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Calculation of induced currents in a human body represented by a spheroidal model

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Abstract

There has been much discussion about possible health risks from exposure to power system electric and magnetic fields. The induced current densities in a human body located in these extremely low frequency fields can be determined by calculation. The basic restriction of the ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines for 50 Hz fields is 10 mA/m^2 (to workers). The aim of this study is to examine the induced current densities due to power system fields in the working environment by using the spheroidal calculation model.

The study includes 27 workers exposed to electric and magnetic fields from power systems in different work environments. The fields in the workplaces were measured for calculation. The internal field and current density induced in a human body by the electric and magnetic fields was calculated using the spheroidal model, which is suitable for evaluating the current density in the whole body. Tissue conductivity of 0.2 S/m was used in this calculation.

The highest measured values in different workplaces were 0.14 kV/m ... 11.2 kV/m for electric fields and 0.57 μT ... 16.2 μT for magnetic fields. The calculated internal fields caused by the electric fields were 0.097 mV/m ... 7.79 mV/m. The induced internal currents were 0.019 mA/m^2 ... 1.56 mA/m^2 by electric fields and 0.0050 mA/m^2 ... 0.14 mA/m^2 by magnetic fields. When the current densities were roughly summed the values were 0.024 mA/m^2 ... 1.70 mA/m^2.

The internal current densities are clearly below the ICNIRP guidelines, 10 mA/m^2. For the general public the exposure limits are lower because of safety margins. The calculated values are far from these values as well. The calculated internal currents caused by electric fields are about ten times higher than the currents caused by magnetic fields.

1 Background

The potential health effects of extremely low frequency electric and magnetic fields have been studied for several years. There have been many studies searching for effects due to ELF fields, and the results obtained by different groups have differences [1]. In general, exposure to ELF fields is not considered to be a hazard to public health. However, the knowledge of the biological effects of ELF fields is not yet sufficient. In order to confirm that electric power systems have no effect on human health, further research should be done.

The basic restriction of the ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines for 50 Hz fields is 10 mA/m^2 [2]. The restriction is provided on current density to prevent effects on nervous system functions [2]. In the occupational field exposures at 50 Hz the reference levels are 10 kV/m for electric field strength and 500 μT for magnetic flux density [2]. For the general public the reference levels at 50 Hz are 5 kV/m and 100 μT [2].

The Finnish power transmission network has voltage levels of 110 kV, 220 kV, and 400 kV. At those voltage levels there are both transmission lines and switching substations. In 1996, the total length of the transmission network was 21 331 km and there were 57 substations where the higher voltage was 400 kV or 220 kV [3]. These cause high electric and magnetic fields in their environment.

External electric and magnetic fields, e.g., of transmission lines, induce internal currents in the human body. Internal currents induced by fields are low. Therefore they are difficult to measure in real working environments. One method to evaluate the biological effects is to calculate internal fields and current densities. This can be done with different calculation models.

In order to calculate the internal electric field in a human body, one needs to know the external field, the exposure environment, and the geometry of the human body. Due to the complex geometry of the human body, precise calculation of the internal fields is difficult. To simplify the calculation of internal fields and current densities, different models have been developed. By means of the simple models a rough estimate for the magnitude of the internal currents may be obtained. [4]

In this paper, a simple geometrical model for calculating the internal electrical fields and current densities has been used. The aim of this study is to examine the induced current densities due to power system fields in the working environment by using the spheroidal calculation model.

2 Studied working environments

The study includes 27 workers exposed to electric and magnetic fields from power systems in different environments. The environments included 110 kV, 220 kV and 400 kV switching substations, and 110 kV transmission lines. Environments of all workers are described in table 1. More than one workers worked in some places.

The external electric and magnetic fields in the workplaces were measured for calculation. The internal field and current density induced in a human body by the electric and magnetic fields was calculated by using the spheroidal model, which is suitable for evaluating the current density in the whole body.

Table 1. Work environments of studied workers.

worker	work description
I001 - I003	transmission line construction, new line besides old 110 kV line
I004	cable installation, near 110 kV substation and transmission line
I005	transmission line construction, new line besides old 110 kV line
I006	transmission line construction, new line besides old 110 kV line
I007	station expansion, 110 kV substation
I008	transmission line construction, new line besides old 110 kV line in same tower
I009	transmission line construction, new line besides old 110 kV line
I010	station expansion, 110 kV substation
I011	station expansion, 400 kV and 110 kV substation
I012, I013	maintenance, 220 kV substation
I014	station expansion, 400 kV and 110 kV substation
I015	station expansion, 110 kV substation
I016	station expansion, 110 kV substation
I017	station expansion, 110 kV substation
I018	station expansion, 110 kV substation
I019	station expansion, 110 kV substation
I020	station expansion, 400 kV substation
I021	station expansion, 400 kV substation
I022, I023	station expansion, 400 kV substation
I024, I025	station expansion, 400 kV substation
I026, I027	station expansion, 400 kV substation

3 Methods

3.1 Measurement methods

In electric and magnetic field measurements IEEE Std. 644-1979 for measurement of transmission line electric and magnetic fields was applied. The fields were measured for each worker in all work environments during the measurements. The electric and magnetic fields were measured with meters made by IVO. The electric and magnetic fields were measured periodically and whenever the work place changed. The measurement height was 1 m.

