Induced current into the human body by power frequency electric and magnetic fields

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Abstract — The induced currents into the human body by extremely low frequency simultaneous electric and magnetic field are computed by using a special formulation and 3D Finite Element method. The electromagnetic source fields and the induced currents are computed separately, allowing taking into account realistic radiating sources and anatomical models of the human body. Preliminary results using a simplified model of the body are presented.

I. INTRODUCTION

The power frequency electromagnetic field induces micro-currents inside the human body. Even if some simple considerations suggest that the energy of this radiation is too weak to be harmful for living systems [1], long-term effects are not well known, and so far firm conclusions cannot be drawn [2]. Hence, the quantification of these induced currents is a major issue for the medical research and for the definitions of industrial standards. In most of the scientific literature, only one of the two components of the electromagnetic field is taken into account, that is only the capacitive effects [3][4] or inductive effects [5][6] are computed. Inspired by a previous work of A. Bossavit [7], we developed a method to compute the induced current into the human body by both the electric and magnetic field.

II. THE FORMULATION

So as to find the equations to be solved, let's start from the complete Maxwell equations in the harmonic regime:

$$\nabla \times \mathbf{E} = -j\omega\mathbf{B} \qquad (1)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + j\omega\varepsilon\mathbf{E} \qquad (2)$$

Let A be a magnetic vector potential:

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad (3)$$

By substituting (3) in (1), one sees that the electric field can be expressed by:

$$\mathbf{E} = -j\omega\mathbf{A} - \nabla\phi \qquad (4)$$

where the scalar potential ϕ depends upon the gauge chosen for the vector potential $\mathbf{A}$. By taking the divergence of (2), and by using the Ohm's law $\mathbf{J} = \sigma\mathbf{E}$ together with (4) one obtains the following form of the continuity equation:

$$-\nabla \cdot \left[(\sigma + j\omega\varepsilon)(j\omega\mathbf{A} + \nabla\phi) \right] = 0 \qquad (5)$$

The interface conditions at the boundary human body/air are provided by the following relation:

$$\left[\!\left[\mathbf{n} \cdot (\mathbf{J} + j\omega\varepsilon\mathbf{E}) \right]\!\right] = 0 \qquad (6)$$

Indeed equations (5) and (6) are quite general. The next step is to obtain from them the formulations used in the particular cases of human exposure to **H**, **E** and **H**+**E**.

A. Magnetic field exposure

Assume that the electric field is negligible. Due to the weak conductivity of the living tissues (of the order of 0.2 S·m^{-1}) it can be comfortably assumed that at low frequency the magnetic field is not modified by the currents into the human body [5]-[7]. Hence, the flux density **B** – or, more precisely, a vector potential **A** – can be obtained by a classical preliminary computation (where the human body is replaced by the void), and plays the role of a source term in (5). The benefits of such decomposition of the computational task are discussed extensively in [5][6]. Moreover, displacement currents can be neglected. Thus one obtains the following "H-exposure" version of (5):

$$-\nabla \cdot \left[\sigma(j\omega\mathbf{A} + \nabla\phi) \right] = 0 \qquad (5^H)$$

where the only unknown is the scalar potential ϕ. This equation is solved only inside the human body. The boundary condition is obtained by removing all the displacement terms from (6):

$$\mathbf{n} \cdot \mathbf{J} = 0 \quad \Rightarrow \quad \partial\phi/\partial n = -j\omega\mathbf{A} \cdot \mathbf{n} \qquad (6^H)$$

One observes that these two relations are the strong form of the well known ϕ-**A** formulation. When the human body is in electrical contact with the ground, a part of the soil must be included in the computational domain [7].

B. Electric field exposure

Assume now that the magnetic field is negligible, and consequently: $\mathbf{A} = 0$. In this case displacement currents can be neglected in the human body (in spite of its very high permittivity) but certainly not in the air: hence (5) reduces to the classical "dielectric formulation":

$$-\nabla \cdot \left[(\sigma + j\omega\varepsilon)\nabla\phi \right] = 0 \qquad (5^D)$$

This equation ought to be solved in the whole domain (radiating source + human body). Equation (6) reduces to:

$$\mathbf{n} \cdot \mathbf{J} = \mathbf{n} \cdot j\omega\varepsilon_0\mathbf{E}_{air} \qquad (6^D)$$

A more elegant solution is to take into account the high permittivity of the living tissues (of the order of 10^6 at 50 Hz) to obtain by a preliminary computation the right hand term of (6^D). In fact, due to the high permittivity of the body, the electric field is nearly perpendicular to the body: hence the term $\mathbf{n} \cdot j\omega\varepsilon_0\mathbf{E}_{air} = \tau$ can be computed by replacing the human body by an equipotential surface. Then, τ is used as source term in a further "E-exposure" problem, whose domain is bounded to the human body:

$$-\nabla \cdot (\sigma\nabla\phi) = 0 \qquad (5^E)$$

$$\mathbf{n} \cdot \mathbf{J} = \tau \qquad (6^E)$$

Again, the original computation is splitted into two smaller (and simpler!) computations.

