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Abstract-The first part of the paper is focussed on own direct measurements of human body resistance-capacitance, in indissoluble connection with two resistances: the leakage and respective, the discharge ones. There are presented methods, set-ups and argued explanations for the large dispersion of the obtained results. The human impedance (capacitance shunted by leakage resistance) was measured by performing the ratio between the well known ac voltage (as r.m.s. and frequency) and the established current. In order to determine the skin resistance between different parts of the human body (wrist, elbow, shoulder, ankle), there were performed both ac and dc measurements.
The second part aims to investigate the relationship between the real skin resistance (in the main, determined by volume resistivity, not just surface one) and the factual disturbing potential of the associated discharge in order to evaluate the impact of the series resistance in an ESD gun upon the susceptibility test results.

Key words-ESD susceptibility, human body capacitance, human skin resistance

I. How close to reality are the universally accepted parameters of Human Body and Machine Models fixtures for immunity tests?

It is quite a truism of our days to discuss about the economic impact of the more than a quarter of solid state circuitry failures owing to the little sparks associated with static charge accumulations. And the expected bad influence could be even higher, due to the enhancement of integration density and working frequency alike. There are International Organizations, elaborating standards and methodologies, aiming to increase the repeatability and predictability of the ESD immunity tests, considering all the tiny and sensitive details.
The overall challenge is obvious: human operators produce, during their daily routine, the large majority of static charge accumulations. The vulnerability (established by design and production) of any device or equipment must be tested by universally accepted and realistic methods, in order to certify the inclusion of that apparatus in the rank imposed by the expected working conditions.
The global approach is in the main accepted: there is a charged capacitor that will attack the victim by discharging through a limiting resistance.
So, the always altering and unpredictable "subject" is the human creature, anytime accumulating tribo-electricity. Human means "unique", also from the point of view of ESD behaviour. One reason of diversity is the leakage resistance (R_L) from the body to the ground, "connected" parallel to the human capacitance, correlated with the series resistance of the human skin, (R_S), limiting the value of the discharge current. For instance, a physical worker will have much higher skin resistance than an intellectual one, while an emotive sweating person has a much lower value of this important parameter comparing with a "tough" one.
Lastly, willing to perform pragmatic but also repeatable tests, the technical solution was to replace the individual (charging and then discharging from the fingertip to an object in the touchable neighbourhood) with a quasi-similar R-C electric circuit, included in an ESD gun (or ESD simulator), made in accordance with the compromise imposed by international standards.
These are the respected and even actual Human Body and Machine Models, celebrating their centennial, while being many times brought up-to-date, even in 2012 (ANSI/ESDA/JEDEC, 2012), [1]. Undoubtedly, these models represent only average, decent compromises, aiming to guarantee the repeatability and reproducibility of the immunity tests, the real situations meaning a very large up or down dissipation of the R-C human parameters.
There are many set-ups, methods or approaches endeavouring to measure the human body capacitance and the associated resistance. Evidently, any time when humans are "evaluated", the dispersion is large and the attempt

of finding a reasonable "average" is difficult and always controversial. Under these circumstances, two questions arise in front of any research team dealing with ESD:

- How far from real encountered values are the old assessments adopted in Human Body Model and Machine Model?
- To what extend is really influenced the ESD behaviour of electronic sensitive devices by the natural scatter of R-C human parameters. Other words, it is clear for anyone that has previously performed measurements upon these parameters that 100-200 pF is a lower capacitance comparing with the real ones and the 1500 Ω (decreasing up to zero in Machine Model) resistance is covering just the extremely worst situation.

Are these differences actually significant for the destructive potential of the discharge?
Might be these discrepancies credible explanations for the failure in the real world of a device that has formerly passed the standard immunity tests in a legally certified laboratory environment?

