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Computation of currents induced by ELF electric fields in anisotropic human tissues using the Finite Integration Technique (FIT)

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Abstract. In the recent years, the task of estimating the currents induced within the human body by environmental electromagnetic fields has received increased attention from scientists around the world. While important progress was made in this direction, the unpredictable behaviour of living biological tissue made it difficult to quantify its reaction to electromagnetic fields and has kept the problem open. A successful alternative to the very difficult one of performing measurements is that of computing the fields within a human body model using numerical methods implemented in a software code. One of the difficulties is represented by the fact that some tissue types exhibit an anisotropic character with respect to their dielectric properties. Our work consists of computing currents induced by extremely low frequency (ELF) electric fields in anisotropic muscle tissues using in this respect, a human body model extended with muscle fibre orientations as well as an extended version of the Finite Integration Technique (FIT) able to compute fully anisotropic dielectric properties.

1 Introduction

Simulations that take into account the anisotropy of muscle tissue were already performed by (Dawson and Stuchly, 1998). This paper reports a number of other authors that earlier incorporated anisotropic tissue properties within numerical methods like FD, FDTD and FEM. Dealing with SPFD and magnetically induced fields and currents, the paper of (Dawson and Stuchly, 1998) presents plenty of results for miscellaneous exposure conditions under the limitation of considering all the muscle fibers oriented parallel or perpendicular to the longitudinal axis of the body. These hypotheses can offer an image of the limits of induced current densities as they represent extreme cases, however as mentioned in the paper, the anisotropy of muscle tissue changes the current paths giving thus importance to the real fiber orientation especially for organ dosimetry.

In order to present our method for computation of electrically induced currents in the human body accounting for the anisotropy of skeletal muscles, we perform some simulations with a realistic human body model standing under a transmission power line employing the algorithm of the Finite Integration Technique (FIT) – a numerical method which discretizes Maxwell's equations on a grid pair preserving the analytical properties of the original equations (Weiland, 1977).

The human body model known as HUGO is based on the cryosection images provided by the Visual Human Project of the National Library of Medicine, Maryland, USA, which were assembled in a 3-D voxel model and then extended with muscle fiber orientations by a working group at the Institute of Biomedical Engineering, University of Karlsruhe, Germany (Sachse, 1998). It is known that muscle tissues present a transversal isotropic anisotropy with regard to their dielectric properties (Sachse, 1997). This property leads to diagonal material tensors in a local coordinate system aligned to the main directions of the fibers, while in a global coordinate system the anisotropy of muscle tissue is depicted by a full and symmetric tensor.

In a previous paper (Motrescu and van Rienen, 2004) we published details about the human body model, dielectric properties of biological tissues, and the extension of the Finite Integration Technique for computing anisotropic tissues. At that time, we performed simple electrostatic simulations with anisotropic muscle tissues considering different anisotropic ratios for the validation of our method. Comparison to the isotropic case has shown that the anisotropy of muscles changes the distribution of the electric potential inside the muscles and consequently the displacement current computed with this potential.

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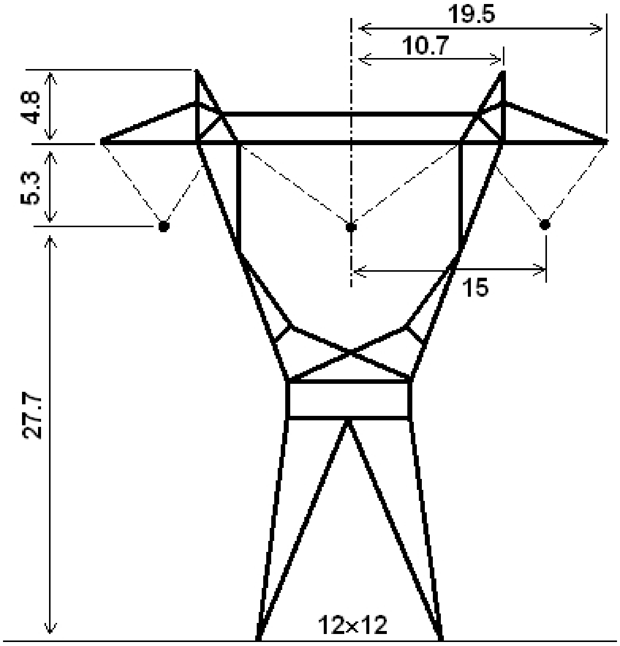

Fig. 1. Tower geometry (All dimensions are given in meters).

