Simplified model of the human generated electromagnetic field during an ESD event

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Abstract

A multiple-sphere electromagnetic model of an operator-victim system is here proposed. The model could substantially be assumed as the generalization of an electrostatic approach initially finalized to the calculation of partial capacitances. Such lumped parameters are inserted into an RLC network subject to capacitive discharge. Resolving the network for the currents allows the ESD total current to be reconstructed and, additionally, the complex man-victim charge transfer to be explicited. The partial currents specifically associated to the discharges of each pre-charged capacitance form the set of pre-assigned feeding currents required by a subsidiary field computation. The latter, which substantially represents the subject of the present paper, is given by exploiting an exact solution of Maxwell’s equations made applicable to each elemental monopole having the same spherical configuration of the original electrostatic model. The low body-partitioning degree adopted makes the technique especially recommended for engineering applications where the thin-wire approximation is inapplicable.

1 Preliminary remarks

Conversely to “radhazard” problems, the human body takes here the role of unintentional electromagnetic threat for susceptible victims (see, for example, Mardiguian [1]). Electronic components and devices, the signal levels of which are disturbed by induced effects of human-generated electrostatic discharge (ESD), identify a typical class of victims. In that exposed to indirect effects (often only resulting in malfunctions), it is tacitly understood that such vulnerable elements are positioned at a certain distance from the conducting...
route carried by the ESD current, thus preserved from more dangerous direct effects (often resulting in definitive failure). Apart from some crucial examples including non-linear loads (Poljak [2]), connected EMI problems present, in general, no special theoretical difficulties since the coupling mechanisms involved demand usual investigation methods. Instead, the model of the electromagnetic field surrounding a system subject to discharge, a priori required for the calculation of the induced effects, still needs to be formulated for an appropriate engineering treatment. The familiar recourse to a short current dipole, assumed to represent the sparking arc as a unique ESD source of quasi-static (Tabata [3]) and radiation (Wilson [4]) effects, is a simple but questionable practice. In fact, extensive laboratory experiences (Tabata [3], Bendjami [5], Giannetti [6]) are supporting the conviction that the discharging human body and sink (victim with grounding system) are so significant field sources (Mardiguian [1], Mardiguian [7], Pommerenke [8]) that the sole arc appears as a second-order contributor to the total excitation field (Giannetti [6]).

In the light of the above observations, selecting an appropriate but tractable field computation, in spite of the odd-looking and corpulent geometry of the source involved, becomes a demanding task. The present paper is aimed at proposing a composed approach in which the current distribution on the surface of the human body is given by the preliminary calculation described in Amoruso [9]. Substantially, the antenna-like body is decomposed into 11 conducting elemental blocks represented by leakage capacitances, serial resistances and inductances. These lumped parameters are inserted into a complex RLC network, treated by PSPICE, to give the current distribution over the human body. A further electrostatic entity, a floating or grounded sink, could be included as a 12th element connected directly, or by an interposed gap-shorting arc, to the man. Sensitive electronics is intended as being indistinguishable from, and disseminated over or inside, a larger object, the latter properly representing the 12th element. It is worth considering that the blocks are replaced by as many equivalent conducting spheres interconnected by unperturbing filaments. The equivalence for the spherical model is referred to the leakage capacitance in presence of the remaining parts of the overall body (electrical images included). The set of equivalent spheres was found by adopting an electrostatic-field version of the diakoptic technique, originally applied to circuit analysis (Amoruso [10]). Consider that simply using, for each block, a sphere with same surface of the exposed actual area, therefore assuming the blocks as being each other uninfluential, proves to be an adequate approximation only if the investigation is restricted to the total capacitance of the interconnected system (Chow [11]). In this case, the first-order approximation on the partial capacitances only causes, by error compensation, a second-order approximation on the total capacitance. Instead, preference has been expressed in Amoruso [10] for the diakoptic method in that the mutual influences are in this way taken into account. Partial physical capacitances to ground, variable in function of man’s posture, and mutual capacitances between disconnected sub-aggregates (Amoruso [12]), are given with an error at most approaching 10%. This restriction is not detrimental for several practical applications, the present one
included, for the reasons which will be cleared later. Once the partial capacitances are assessed, then the network can be resolved for the currents. The given surge currents can be subdivided into two correlated sets: serial currents (distributed over the body) and coupling (to ground) currents. As will be appreciated later, the latter set of currents is the prerequisite for the calculation of the surrounding human-generated ESD field. Such a calculation, which substantially represents the subject of this paper and forms the second part of the procedure, has been developed after having appropriately accommodated the original multi-sphere electrostatic model to the radiation study. In fact, it is worth bearing in mind the legitimate strategy of starting with a simple static approach before generalizing the calculation of the excitation field (Schelkunoff [13]).

