree that the occurrence of an arc can be considered as the closure of a switch connected to a linear circuit. Switch closure is relevant because the action of an air-breakdown arc is to suddenly reduce the voltage from a high to a low value. This is approximately equivalent to the application of a voltage step, and the response to a step can be calculated from impedance using transform techniques.

A swept-frequency experiment was set up to measure the impedance between a person's fingertip and a flat plate, over the frequency range from 1.874 MHz to 3 GHz, using the HP8753C vector network analyzer and the HP85047A S-parameter test set as shown in Fig. 1. A typical impedance measurement is shown in Fig. 2. The step response was then calculated using a chirp-Z Fourier transform technique built into the network analyzer. Fig. 3 is an example of the initial fast transient in a human ESD current waveform as obtained from human-subject impedance measurements and the Fourier transform technique. The oscillations at the end of the initial spike are interpreted as being due to discharge wave reflection at the finger-hand junction, because the 0.6 ns time interval between the spike and the first sub-peak corresponds to the round-trip time of a wave propagating on a typical 9 cm index finger. Further evidence for this interpretation is the fact that changes in the position of the hand and the other fingers affect only the small oscillations at the end of the initial spike.

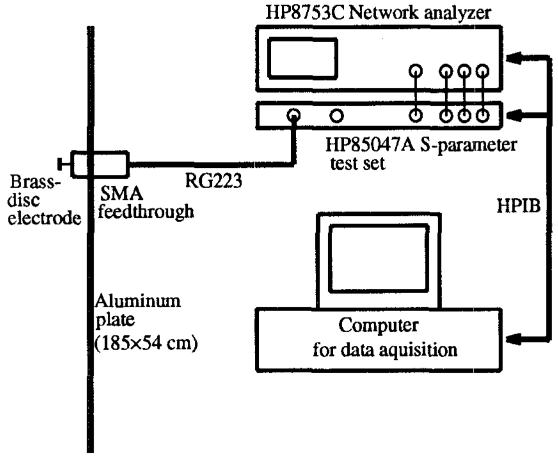

Fig. 1. Block diagram for human impedance measurements.

3. Simulator design

Proper simulation of a human ESD event requires a simulator made of a lossy dielectric material with electrical characteristics similar to those of the human body. Eccosorb-VF is a flexible conductive plastic film having approximately the desired characteristics. A 60-mils thick strip of this material was shaped as in Fig. 4 to resemble a finger attached to a wider hand-plus-arm segment. Its input impedance for a fixed "arm" width of 5 cm and various "finger" widths is shown in Fig. 5, which leads to the conclusion that a finger width of 1 cm is the best of the values tried. An arm width of 15 cm was also tried but was less satisfactory. Fig. 6 shows the step response of this model with 5 cm arm width, as obtained from impedance measurements and calculated as before. Clearly its spike amplitude and indication of finger-hand discontinuity are comparable with the human subject case shown in Fig. 3.

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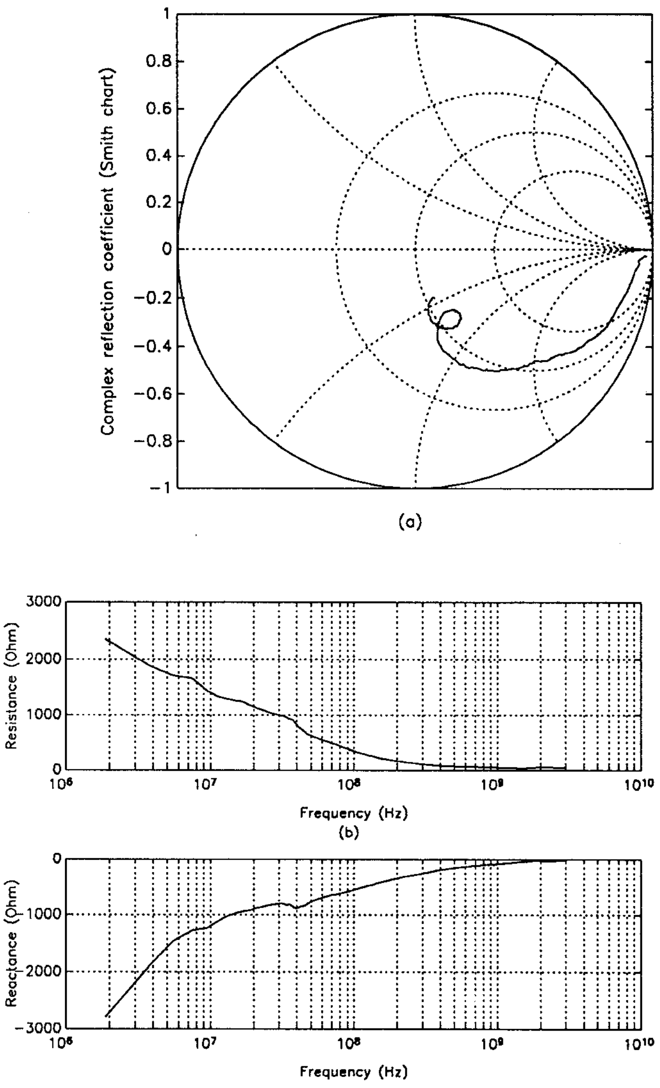