In this paper we publish results from electro-quasistatic simulations with a model which includes the anisotropy of both conductivity and permittivity, the latter expressing the capacitive effect at the separation plane between different tissue types.

2 Materials

As already mentioned, the electric field source chosen for our simulations is represented by a high voltage transmission power line operating at 765 kV and 50 Hz with parameters taken from EPRI (1982). Within an electromagnetic simulation software package based on the Finite Integration Technique (CST EMStudio^{TM}), a high voltage tower of lattice type, made of steel, for a single horizontal circuit, was modelled with the main dimensions given in Fig. 1.

The power line consists of two such towers situated at a distance of 408 m from each other such that the conductors in between have a length of 396 m corresponding to the average span length provided in EPRI (1982). For each phase consisting of four conductors with a diameter of 4 cm, spaced 60.96 cm from each other, we calculated an equivalent diameter of 43.63 cm with the formula given in Eq. (1) which is valid for conductors structured in regular bundles and calculation of fields that are far from the conductor surface (Deno and Zaffanella, 1982).

$$d_{eq} = D\sqrt[n]{\frac{nd}{D}} \tag{1}$$

In Eq. (1), D is the bundle diameter, n is the number of subconductors and d is the diameter of the subconductors.

Table 1. Minimum clearances for the 765 kV transmission power line.

Distance	Value in meters
Phase to tower	4.2
Phase to ground	16.2
Phase to phase	13.8

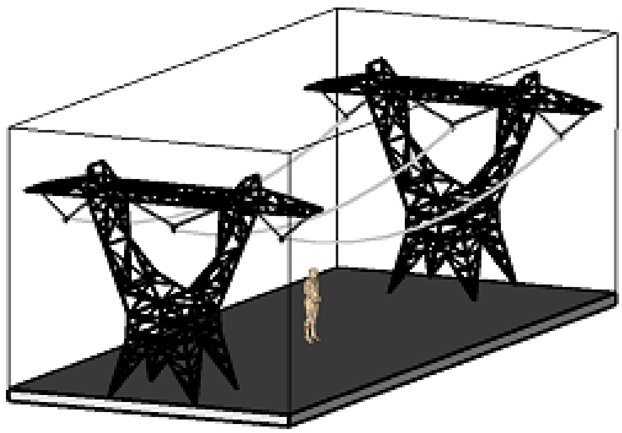

Fig. 2. Human body standing under the power line. Perspective view of the computational domain.

Shield wires were omitted considering that because they are positioned above the phase conductors, their influence is very small near the ground level. All the insulators were modeled as simple insulating rods while the ground was assigned to a perfect electric conductor (PEC) layer in galvanic contact with both towers assigned to the same layer. The ground was assumed to be perfect electric conductor based on the fact that earth surface charges redistribute very fast (0.1 to 100 ns) under a change in the applied field compared to the period of power frequency (Deno and Zaffanella, 1982). The power line configuration does not exceed minimum clearances recommended by the designers and provided in Table 1. At midspan the conductors reach the level of 16.2 m above ground which is equivalent to the minimum phase to ground clearance. The entire computational domain shown in Fig. 2 where the human body is standing under the power line, has the following dimensions: 414 m×52 m×40 m.

3 Methods

Due to the large sizes of the transmission line, we perform the simulation in two steps. In a first step the human body is removed from the computational domain and the power line, discretized on a grid of 6.4 million nodes, is simulated within the CST EMStudio^{TM} software package as an electrostatic problem with open boundary conditions.