![Figure 1](image)

Figure 1: Capacitively loaded monopole of spherical form.

2 Electromagnetic model

2.1 Supporting premises

ESD is a partially understood physical phenomenon which makes the construction of related models still uncertain. When such an event occurs, the motion of the electric charge, previously deposited in electrostatic equilibrium over the surfaces of the coupled conductors, produces a complex electromagnetic field. The difference between the electrostatic energies stored before and after the dynamic phase essentially dissipates, under form of heat, into the resistive paths carried by the discharging current (sparking gap included) (Greason [14]). However, a residual amount of that differential quantity is converted into radiating energy, even though it is not simple to quantify exactly how the energy loss in question is partitioned. In any case, it has been verified that the former portion of converted energy, the predominant one, is prone to increase further, at the expenses of the latter, as the discharge voltage increases (Honda [15]). A similar behavior is observable, even assuming the voltage unchanged, when arc
length and intruder geometry vary (Pommerenke [16]). A further agent which makes the model a rather difficult task is the approaching speed of the intruder, recognized to be jointly responsible for the non-linear character of the arc resistance (Renninger [17]). Even removing the above unpredictable variables, this is the case for a contact ESD, the so far disregarded frequency dependence of path resistance becomes, by elimination, an important feature. In any case, current’s waveform and peak value are subject to significant changes in function of the discussed variables, which result in a selection of the spectral components actually involved in the electromagnetic field.

Everything considered, adopting an approximate excitation-field model, the computational errors of which are within the described uncertainties affecting the physical interpretation of the charge transfer, seems a legitimate practice. Accordingly, the pre-charged sphere system, representing the electrostatic coupling of the human body to ground and victim, is estimated to be an adequate premise for the computation of the ESD radiation. In other words, the same spheres are assumed, during the dynamic phase, as simultaneous radiators. As previously pointed out, the model in Amoruso [9] was arranged to attain a final RLC network the resolution of which gives, in particular, the total current at the ESD contact or air-discharge point. Even the displacement currents to ground (associated to the leakage partial capacitances), as well as the serial (junction) currents pervading the human body was easily calculated. In particular, the former class of currents, namely those subject to conduction to displacement transition during the simultaneous discharge of the anatomical blocks, are identified as feeding currents associated to the corresponding blocks. Therefore, the latter are individually modeled by capacitively loaded monopoles of spherical form, see a sample in Fig. 1. This assumption derives from removing the serial junctions of the original multi-sphere model and replacing them by current-impressed filaments singularly feeding the disjoined spheres. Consider that the described model rearrangement is not responsible for field perturbations because

- the assigned current distribution exactly represents the charge transfer when the stray capacitances C of the RLC network are simultaneously discharged. Inspecting methodically the network permits recognition of the correlation between inter-sphere serial currents and single-sphere discharging currents;
- the manner of feeding each sphere, ultimately dictated by anatomical considerations, is consistent with the original topology of the RLC network. As will be appreciated later, both the orientation of the straight virtual filament connected to the sphere and the feeding-current direction, see Fig. 1, importantly affect the field computation.

The orientation of each filament is substantially dictated by the conical cavity made inside the connected sphere (tactily assumed solid) and co-axially penetrated by the final segment of the filament. The latter is attached to the sphere centre 0 where the apice of the conical hole is positioned. The opposite end of the conductor could be considered as connected to a common zero-potential reference placed at infinity. This is an educated guess consistent with
the condition of isolation applicable to the attached sphere. In fact, the associated capacitance benefits from the property of taking into account the electrostatic influence of the surrounding spheres, image ones included. For example, for an upright man with a horizontally raised arm, see Fig. 2, the conical-hole orientation, and, in turn, the on-axis filament, will be vertical, with the cone apice upward, or horizontal, with the apice pointing outward, for the spheres representative of the head or horizontal arm, respectively. Specifying the aperture angle $2\theta_0$ of the conical hole is unimportant as far as the evaluation of the excitation field, at a generic observation point, is concerned. However, according to boundary conditions circumventing field singularities, such an angle is not permitted to vanish. Accordingly, the quantity $2\theta_0$ is expected to assume a non-null value consistent with the finite radiation resistance realistically assigned to the spherical monopole (see Appendix).