C. Magnetic and electric field exposure

So far, we can compute the current density which is induced by a simultaneous exposure to the **H** and **E** fields by the following three-steps method:

1) Compute the magnetic potential **A** in absence of the human body.

2) Compute the term $\tau = \mathbf{n} \cdot j\omega\varepsilon_0 \mathbf{E}_{air}$ by replacing the human body by an equipotential surface.

3) Compute the scalar potential by solving (5^H) in the human body, with (6^E) as boundary condition:

$$-\nabla \cdot [\sigma(j\omega\mathbf{A} + \nabla\phi))] = 0 \qquad (5^{HE})$$

$$\mathbf{n} \cdot \mathbf{J} = \tau \qquad (6^{HE})$$

Alternatively, one may solve (5^H) and (5^D) instead of steps 2) and 3), and superpose the results in the human body. This solution is correct, but not as interesting as the former, in that the dielectric problem (5^D) is much harder than (5^E).

One wonder if were it possible to "condense" steps 2) and 3) into a single step, by solving directly (5^{HE}) with the same boundary conditions that one would use for the dielectric problem (for instance to impose a certain voltage between a power line and the ground, as in the following example). Interesting idea... but false: due to the inductive phenomena, the electric field is not curl-free, and the constraints on ϕ which work with (5^D), would fail when applied to (5^{HE}). Moreover, this approach is computationally less interesting than the proposed three-steps method.
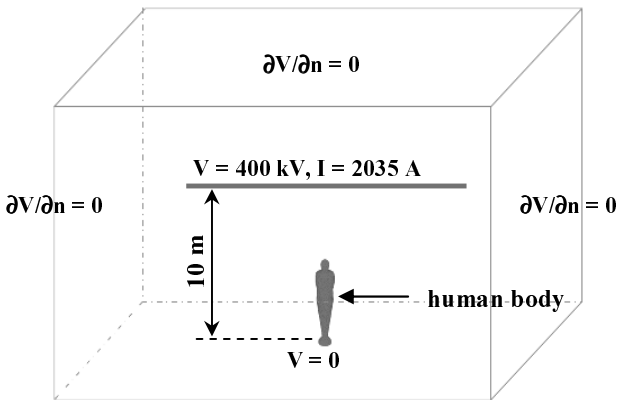

Fig. 1. Geometry of the problem

III. PRELIMINARY RESULTS

As example, we computed the current induced into the human body by the field radiated by a high-voltage power line (V=400 kV, I= 2035 A), modeled as an infinite wire, placed at 10 m from the soil [8] (fig. 1). The vector potential **A** has been analytically computed by using Biot-Savart's law. The equations which have been solved are (5^H) = **H**-exposure problem, and (5^D) = dielectric problem.

At present time, the model used for the human body is an homogeneous (σ=0.2 S·m^{-1}, ε_r=10^7) axisymetric solid. One sees (fig. 2) that in this case the electrically induced currents dominate, even if some minor modifications to the current distribution due the effect of magnetically induced currents can be observed.
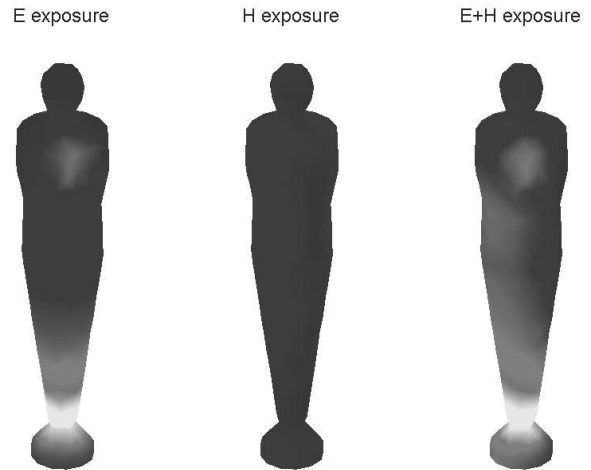

Fig. 2. Induced current by **E**, **H** (separately) and **E** + **H** fields

IV. CONCLUSION

A method to compute induced currents in the human body by both **E** and **H** fields, is presented. This method is much more effective than a direct "full computation", in that the original problem is decomposed in three simpler problems, which are solved in cascade. More realistic examples of exposure, together with an heterogeneous anatomical model of the human body will be presented in the full paper.

V. REFERENCES

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