The potential value found at the level of two meters above ground, is imposed in a second step as a boundary condition in an electro-quasistatic simulation with a much finer grid and fully anisotropic material properties, with the computational domain consisting of the human body surrounded by air. The second step computation is performed within a C^{++} software code (implemented by us for this purpose) that uses the CST EMStudio^{TM} only for the visualization of the computed fields.

3.1 Electrostatic simulation

Since electrostatic fields exist only in non-conductive media, there are no conduction, convection, or impressed currents in the mathematical model of electrostatics (van Rienen, 2001). The electric fields and displacement currents are calculated by solving in conjunction with the potential theory, a Poisson type equation of the form:

$$div\,(\underline{\varepsilon}\;grad\;\varphi) = -\rho \tag{2}$$

where $\underline{\varepsilon}$ is the rank two tensor of dielectric permittivity, φ is the electric potential and ρ the charge density. When discretized with FIT, the formula in Eq. (2) becomes:

$$\tilde{\mathbf{S}}\mathbf{M}_{\varepsilon}\tilde{\mathbf{S}}^{T}\Phi_{E} = \boldsymbol{q} \tag{3}$$

with the discrete divergence operator $\tilde{\mathbf{S}}$, the material operator $\mathbf{M}_{\varepsilon}$ and the discrete gradient operator $\mathbf{G}=-\tilde{\mathbf{S}}^{T}$. The discrete potential is denoted by Φ_E and the discrete charge density by $\boldsymbol{q}$.

The electric fields arising from a power line over a flat ground are practically vertical near the ground level (Deno and Zaffanella, 1982) reaching the maximum values at midspan. Figure 3 shows the lateral profile of the power line taken at two meters above the ground level in the midspan. Maximum values of both, potential (11.230 kV) and electric field (5.796 kV/m) were found under the midphase. This conforms to the potentials allocated on the phase conductors i.e. 441.672 kV on the midphase B and a negative potential of –220.836 kV on both lateral phases, A and C. The situation corresponds to the time t=0, (origin of the time axis) in Fig. 4 where the three-phase harmonic voltage system was represented. The phases were considered in a “wye” configuration. The ground potential was set to zero volt.

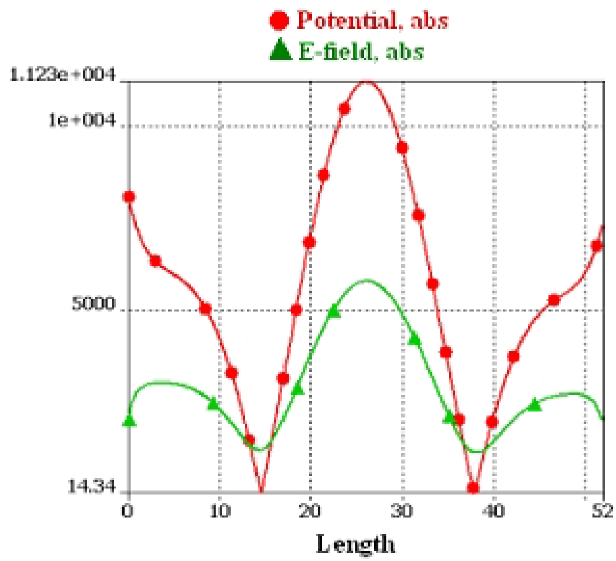

Fig. 3. Lateral profile of the power line at the level of two meters above ground (Markers have only an identification role).

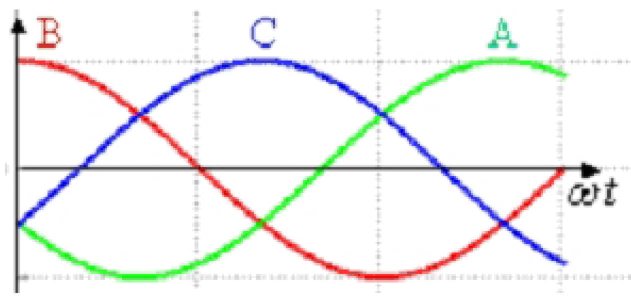

Fig. 4. Three-phase system of 50 Hz voltages.

