Magnetic Field-Induced Currents in Human Body in the Proximity of Power Lines

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Abstract- The paper presents a model for the interaction between humans and ELF magnetic fields generated by power lines. Electric current densities induced due to 50 Hz magnetic fields in a human model placed in a close proximity of 500 kV lines are presented and analyzed. The specific absorption rate (SAR), is investigated for various human model locations under the power lines. Also examined in this work is the case of live line maintenance workers, where they may be located near the central and the outermost phase conductors. The induced current density and SAR are computed and discussed.

Keywords: ELF magnetic field, Induced current density, S.A.R., Live line maintenance.

A. Introduction

One of the main topics in the research activity concerning magnetic fields at power frequency is nowadays the analysis of the interaction between these fields and the living organisms [1-3]. In fact, the experimental studies on animals or cellular cultures, aiming at determining the possible biological effects of the exposure to ELF electromagnetic fields, need a deepen knowledge of the interaction mechanism between living organism and electromagnetic fields particularly for the interpretation of the experimental results and for extrapolating them to human beings.

Magnetic fields from high voltage transmission lines can be calculated, as well as measured [4,5]. The calculations and measurements become more complex for the distribution line, substations, and other locations where there are multiple conductors of varying current loads and the vicinity of the conductive ground needs to be considered.

The existing database on biological effects of power line frequency magnetic fields indicates that many parameters of the exposure field, as well as some characteristics of biological systems influence the interaction. Some of the carefully performed experimental works show that at least some effects depend on the induced electric fields and currents in biological systems [6]. These effects have thresholds dependent on the magnitude of the induced currents. These findings provide motivation for the modeling of induced currents in a lineman underneath the line and close to the transmission line.

In several situations it is necessary to determine currents induced in biological bodies or parts thereof to obtain the distributions of the mass-normalized rates of electromagnetic energy absorption (i.e., specific absorption rates, or SAR). Since biological effects depend on currents through important organs such as the brain, the heart, the central nervous system, etc., a detailed knowledge of the electric currents due to magnetic fields, should allow one to quantify the hazard and keep the maximum SAR at any location within the ANSI limit.

B. Model and Method of Analysis

II.1 Power line magnetic fields

The human body model used for the evaluation of induced current density is situated in this work underneath and close to a 500 kV transmission line. The line is a single circuit line, the phase conductors are 3x00 mm^2 with a sub-conductor spacing of 45cm and a minimum clearance to ground of 10 m, Fig.1. The line is fully loaded with 2000A per phase. The human body model is situated in two positions underneath the line, namely, under the outermost phase conductor (at which the maximum field exists), and at the edge of the right-of-way.

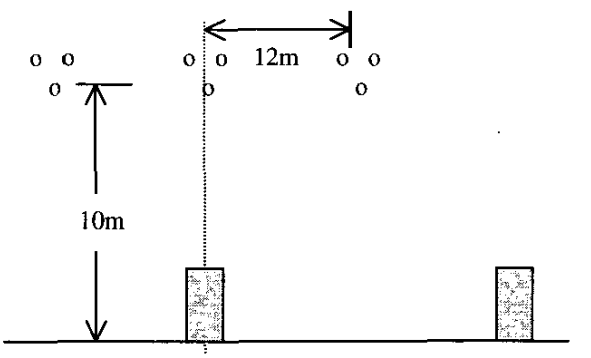

Fig.1 500 kV line configuration

Magnetic field was computed in the space surrounding the power line. The equi-field contours inside a rectangular cross-section in space containing the human body for the above two positions are shown in Figs.2 and 3, respectively. It is emphasized that these magnetic field values also represent those present within an enclosed human body, since biological materials are non-magnetic, and therefore their magnetic permeability is equal to that of the free space. That body is modeled here by a prolate spheroid whose axes dimensions are equal to of the

rectangle sides. At the outermost conductor the magnetic field is seen to vary from 36 μT at the feet to about 44 μT at the head, while at the edge of the right-of-way the magnetic field varies from only 13.6 μT at the feet to about 14.8 μT at the head.

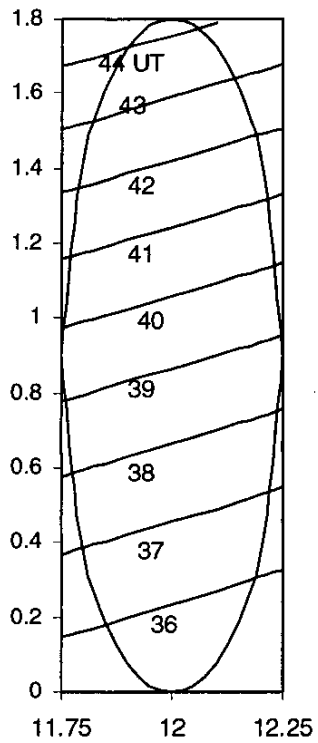

Fig.2 Equi-field contours within a human body underneath the outermost phase conductor

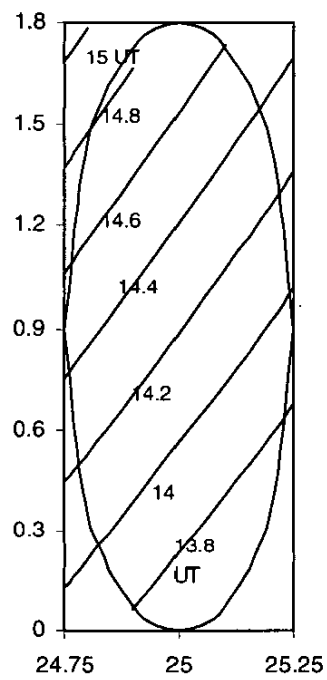

Fig.3 Equi-field contours within a human body at the right-of-way

The orientation angle of the incident magnetic field varies along the human model height. The orientation angle of the incident magnetic field beneath the outermost conductor decreases within 3 degrees along the human model height from top to bottom, with a mean value of about 28.5 degrees. In contrast, at the right-of-way, the orientation angle increases within 8 degrees along the human model height with a mean value of about 40 degrees.