Fig. 2. Measured input impedance of human being at the index finger. (a) Input impedance. (b) Input resistance. (c) Input reactance.

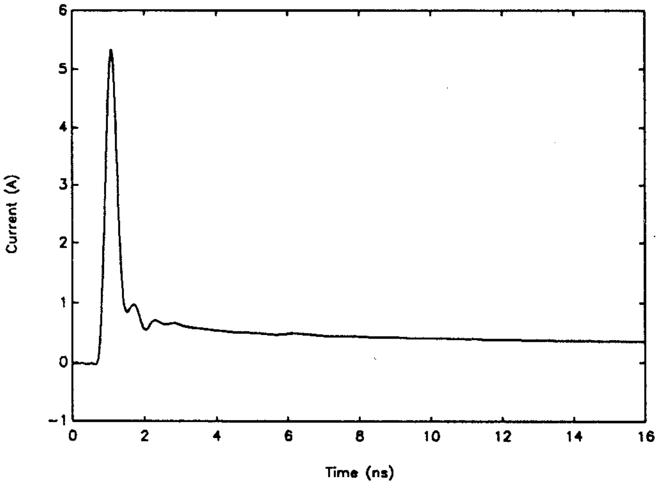

Fig. 3. Step response of human body with the index finger as the measurement port, as computed from a frequency-domain impedance measurement (1.874 to 3000 MHz). Voltage step amplitude is 1 kV.

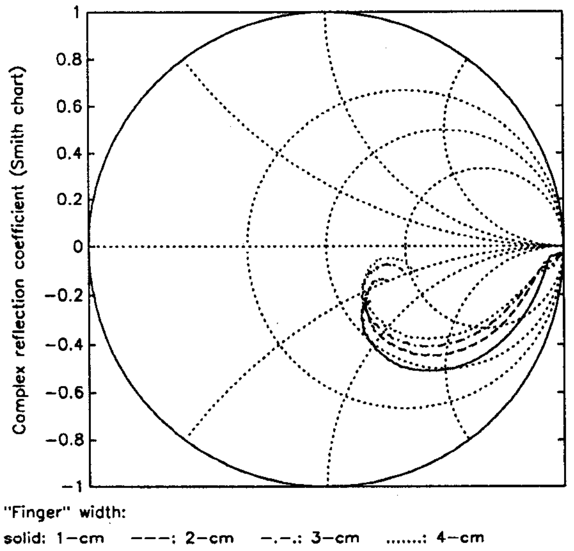

Fig. 5. Input impedance of Eccosorb-VF dielectric strip simulator with an arm width of 5 cm.