Last, it is worth considering that the described multiple-monopole model tacitly invites to appropriately interpret the physical contribution of the arc to the field reconstruction. In fact, as the model is structured, the shorting arc is quite negligible as a proper additional field source. This merely because it results to be a short junction incorporated in the virtual filament feeding the connected final sphere (victim or closer image element). Rather, the arc is responsible for an indirect but remarkable influence, on the excitation field, which consists in affecting, by its own resistance, the distributed current waveforms.

![Diagram of a multiple-monopole model](image)

Figure 2: Multiple-monopole model of an upright man with one horizontally raised arm.
2.2 The governing equations

As previously described with reference to the radiator of Fig. 1, the impressed current substantially feeds the capacitive load represented by the conducting sphere in isolation. Accordingly, the current $i(t)$ experiences a conduction-to-displacement transition at the outer surface of the sphere (of radius $a$). The radiation surrounding the above transmitting monopole is described by a spherical wave formulated as follows

$$E_r = \frac{i[t-(r-a)/c]}{4\pi\varepsilon_0 r^2} \quad (2)$$

$$E_\theta = -\eta i[t-(r-a)/c] \frac{1 + \cos \theta}{4\pi r} \quad (3)$$

$$H_\varphi = \frac{E_\theta}{\eta} \quad (4)$$

Here, $E_r$, $E_\theta$ and $H_\varphi$ represent, with reference to a spherical coordinate system $(r,\theta,\varphi)$ centred on $0$, the radial and meridian electric fields and azimuthal magnetic field, respectively, at the generic radial distance $r \geq a$. Consistent with the surrounding free space are the permittivity $\varepsilon_0$ and permeability $\mu_0$, both involved in the definition of intrinsic impedance $\eta = \sqrt{\mu_0/\varepsilon_0} = 377$ $\Omega$ and propagation velocity $c = 1/\sqrt{\mu_0 \varepsilon_0} = 3 \times 10^8$ m/s. The retardation of the expanding/contracting wave, in conformity with the current direction, is represented by the quantity $(r-a)/c$. It is tacitly agreed that $i(t)$ flowing towards the origin $0$ is positive, in which case the wave propagates outwards. For the sake of precision, consider that the preliminary lumped-parameter network analysis, adopted after Amoruso [9], gives simultaneous, thus retardation-free, time dependent currents $i(t)$. Each of them should be assumed as impressed at the surface of the generic sphere, exactly where the conduction-to-displacement transition takes place. Accordingly, the function $i[t-(r-a)/c]$, embodied in the above field formulation, represents the retarded displacement current expanding with the same velocity $c$ of the spherical-wave front (for notation convenience, $i[t-(r-a)/c]$ is replaced by $i(t)$ if $r = a$).

Eqns (2)-(4) are elsewhere ascertained to be exact solutions of Maxwell’s equations when reference is made to the elementary example of a one-ended indefinitely long and straight current-carrying filament in isolation (see Schelkunoff [18] and related applications in Smyth [19] and Amoruso [20]). However, under the circumstances (in terms of boundary conditions) described in the previous sub-section, eqns (2)-(4) are also applicable to the radiating monopole shown in Fig. 1, namely to each element of the multiple-monopole model here adopted. It is worth considering that the formulation expressed by the above set of equations describes a pure TM mode wave, irrespective of
frequency. As the frequency increases starting from static conditions, higher modes of propagation remain, as a matter of fact, not excited provided the conservative principle for the charge is appropriately preserved (Schelkunoff [13]). The presence of an indefinitely long, infinitesimally thin conductor, supplying charge to the monopole or abstracting charge from it, is the prerequisite for meeting the above condition. Consider, in addition, that the spherical wave is permitted to propagate at constant velocity (equal to c) as the filament is assumed to keep straight, throughout.