3.2 Electro-quasistatic simulation

At the frequency of 50 Hz the electromagnetic field has a wavelength of 6000 km which is very large compared to the size of a person so that the quasistatic assumption is fulfilled. For a predominantly electric field (electro-quasistatic, EQS), the time-derivative of the magnetic flux is negligible while the displacement currents have to be taken into account. Regarding the time harmonic EQS fields, these assumptions reduce the Maxwell’s equations to the following complex Poisson type equation:

$$div\,((i\omega\underline{\varepsilon} + \underline{\sigma})grad\;\underline{\varphi}) = div(\underline{\boldsymbol{J}}_i) \tag{4}$$

The propagation medium is considered anisotropic described by the rank two symmetric tensors $\underline{\sigma}$ and $\underline{\varepsilon}$ having no electric charges in motion. The complex amplitude of the electric field is defined as the gradient of the complex scalar potential $\underline{\boldsymbol{E}}=-grad\;\underline{\varphi}$. The complex impressed current density is denoted by $\underline{\boldsymbol{J}}_i$.

With FIT, the continuous equation in Eq. (4) is discretized into the following one:

$$\tilde{\mathbf{S}}(i\omega\mathbf{M}_{\varepsilon} + \mathbf{M}_{\sigma})\tilde{\mathbf{S}}^{T}\underline{\boldsymbol{\Phi}}_{E} = \tilde{\mathbf{S}}\underline{\boldsymbol{j}}_i \tag{5}$$

with the discrete divergence operator $\tilde{\mathbf{S}}$, the material operators $\mathbf{M}_{\varepsilon}$, $\mathbf{M}_{\sigma}$ and the discrete gradient operator $\mathbf{G}=-\tilde{\mathbf{S}}^{\mathbf{T}}$. For the electro-quasistatic computations, the algorithm of FIT extended with fully anisotropic material properties was implemented in a software code which uses solvers from PETSc (Balay et al., 1997) for the solution of linear algebraic systems. The human body model of 8 mm resolution consisting of cubic voxels and extended with muscle fibre orientation was imported within the software code in a box with sizes: 592 mm×336 mm×1872 mm. At left, right, front and back we added on each side 72 mm of air. On the top-bottom direction, the air was added such that for different positions of the human body on this direction, the computational domain has always a height of two meters. This restriction comes from the fact that at the top side we impose through the Dirichlet boundary conditions, the maximum value of the unperturbed potential computed within the electrostatic simulation at the level of two meters above the ground, i.e. 11.230 kV. At bottom side we impose the corresponding ground potential from the electrostatic simulation i.e. zero volt. The left-right and front-back sides were treated conveniently with Neumann boundary conditions. This set of boundary conditions enforces the fields to be parallel to the longitudinal axis of the human body keeping thus the direction of the unperturbed electric fields under the power line near the ground level. The entire domain is discretized with a number of approximately 1.4 million mesh-nodes when the mesh is regular having the same size with the human body model resolution i.e. 8 mm. With respect to the position of the human body relative to the bottom boundary of the computational domain, we imagined three situations:

- Both feet touching the ground;
- Only one foot touching the ground;
- Both feet in the air.

With respect to the dielectric properties of tissues we imagined the following five situations:

- All tissues are isotropic;
- Anisotropic muscle with realistic fibre orientation;
- Anisotropic muscle with all fibres oriented on the top-bottom direction of the body;
- Anisotropic muscle with all fibres oriented on the left-right direction of the body;
- Anisotropic muscle with all fibres oriented on the front-back direction of the body.