3.2 Calculation method

3.2.1 Properties of tissues

Due to the interaction of electric and magnetic fields with the human tissue, electric currents are induced. If the internal electric field in the tissue is E, the current density, J, can be determined as follows:

$$J = \sigma E \qquad (1)$$

Here, σ is the electrical conductivity of the tissue. Quite naturally, different tissues have different conductivities. This makes the detailed calculation of internal current densities a very difficult task. However, by using simple models the human body can be treated as homogenous. According to Bernhardt [5], the average conductivity of the tissue is from 0.1 S/m to 0.2 S/m. An appropriate value for the conductivity of the tissue in calculation is then 0.2 S/m.

The permittivity of human tissue, ε, is large, about $10^5\ \varepsilon_0$, where ε_0 is the permittivity of free space. Despite this, at low frequencies tissues are perfectly conductive, and have no capacitive properties depending on the frequency. The magnetic field gives rise to an electric field in the tissue. This, in turn, results in eddy currents. Human tissue can be considered paramagnetic, and in practical calculations its permeability, μ, is essentially the permeability of free space μ_0.

3.2.2 Prolate spheroid theory

The prolate spheroid model describes the interaction of electric and magnetic fields and a homogenous prolate spheroid consisting of tissue. Due to its geometry, it is preferred in approximating the internal electric field in the whole human body. Prolate spheroid model of a human in electric field is presented in figure 1 and in magnetic field in figure 2.

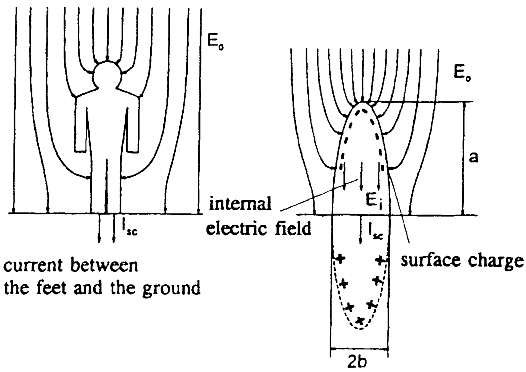

Figure 1. A human and it's prolate spheroid model in an external electric field, E_0, and induced internal electric field E_i. Major axis of prolate spheroid is 2a and minor axis is 2b.

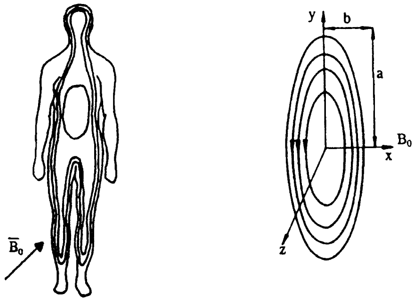

Figure 2. A human and it's prolate spheroid model in an external magnetic field, B_0. Major axis of prolate spheroid is 2a and minor axis is 2b.

The effect of the external electric field is considered first. For a homogenous, prolate spheroid in a sinusoidal, low frequency, vertical electrical field E_0, the peak value of the internal electric field E_i is according Hill [6]:

$$E_i = j \frac{2\pi f \varepsilon_0}{\sigma (N/4\pi)} E_0 \tag{2}$$

Here, ε_0 is $8.854 \cdot 10^{-12}$ F/m, and $(N/4\pi)$ is the depolarity factor for a prolate spheroid. In case of a human body, appropriate values for the depolarisation factor are, for an isolated ellipsoid 0.035, and for a grounded ellipsoid, 0.02. By using eqn (1), the internal current density can be obtained.

Spiegel [7] has derived equations for the internal electric field in a prolate spheroid due to a magnetic field. By manipulating these formulae and using eqn (1) for the internal current density, it can be noticed that the current density is largest in the vicinity of the surface of the spheroid. When the formulae are simplified, the maximum value for the current density J_B at the surface of the prolate spheroid in a horizontal magnetic field of magnitude B is obtained:

$$J_B = -j\, 2\pi f \sigma b B_0 \tag{3}$$

Tissue conductivity of 0.2 S/m was used in calculations. Appropriate value for the minor axis of the spheroid, b, when modeling human body is 0.14 m.