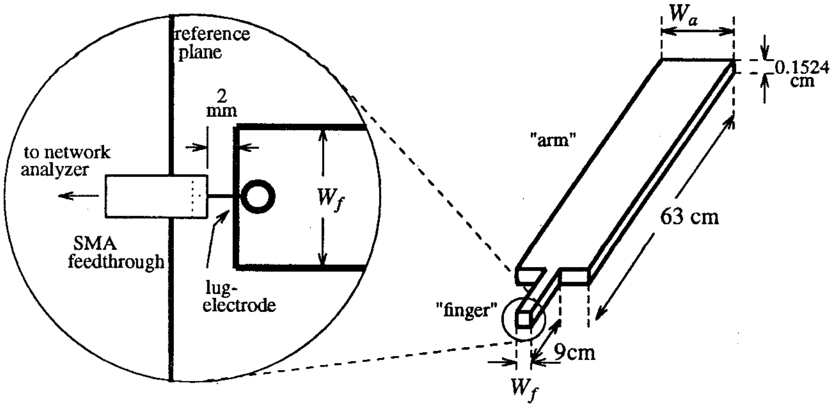

Fig. 4. Dielectric strip ESD simulator (not to scale).

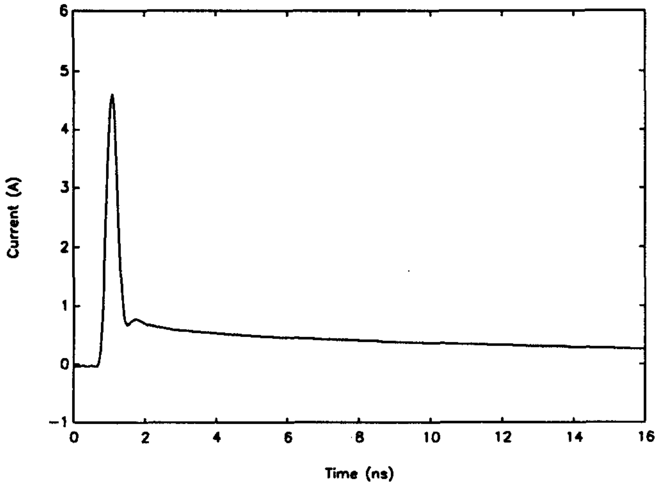

Fig. 6. Step response of lossy dielectric strip, as computed from a frequency-domain impedance measurement (1.874 to 3000 MHz). Voltage step amplitude of 1 kV.

4. Measured time-domain discharge of a human subject

Time-domain discharge experiments were conducted with the Tektronix 7250 transient digitizing oscilloscope whose 6 GHz bandwidth is sufficient to resolve pulses with rise times as short as 50 ps. In the experiments, a delay line was used that reduced the bandwidth to 3 GHz and the rise time to 100 ps. The subject was charged to 1 kV (measured with an electrostatic voltmeter) and discharged into a 1-Ω current monitoring resistor (CMR) which was grounded to a large aluminum plate as shown in Fig. 7. Fig. 8 shows an example of such a discharge current on an expanded time scale, with the essential features comparable to Figs. 3 and 6.

5. Measured time-domain discharge of a dielectric strip

The dielectric strip simulator of Fig. 4 was modified for electrical charging by connecting a high-voltage power supply to the end farthest from the "finger" via a 100 megohm resistor. The fingertip was then discharged into the measurement apparatus of Fig. 7 by bringing it closer to the contact point until an arc occurred. An example of the resulting time-domain current is given in Fig. 9 for the case of charge-up to 1 kV, again on a scale comparable with Fig. 8 : the two cases are seen to be quite similar in their essential features. The oscillation immediately following

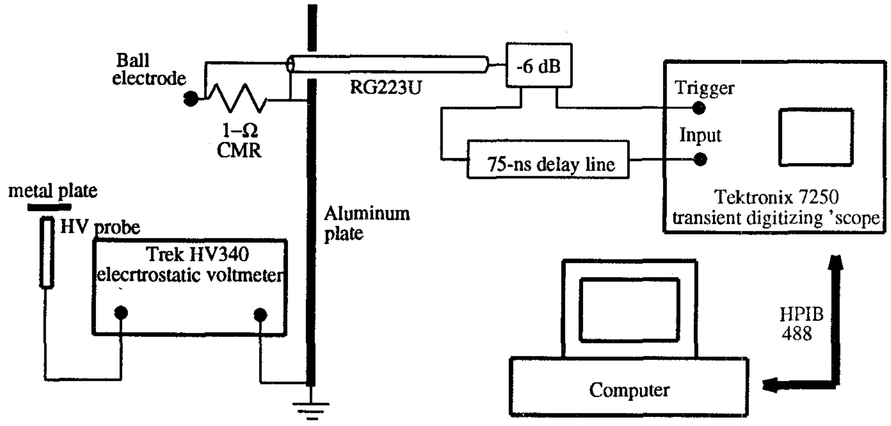

Fig. 7. Experimental setup for time-domain ESD current waveform measurements.