Combining the two sets from above, we run a number of fifteen simulations. The dielectric properties of the isotropic tissues used in simulations were taken mainly from (Andreuccetti et al., 1997) which is a web server application calculating the dielectric properties of human body tissues using the parameters published by (Gabriel et al., 1996a). The anisotropic properties of muscles, in a ratio of 1.17 for the conductivity, and 2.27 for the permittivity, were taken directly from (Gabriel et al., 1996b).

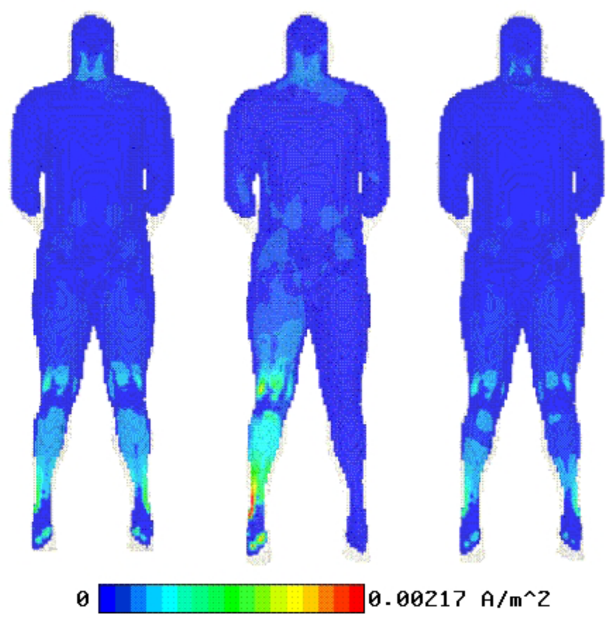

Fig. 5. Differences between real parts of the induced current densities in a section of the body computed with isotropic and anisotropic (natural orientation) muscles for the cases: left – both feet touch the ground, middle – only one foot touches the ground, right – both feet isolated from ground.

4 Results

As results from the electro-quasistatic simulations we provide a scalar plot of the difference between real parts of the induced current densities in a section of the body computed with isotropic and anisotropic (natural orientation) muscles for the cases when both feet touch the ground, only one foot touches the ground, and both feet isolated from ground.

Maximum values of the current density in different parts of the body are tabulated in Appendix A.

5 Discussions

The current density values from Table A1 show that the basic restriction for human exposure to ELF electric fields, of 2 mA/m^2 (for the general public, in head, neck and trunk) established by ICNIRP (1998) are not exceeded under the power lines.

6 Conclusion

In this paper we investigated the induced current densities in a human body standing under a transmission power line considering the anisotropy of muscle tissues and different exposure conditions. The results were presented in a plot as well as tabulated.

Appendix A

Table A1. Maximum current densites found in different parts of the body expressed as rms values in [mA/m^2] for the situation when the human model touches the ground with both feet, with only one foot or is isolated from ground and muscle tissues are considered isotropic or anisotropic with fibres orientation specified in the left column.

	Ankles	Head	Neck	Trunk
Both feet touching the ground				
Isotropic	2.296	0.779	0.463	0.485
Anisotropic natural	3.682	0.845	0.679	0.587
Anisotropic front-back	2.315	0.887	0.454	0.483
Anisotropic left-right	2.421	0.819	0.492	0.492
Anisotropic top-bottom	3.690	0.849	0.671	0.605
One foot touching the ground				
Isotropic	4.590	0.851	0.505	0.512
Anisotropic natural	7.106	0.923	0.741	0.615
Anisotropic front-back	4.733	0.969	0.496	0.568
Anisotropic left-right	5.601	0.895	0.537	5.385
Anisotropic top-bottom	7.100	0.928	0.733	0.646
Both feet in the air				
Isotropic	1.553	0.649	0.385	0.399
Anisotropic natural	2.444	0.705	0.565	0.484
Anisotropic front-back	1.604	0.740	0.378	0.397
Anisotropic left-right	1.503	0.683	0.409	0.410
Anisotropic top-bottom	1.553	0.649	0.385	0.399

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