The total excitation field is given by summation of the single waves which propagate from each spherical surface of the multiple-radiator system mimicking an operator in presence of the disturbing victim and images. The model gives unrealistic fields only in the interstices among spheres, thus in those unimportant space locations physically occupied by the human body. The calculation of the

Figure 3 : An example of upright standard man (geometrical details unspecified owing to their second-order effects on currents and fields).
outer field is safely applicable even in proximity to the body, compatibly with the spherical form virtually assumed by the partial sources. The above favourable prediction (see later for the experimental validation), is based on the convincement that the single sources simultaneously irradiate average elemental fields which combine to reproduce the total electromagnetic scenario with fairly good precision. In fact, eqns (2)-(4) are inherently exact, as well as accurate is the subsidiary calculation of the electrostatic and electrostatics-related integral quantities (partial capacitances and currents). On the other hand, the physical uncertainties raised in sub-Sect. 2.1 frustrate any realistic attempt of assigning the discharge distribution, over the conducting surface of the corpulent antennalike system, with superior degree of confidence. This even making recourse to powerful methods (see, for example, the careful commentaries found in Poljak [2] and Perez [21]) which appear rather over-dimensioned, as for degree of sophistication, when applied to this class of applications.

3 Examples of field reconstruction and comments

Figure 3 represents an upright operator stretching one arm out and touching an opposite vertical wall. Indeed, the contact is realized by an interposed arc (air-discharge mode). The scenario reproduces the experiment described in Pommerenke [16], where detection points P's were located on the wall at assigned distances from point P_3 of ESD. In this case, the 12th element is not included and two orthogonal families of images are involved. After Pommerenke [16], the points P's are aligned with a detection line inclined with angle $\alpha$ with respect to the horizontal. Fig. 4 a) and b) shows the theoretical oscillograms of the simultaneous E-field and H-field, respectively, for $\alpha=0$ and P-P_3 10 cm apart. The given curves are quite similar to those detected in Pommerenke [16] (further data skipped in caption). According to sub-Sect. 2.2, a more accurate comparison is discouraged by the uncertain nature of the arc.

Table I: Peak values of the electric and magnetic field components when $\alpha$ changes (see Fig. 3).

<table>
<thead>
<tr>
<th>Distance P-P_3 [cm]</th>
<th>E [kV/m] $\alpha=0^\circ$</th>
<th>H [A/m] $\alpha=0^\circ$</th>
<th>E [kV/m] $\alpha=90^\circ$</th>
<th>H [A/m] $\alpha=90^\circ$</th>
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Figure 4: Theoretical oscillograms of the E-field and H-field (curves a) and b), respectively) referred to the case of Fig. 3; $\alpha=0$ and $|P-P_s|=10$ cm; arc length 0.8 mm; essential ESD current data: 20 A, 0.8 ns (peak value and rise-time, respectively).
Figure 5: Displacement current distribution (feeding currents associated to the 11 monopoles) relative to the case of Fig. 3. Decomposition into two families a) and b) for graphical convenience. Current notation as in Fig. 2.
resistance. The assigned distribution of feeding surge currents is expressed in Fig. 5 by a collection of curves. As expected, such a distribution is seriously affected by the arc resistance incorporated as a non-linear component in the final section of the lumped-parameter network and calculated according to Amoruso [9] and Pommerenke [16]. It is a simple exercise to verify that, if the arc resistance is given by trial and error and the non-linearity is disregarded, impressive fittings of the oscillograms reported in Pommerenke [16] are permissible. However, apart from arbitrary manipulations and related discussion, it has been discovered how sensitive is the field calculation to a specific second-order detail in the current waveform. Such a detail is recognized to be the slowly-varying fine structure, as that appreciable in Fig. 4 in the first instants after the current onset, which precedes the fast-varying portion of the front. In fact, in spite of the common timescale origin, the structures in question turn out to be a practical substitute of, perhaps more realistic, pure retards. The latter are, of course, the result of a finite velocity assumed for the surge current travelling down a transmission line-like human body. Therefore, use has been made of a careful fitting technique, as that given in Heidler [22], originally adopted for reconstructing lightning-current waveforms. Table 1 reports E-field and H-field maxima at specified distances from P5 and orientation α. A further result, in accord to Pommerenke [16], is the moderate change in waveform and magnitude to which the above field components are subject in function of α alone. With

Figure 6: Seated man, in front of grounded victim, causing contact ESD. Observation point P distanced of 10 and 20 cm from the spherical victim (radius 20 cm).
Figure 7: As Fig. 4; case of Fig. 6; P horizontally distanced of 10 cm from the victim.
Figure 8: As Fig. 7; P horizontally distanced of 20 cm from the victim.
Figure 9: As Fig. 5; case of Fig. 6.
special reference to the H-field oscillogram of Fig. 4 b), consider that the most contribution is of course given by the horizontal arm. This accounts for the indistinguishable character of the peaks subsequent to and time-shifted from the first one.