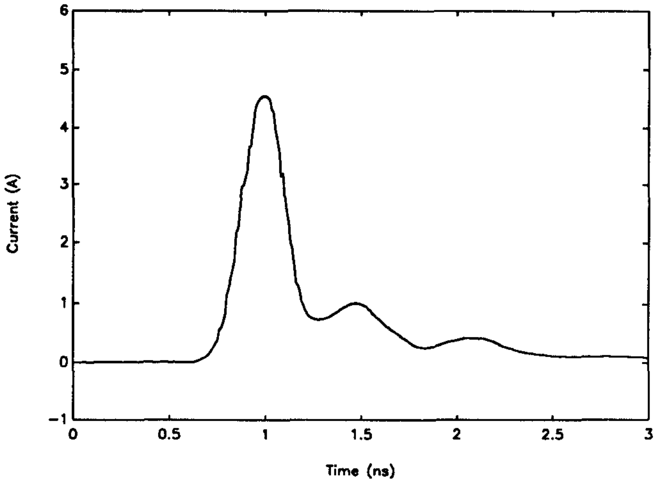

Fig. 8. Initial current spike of low-voltage human ESD impulse. Charge-up voltage is 1 kV.

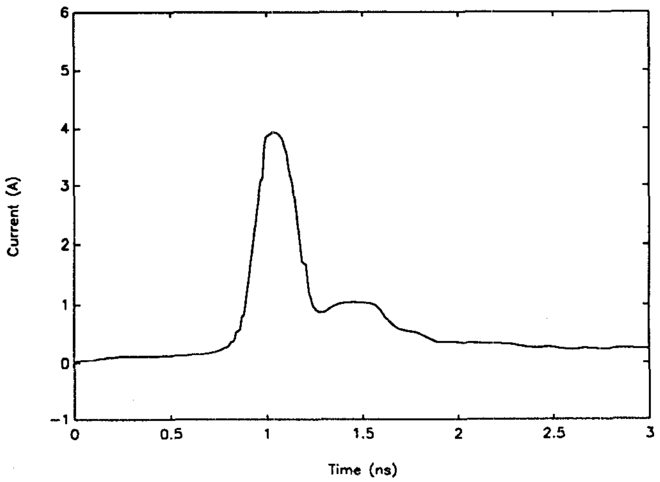

Fig. 9. Initial current spike of 1 kV discharge at "fingertip" of dielectric strip simulator.

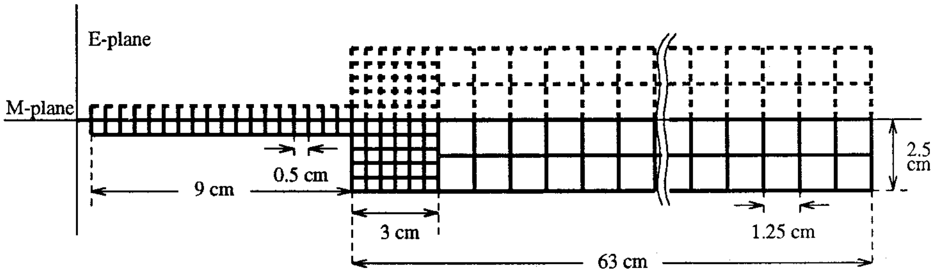

Fig. 10. Wire grid computational model of dielectric strip ESD simulator.

the initial spike is, as before, low in amplitude, suggesting high wave attenuation on the finger segment. At later times there is no indication of reflection from the distant end of the "arm", suggesting high wave attenuation along the arm segment. This high attenuation effectively isolates the "finger" region from the distant end of the arm, at least for nanosecond-scale transients, rendering unnecessary the use of a special ground-return strap intended to carry transient currents. A ground return is required only for the relatively very slow charge-up currents, for which normal system grounding via power line ground is quite sufficient.