II. Other ourselves attempts for measuring the Human Body Capacitance

We have previously presented three, mainly indirect, methods for measuring the realistic human capacitance, [2], [3] and [4]. In the first part of the here exposed paper, we shall communicate the results obtained by applying a direct method for measuring the R-C parameters of the human body, with other words, the method implemented in many DMMs. The volunteers were right the authors of the paper, presenting a large dispersion of their physical dimensions.
The method applied in DMMs (intending to act as a conventional type of capacitance meter) is the injection of a low voltage (0.1 to 0.5 V_{rms}) with low frequency (2 to 5 Hz), the resulting capacitive impedance being the ratio between the applied voltage and the resulting current. Why such quasi-low values? The answer is offered by the fundamental formula (1):

$$C = \frac{I_{meausred}}{2\pi f U_{applied}} \qquad (1)$$

The larger is desired to be the measuring range (up to hundreds of μF), the lower must be the applied voltage and its frequency, in order to keep the current to be measured at a reasonable (and bearable) value.
We established an experimental set-up, based on a sinusoidal low voltage generator and a voltage amplifier, applying a 10 V_{rms} voltage to the "volunteer", connected as an armature, a capacitance plate-coat towards the ground, while serially measuring the associated current. According to previous measurements, the human capacitance doesn't exceed the nF order, so the restrictions regarding the low values of voltage and frequency (with undoubted inconveniences) are not applicable. We can use tens of volts and hundreds of Hz.
Some of our obtained results, expressed in MΩ, are presented in Table 1.

Table 1. Human (capacitive) impedance to the ground, directly measured at various low frequencies, for essentially different isolations from the earth, (MΩ)

Human isolation from the ground / f (Hz)	Poor (antistatic shoes and floor)	Medium (only antistatic floor)	Good (thick rubber carpet)
5	0.51	5.12	47.23
10	0.49	5.08	42.15
20	0.48	4.92	31.34
40	0.48	4.75	15.63
400	0.41	4.62	1.59

We can extract some obvious conclusions, starting from the evidence that capacitive impedances are inversely proportional to the involved frequency:

- The here measured impedance is not pure capacitive (in the situation with the human very well isolated from the ground);
- The impedance is quite resistive (so, we really don't measure a capacitance), if the human is not perfectly isolated from the earth.

III. Treating (maximize or digitally compensate) the electrical leak resistance

Any time we simultaneously deal with electric safety and anti-static precautions, the most advisable decision is focussed on antistatic, dissipative materials, like, in our experiment, antistatic shoe-sole and floor. When charging the human capacitance at a potential, we have always a leakage resistance to ground, R_L, "placed" parallel to the measured capacitance.

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We measured the equivalent value of this outflow resistance, for the three situations considered in Table 1, by applying the formula (2):

$$U = U_0 \cdot e^{-\frac{t}{RC}} \tag{2}$$

The human was charged at various voltages (up to 300 V, delivered by the built-in source of Keithley 6517 electrometer), by re-using the experimental set-up described in [3], powered with a 2 GHz bandwidth oscilloscope. The previously measured capacitance of the volunteer, standing up, vertical position, was 210 pF. The scope was set to measure the time passed from the moment of opening the charging switch till the decrease of measured voltage up to 37%.

In the first situation the human was antistatic equipped (including shoes with sole having graphite-grains insertions) and so was also the linoleum floor (in direct contact with the shoe-soles). The average measured value for the leakage resistance was 490 kΩ.

In the second situation, he wore special sport training shoes, but still direct on antistatic floor. The new measured self-discharge resistance had a 5.23 MΩ, mean value.

The last situation meant very “tough” conditions for the isolation: thick-sole shoes and a 10 mm ceramic support placed on a 20 mm-thickness rubber carpet. The relative humidity in the laboratory was lower than 40%. The discharging time was a little higher than 0.1 sec, involving a mean value for the leakage resistance of 51.7 MΩ.

The conclusions derived from these measurements could be very useful. If we are concerned about non-accumulating charges, the anti-static materials are the best option. On the contrary, if our intention is to measure the leakage resistance, more or less placed parallel with the directly measured human capacitance to ground, the isolation provided by shoe-sole and carpet must be the highest possible.

Further more, the values in the second column of Table 1 are effectively not influenced by the frequency, the impedance is merely resistive, because the shunting effect of the low leakage resistance (490 kΩ) is conclusive. The situation is not very different for the third column (R_L = 5.23 MΩ), its shunting action being still critical.