The investigation has been extended to include the typical on-ground case of a seated man touching a grounded victim (vertical wall removed, see Fig. 6; experimental reference not available). Figs. 7 and 8 give the total field components for P horizontally aligned with and distanced of 10 and 20 cm from the victim. The latter is a sphere of 20-cm radius, so that its centroid and P are 30- and 40-cm apart. It is worth observing that the significant sequence of H-field peaks are now produced by a number of sources, disseminated throughout the human body, of comparable importance and fed by differently time-shifted currents. Specifically, the closest monopole, representing the victim, contributes moderately in excess to the remaining and more distanced monopoles owing to the reductive effect of setting θ=π/2, as required, in Eq. (4). The distribution of feeding currents, displayed in Fig. 9, are given imposing a vanishing arc resistance (ESD contact mode).

4 Conclusions

As often pointed out elsewhere, see for example (Leuchtmann [23]), a rigorous electromagnetic approach is in principle useful for a deeper understanding of the electromagnetic phenomena involved. However, practical applications could encourage use of simplified, even though sometimes unusual, models. This is the case for the subject matter treated in the present paper, where the current is not supplied by a voltage generator (therefore, it can not be rigorously assigned) and, furthermore, the common thin-wire approximation is inappropriate. Accordingly, the full problem has been decomposed into two subsidiary problems, the first of which is aimed at evaluating the current distribution by resolving a lumped-parameter network under capacitive discharge. The electrostatic model, preliminary adopted for evaluating the set of partial capacitances to be inserted into the above-mentioned RLC network, has been recovered and an attempt of generalization, thus also giving the radiative contribution of the overall field, has been attempted. A comparative examination of the results by experimental data leads to the conviction that, instead of the field calculation in itself, any departure is rather attributable to the computational uncertainties deriving from assessing the resistance of the current route. Such a difficulty could reasonably be overcome, in the case of air-discharge mode, by a minute calculation of the pre-discharge electrostatic field in the short gap between the hand-held intruder, if any, and the opposite electrode representing the sink. This advice derives from the ascertained correlation between arc resistance and electrostatic field pattern in the gap. Such a specific physical problem is estimated to be quite separable from, thus not detrimental for, the validity of the electromagnetic model in itself. Accordingly, apart from the present subject pertaining to ESD-related indirect
effects, the discussed multiple-monopole method seems prone to general applications. The model is especially recommended for resolving, with negligible computation time and computer memory, a considerable amount of engineering problems in which a high precision is not required or is beyond realistic expectations. However, such a performance makes the solution especially prone to give more insight into the ESD-excited field. In fact, the investigator is stimulated to reiterate the procedure to ultimately obtaining both extended electromagnetic scenarios and methodical field responses in function of critical variables. Even the very contribution of the short arc to the excitation field seems definitively cleared. However, an accurate experimental work, addressed to better estimate, in general, the degree of precision attainable by such a technique, is still needed.

References


Appendix

Applying the basic definition of radiating resistance $R_r$ to the monopole of Fig. 1, easily gives

$$R_r = \frac{n}{8\pi} \int_{\theta_o}^{\pi} \frac{(1 + \cos \theta)^2}{\sin \theta} d\theta \quad (A1)$$

With reference to the vector $E_\theta$, the 0-centered spherical surface, on which such a field component is destined to lie tangentially, is not required to approach infinity. This because $E_\theta$ holds regular for (namely tangential to) any spherical surface of radius $r>a$. Eq.(A1) could conveniently be rearranged as follows

$$R_r = \frac{n}{4\pi} \left( 2 \int_{\theta_o}^{\pi/2} \frac{d\theta}{\tan \theta} - 1 \right) \quad (A2)$$

where the integral in brackets approaches the value $10^m$ if $\theta_o$ is set equal to $10^{(6^m)}$. Therefore, if $I_{oj}$ denotes the peak value of the generic spectral component of the surge current $i_t(t)$ feeding the j-th monopole, the total resistance $R_{\tau}$ of the radiating assembly becomes
where $I_o$ is the peak value of the total current for that frequency. Setting $\theta_o=0$ in eqn (A1) gives $R_r$ tending to infinity, as deduced from the singularity expressed by eqn (2) when $\theta=\theta_o=0$. A rationale to establish the value of $2\theta_o$ could be derived from mere anatomical considerations involving the modeled block. However, such a limit angle can here remain unspecified since the observer is invariably distanced from those critical points and, additionally, evaluating $R_r$ is not strictly required.