6. Computer simulation of ESD pulses

Computer simulation and theoretical analysis of ESD pulses were performed using the Richmond-Tilston [7] thin-wire method-of-moments program. With this program, a conductive body is modeled as a mesh of wire segments on which the current distribution is approximated by a piecewise-sinusoidal expansion function [7,8]. In order to model a lossy dielectric material, each short wire segment is loaded with a lumped-element network (e.g. an RC circuit). The dielectric strip simulator is modeled as the loaded wire network in Fig. 10, in which symmetry planes are shown as electric (E) and magnetic (M); these inherent symmetries were utilized to reduce the number of unknowns and the computation time. The model was driven at the "fingertip" by a voltage generator delivering a rectangular pulse of sufficiently long duration that the turn-on transients had died out before the turn-off time. In other words, the pulse turn-on followed by equilibrium represents charge-up of the simulator and turn-off represents the occurrence of a short-duration arc. For the R-C loading representing the Eccosorb-VF material, the turn-off transient is shown in Fig. 11 in which the primary spike and the following oscillation due to the "finger-hand" junction are clearly evident.

7. Conclusions

A number of analytical, combined experimental-analytical and purely experimental techniques have been described, all displaying similar graphs of the initial spike in a fingertip arc discharge current pulse. The analytical techniques model the arc as an ideal switch or as the turn-off of an ideal voltage generator. The correspondence between analysis and time-domain human subject experiments at a 1 kV charge-up voltage suggests that the short arc at this low voltage forms very quickly and approximates an instantaneous switch action.

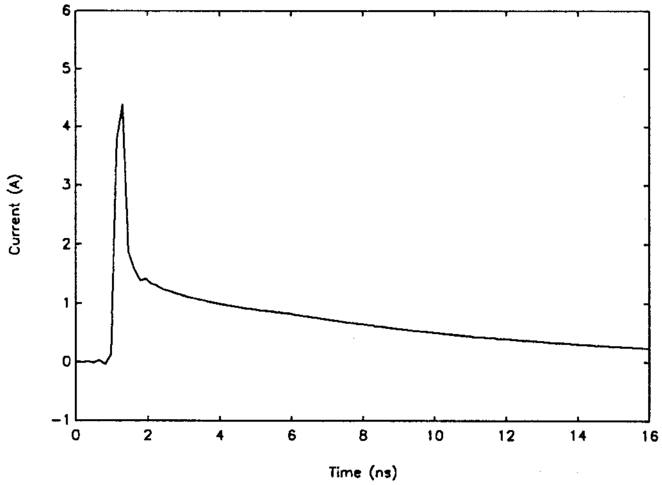

Fig. 11. Discharge current of lossy dielectric strip as obtained by taking an FFT of a method-of moments calculation (2 to 3072 MHz). Voltage pulse amplitude is 1 kV.

A lossy dielectric strip simulator is proposed and the results suggest that it is effective in representing early-time ESD phenomena with a human subject. This confirms the utility of the travelling wave interpretation of the ESD phenomenon, and of the resulting design using continuous, lossy material to represent the human body. In particular the results confirm the effectiveness of using swept-frequency impedance measurements to establish equivalence between the simulator and human cases.

Further support is provided by frequency-domain method-of-moments analysis of a loaded-wire-grid model of the simulator. The method of FFT-calculated time-domain response is of sufficient accuracy to show that an entirely theoretical analysis is feasible for ESD simulator design.

The ESD simulator design concept can be extended readily to model the whole body by adding an appropriately longer and wider lossy dielectric strip to the strip already used to model the finger, hand and arm. Further, based on the assumption that higher-voltage discharge characteristics are determined in large part by the peculiarities of wide-gap arcs, it is reasonable to expect that the lossy dielectric strip simulator will be effective at high charge-up voltages as well as at low voltages.

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9. Acknowledgments

This work was supported by Bell Canada, by the Ontario University Research Incentive Fund, and by the Natural Sciences and Engineering Research Council of Canada. The authors express their appreciation for the extensive interaction provided by Bell Canada and Bell-Northern Research, and in particular by Mr. Marcel M. Cohen.