Only in the forth column, there are values significantly influenced by frequency. Even in this situation, R_L = 51.7 MΩ, the dependence between measured impedance and frequency is quasi-inversely proportional (dominant capacitance), only for frequencies higher than 20 Hz.

These results and conclusions might be consolidated by the formula of the equivalent impedance of parallel R-C combination:

$$Z_{echiv} = \frac{R_L}{\sqrt{1+\omega^2 C^2 R_L^2}} \tag{3}$$

In order to have a lower than 10% influence on the reading of the here developed capacitance meter, the conditions imposed by (4) must be fulfilled:

$$\frac{1}{R_L^2} \leq 10\% \cdot (\omega C)^2 \quad \text{or} \quad \frac{1}{R_L} \leq 2fC \tag{4}$$

In the issue, if we want to apply this direct capacitance measuring method, the frequency must be higher than 50 Hz and the isolation toward the earth-ground very good, warranting a leakage resistance higher than 50 MΩ.

IV. The human skin (surface) resistance, factor of influence in measurements upon the global capacitance.

The question is quite complicated and the dispersion is very large. At a first glance, the theory is hard and fast: the static charge accumulation and associated discharge is entirely a surface phenomenon. Dealing with human operators, the resistance firstly involved in charge dissipation and later serving as discharging path to the “victim” couldn’t be purely a surface one. The very superficial layer of dead cells (having high resistance values) is thin and easily penetrated by currents. In fact, we don’t have only a surface resistance, but a volume one, with vivid cells, electrolytes and tissues. We always have to consider the relative humidity in the laboratory room, without neglecting the specific elements associated with any human, for instance the quantity of sweat, influenced by emotions, overall temperature or personal metabolism.

In order to evaluate the impact of skin serial resistance R_S to the measured human capacitance, it is necessary to start from the equivalent impedance of a serial R-C circuit:

$$Z_{echiv} = \frac{1}{wC}\sqrt{1+w^2 C^2 R_S^2} \tag{5}$$

The influence might be worth to consider while the following condition is fulfilled:

$$w^2 C^2 R_S^2 \geq 0.1 \quad \text{or the equivalent} \quad R_S \geq \frac{0.05}{f \cdot C} \tag{6}$$

As a rough guide, for a maximum usual frequency of 400 Hz and an average, generally accepted 200 pF for human capacitance, the R_S to be taken into consideration as source of error should be higher than 600 kΩ, this being far from the real situations.
We measured the overall resistance between two different parts of the same body. From the discharge point of view, real significance has the values between the central parts of the body to the wrist of the working hand. We applied two special electrodes connected at the power source (first, continuous one and later, 50 Hz alternative). In order to have a firm electric contact we used an electrode gel (C€ certified, produced by Parker Laboratories, Fairfield, New Jersey), recommended for electro-medical procedures (which is a bacteriostatic combination of saline electrolyte in a safe, non-sensitizing, non-abrasive, polymer), especially devised to produce long lasting contact between human skin and electrodes.
As it was expectable, the values measured in c.c. are considerable higher than the same a.c. resistance, due to the penetration of the very thin dead-cells layer.
Some significant results are presented in Table 2.

Table 2. The c.c. and a.c. (50Hz) resistance (kΩ) between the main parts of the human body (male, 87 Kg weight and 179 cm height), usually dry skin

Electrode position / Current	Wrist-elbow	Wrist-shoulder	Wrist-same ankle	Wrist-opposite ankle	Wrist-wrist	Ankle-ankle
0.75 mA, c.c	3.48	6.95	8.78	9.52	8.41	8.59
1.5 mA, c.c	2.93	5.98	7.09	7.15	7.01	6.82
0.75 mA, 50 Hz, c.a	2.87	5.72	7.23	7.85	6.95	7.09
1.5 mA, 50 Hz, c.a	2.41	4.93	5.82	5.93	5.78	5.71

The results also confirm another assertion: the relationship between applied voltage and established current is not linear. The higher is the established current, the lower the resistance, mainly owing to the easier penetration of the dead-cells layer, followed by direct conduction through the vivid ones
Another solid argument about the effective influence of the human volume resistivity and resulting volume resistance of human alive is the incomparable difference between the values presented in Table 2 and those obtained for samples of pig or mutton leather, measured with the 8009 fixture associated with Keithley 6517 electrometer. Applying the method of concentric ring-electrodes, the measured surface resistance was higher than 10 MΩ. This is just one, resistive and electrical, dissimilarity between dead leather and vivid skin.