An estimate for the effect of the combined fields may be obtained by simply adding the maximum values from eqns (2), (1) and (5). The directions and phases of the vectors are not taken into account in this rather crude approximation.

4 Results

The measurement period of each worker varied from 1 to 4 hours. The measurement results of the external fields are shown in table 2. The highest measured values in different workplaces were 0.14 kV/m ... 11.2 kV/m for electric fields and 0.57 μT ... 16.2 μT for magnetic fields.

Table 2. External electric and magnetic fields experienced by the workers.

worker	electric field strength E_0, kV/m	magnetic flux density B_0, μT
I001 - I003	0.35 ... 1.12	1.72 ... 3.47
I004	0.35	1.97
I005	0.87	2.66
I006	0.85 ... 0.87	2.64 ... 2.66
I007	1.3	2.11
I008	0.14	0.57
I009	0.85	2.64
I010	0.14 ... 0.26	0.97 ... 1.02
I011	2.78 ... 10.21	2.40 ... 10.92
I012, I013	5.57 ... 7.44	4.42 ... 6.89
I014	2.78 ... 11.2	2.40 ... 16.2
I015	0.54	1.90
I016	0.54	1.90
I017	0.58	2.01
I018	0.55	2.01
I019	2.95	2.20
I020	1.53 ... 8.45	1.43 ... 10.92
I021	1.53 ... 8.64	1.43 ... 10.92
I022, I023	7.26 ... 8.64	6.16 ... 15.43
I024, I025	7.21 ... 9.18	6.30 ... 10.93
I026, I027	6.83 ... 8.62	4.74 ... 8.71

Internal electric fields and induced currents were calculated based on these results. A rough estimate for the combined induced current density by the electric and magnetic fields can be calculated by summing the separate current densities.

$$J = J_E + J_B \tag{4}$$

The calculation results for the workers are shown in table 3. The calculated internal fields caused by the electric fields were 0.097 mV/m ... 7.79 mV/m. The induced internal currents were 0.019 mA/m² ... 1.56 mA/m² by electric fields and 0.0050 mA/m² ... 0.14 mA/m² by magnetic fields. The sum of induced internal currents by

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electric and magnetic fields was 0.024 mA/m² ... 1.70 mA/m².

Table 3. Current densities induced by electric fields, J_E, by magnetic fields, J_B, and their sum, J, in workers.

worker	induced current density J_E, mA/m^2	induced current density J_B, mA/m^2	total current density J, mA/m^2
I001 - I003	0.048 ... 0.16	0.015 ... 0.031	0.063 ... 0.19
I004	0.048	0.017	0.065
I005	0.12	0.023	0.14
I006	0.12	0.023	0.14
I007	0.18	0.019	0.20
I008	0.019	0.0050	0.024
I009	0.12	0.023	0.14
I010	0.019 ... 0.036	0.0085 ... 0.0090	0.028 ... 0.045
I011	0.39 ... 1.42	0.021 ... 0.096	0.41 ... 1.52
I012, I013	0.77 ... 1.03	0.039 ... 0.061	0.81 ... 1.09
I014	0.39 ... 1.56	0.021 ... 0.14	0.41 ... 1.70
I015	0.076	0.017	0.093
I016	0.076	0.017	0.093
I017	0.080	0.018	0.098
I018	0.076	0.018	0.094
I019	0.41	0.020	0.43
I020	0.21 ... 1.18	0.013 ... 0.096	0.22 ... 1.28
I021	0.21 ... 1.20	0.013 ... 0.096	0.22 ... 1.30
I022, I023	1.01 ... 1.20	0.054 ... 0.14	1.06 ... 1.34
I024, I025	1.00 ... 1.28	0.055 ... 0.096	1.06 ... 1.38
I026, I027	0.95 ... 1.20	0.042 ... 0.077	0.99 ... 1.28

The highest as well as the lowest electric and magnetic fields occurred in the same place. Hence the highest and the lowest current densities by separate fields induced in the same workers. Therefore also the highest and the lowest total current densities induced in those same workers.

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5 Conclusion

The calculation of induced internal current densities in whole body volume can be done quite easily with the prolate spheroid model. When the external field values are measured the current densities can be calculated using simple equations. In the equations simple coefficients are used to describe the geometry and dimensions of human body. In this study the workers were all considered similar.

The calculation results show that the internal current densities are clearly below the ICNIRP guidelines 10 mA/m^2. For the general public, the limits were lower because of safety margins. The calculated values are far from these values as well. The highest calculated internal currents caused by electric fields are about ten times higher than the currents caused by magnetic fields. Therefore more attention should be paid to them than to magnetic fields. This result is fortunate since it is generally easier to protect from electric fields than magnetic fields.

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