V. To what extend does the skin resistance value really influence the results of the immunity tests?

No doubt, there is a large scatter of the measured (or just estimated) values of the human body R-C parameters regarding the static charge-discharge events. The R-C Human Body Model and Machine Model are old, but still actual and generally accepted. Their values merely represent a compromise, aiming to correlate the inherent value of the R-C parameters of an ESD simulator with the disturbing potential of the discharging current. The beyond question parameters of the ESD current are: the peak value, the rise time (reversely proportional to the bandwidth) and the area (the numerical value for the area is a measure of the charge, expressed as the time-integral of the current), this area being strongly influenced by the discharge time.
Conclusively, we need well established R-C parameters in order to have comparable results for ESD immunity tests. These values directly influence the intrinsic disturbing potential of the ESD test-stress, but we have to bear in mind that for the real situations, with humans in the centre of the action, the ESD stress could be much lower or even much higher.
We have previously measured for the discharging $R_{S(kin)}$ value, three to ten times higher values than 1.5 kΩ , (the value imposed by HBM). We wanted to find the real impact of this “spread” upon the destructive effect of the ESD event. We considered as load for the tests, the 50 Ω standard RF impedance.
We have performed many determinations on the discharge current shape, based on scopes with at least 2 GHz bandwidth, comparing the real results with the simulated ones, obtained by using Cadence IC 5.3 package software.
Essentially, we developed an extended Human Body Model, presented in Figure 1. In order to guarantee the same conditions for a realistic comparison, we considered only 1 kV charging voltage (well spread encountered value).

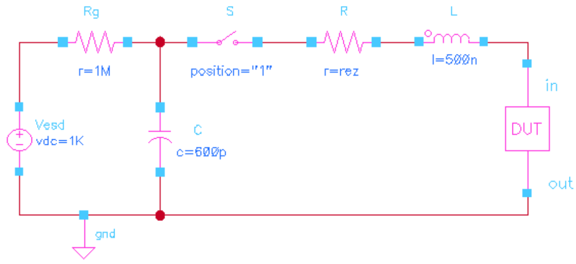


Figure 1. Schematic diagram for a version of Human Body Model, developed in Cadence IC 5.3 software

Aiming to increase the skin resistance effect, we adopted a higher (but presented in usual results), human capacitance of 600 pF. In the same trend, desiring to increment another essential parameter, the current rise time, we also included a serial inductance, appreciated at about the highest usual value, 500 nH.
In Figure 2 is shown the influence of the skin resistance (representative values 1.5 kΩ, 3 kΩ, 10 kΩ) in the assumed model upon the discharge current characteristics.

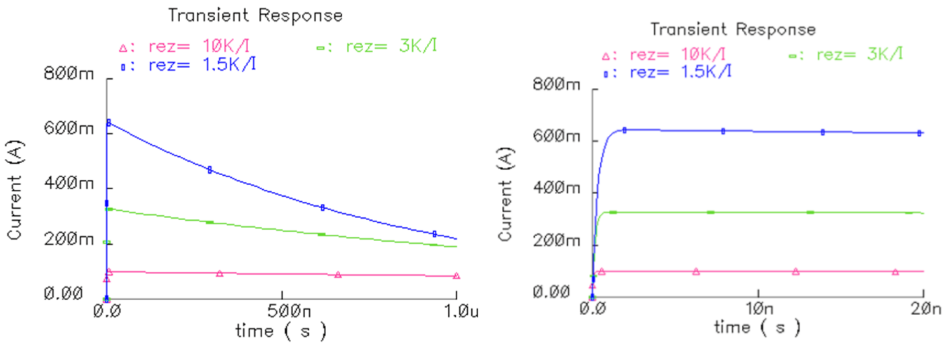


Figure 2. a. Influence of the discharge resistor upon discharge current characteristics, (R_{load} = 50 Ω, V_{ESD} = 1 kV)
Figure 2. b. The time-loop (20 ns), aiming to evidence the influence upon the rise-time

At a glance view, as expected, the beneficial influence of a higher value of the discharge resistance, compared with the value in the model, is materialised in a quasi-proportional decrease of the peak current, accompanied by the reduction of the area limited between the current and the time axis.
Additionally, an increase of discharging resistance involves a shortage of the rise-time.
We have also performed measurements and associated simulation without including the inductance, as in the quasi-classical HBM, presented in Figure 3.

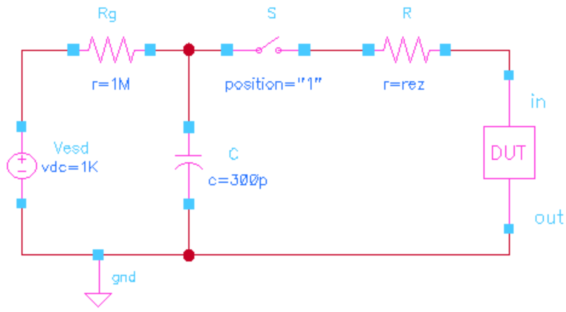
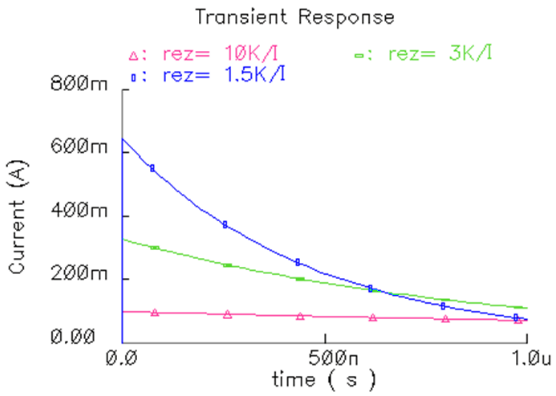


Figure 3. Schematic diagram for Human Body Model, developed in Cadence IC 5.3 software, without serial inductance, with variable R_S

There is a close correlation between measured and modelled waveforms, presented for the same values of the skin resistance in Figure 4.



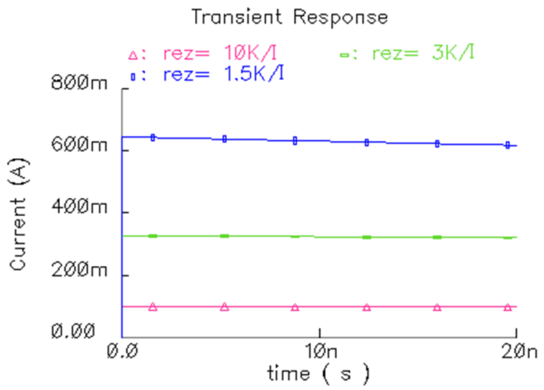


Figure 4.a. Influence of the discharge resistor upon discharge current characteristics, (R_{load} = 50 Ω, V_{ESD}= 1 kV), in the absence of inductive series element
Figure 4. b. The time-loop (20 ns) of the waveform, pointing the insignificant influence of R_s upon the rise-time

VI. Conclusions

We established some specific experimental set-ups for determining the human body capacitance, the associated parallel leakage resistance and the serial-placed resistance of the human skin.
We have provided useful information about the precautions to be taken in order to acquire trustful results for these attempts and also extracted and verified our explanations for the large spread of values, regarding the R-C parameters of the human, while comparing measured results with the values from the generally accepted HBM and MM models.
We supplementary studied, by using Cadence IC 5.3 package software, the real influence of the $R_{S(kin)}$ upon the disturbing characteristics (I_{peak} and t_{rise}) of the discharging currents. A considerable higher value than the “standard” 1.5 kΩ is materialised in a quasi-proportional decrease of the peak current, accompanied by the reduction of the area limited between the current and the time axis.
Supplementary, an increase of discharging resistance involves a shortage of the rise-time.

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