II.2 Assessment of the human model exposure underneath the line

The human body is modeled by a prolate spheroid, which is placed within the rectangular coordinate system. The length of the model, 2a, is taken as 1.8 m and the width of the model, 2b, as 0.5 m. It is assumed that the model is filled with a homogenous biological tissue and the exterior medium is air. The horizontal components B_x and B_y of the external magnetic fields relate to the x-axis and y-axis, respectively. The vertical component B_z of external magnetic field relate to the z-axis. The model is placed at different positions underneath the line where it is exposed to actual fields at these positions.

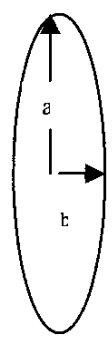

Fig. 4 Prolate spheroidal model [1].

The problem can be considered as quasi-static, since the dimensions of the human body are small compared to the wavelength of the power-frequency. Two additional simplifications of the problem result from the electrical properties of tissues. Biological materials are non-magnetic, and as a consequence the magnetic permeability μ is equal to that of the free space μ_o. It can be shown that the secondary magnetic field produced in tissue by the current flow induced by the external magnetic field can be neglected for frequencies at which the following condition is satisfied [7]:

$$f \mu_o \sigma L^2 << 1 \qquad [1]$$

Where, f is the frequency, σ is the conductivity, and L is the maximum dimension of the body. Additionally, at the 50 Hz the permittivity components ε' and σ (where ε' is the dielectric constant) satisfy the following conditions:

$$\sigma >> 2 \pi f \varepsilon' \qquad [2]$$

The internal electric fields vectors in x, y and z-axis resulting from the three orientations of the sinusoidal magnetic fields are expressed as:

$$\vec{E}_{Bx} = \frac{\omega}{a^2 + b^2}(b^2 z\hat{y} - a^2 y\hat{z})\left|\dot{B}_x\right| e^{j(-\pi/2+\varphi_{Bx})} \quad [3]$$

$$\vec{E}_{By} = \frac{\omega}{a^2 + b^2}(a^2 x\hat{z} - b^2 z\hat{x})\left|\dot{B}_y\right| e^{j(-\pi/2+\varphi_{By})} \quad [4]$$

$$\vec{E}_{Bz} = \frac{\omega}{2}(y\hat{x} - x\hat{y})\left|\dot{B}_z\right| e^{j(-\pi/2+\varphi_{Bz})} \quad [5]$$

Where, E_{Bx} is an electric field around x-axis induced by B_x, E_{By} is an electric field around y-axis induced by B_y and E_{Bz} is an electric field around z-axis induced by B_z. Moreover, the angular frequency $\omega=2\pi f$ where f is 50 Hz and φ is the phase angles of B_x, B_y and B_z.

The total induced electric field in the model can be expressed as:

$$\overline{E} = \overline{E}_{Bx} + \overline{E}_{By} + \overline{E}_{Bz} \quad [6]$$

The total current density induced by magnetic fields is obtained from

$$\overline{J} = \sigma\overline{E} \quad [7]$$

In reality the human body is not homogeneous and the electrical characteristics of the different organs are different. Therefore, the circulating current within an organ depends of the local electric field and on the organ's conductivity. The values of the electrical conductivity of the different organs are as shown in Table 1 [8]:

Table 1 Electrical conductivity of different organs

Organ	Conductivity S/m
Lung	0.1
Liver	0.1
Viscera	0.03
Head	0.05
Brain	0.7
Heart	0.7
Spine	0.01
Arm	0.1
Leg	0.1

For comparison purposes, a base human body conductivity of 0.1 S/m may be assumed, and circulating currents are computed accordingly. For any given organ the true current density can be modified simply by multiplying the base values by the ratio of the actual organ conductivity to the base conductivity.

II.2.1 Induced current density

The variation of the induced current density along the human height of the human model located in different positions beneath the power line is shown in Figs. 5-7.

For a human present on the power line's centerline the current distribution is shown in Fig.5. The maximum induced current density occurs at the top of model head, it decreases rapidly along the head where it reaches its lowest value, and then build up again along the human model height and exhibiting another peak near the lower abdomen.

Figs. 6 and 7 show the results for a human situated beneath the outermost phase conductor and at the edge of the right-of-way, respectively. The general features are similar in all case. However, the relative magnitudes of body currents and the locations of their maxima and minima are distinctly different.

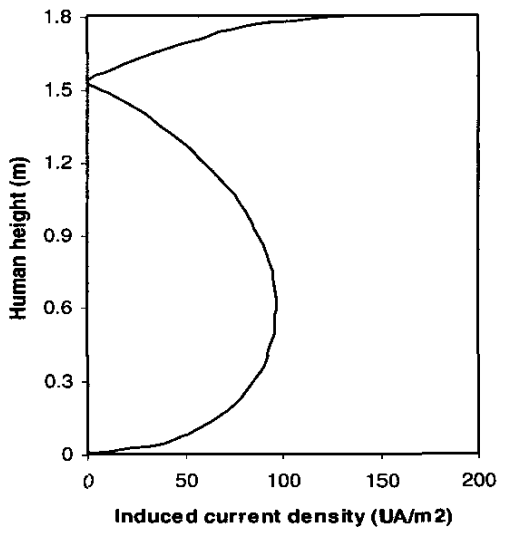

Fig.5 Induced current density in human model at center line

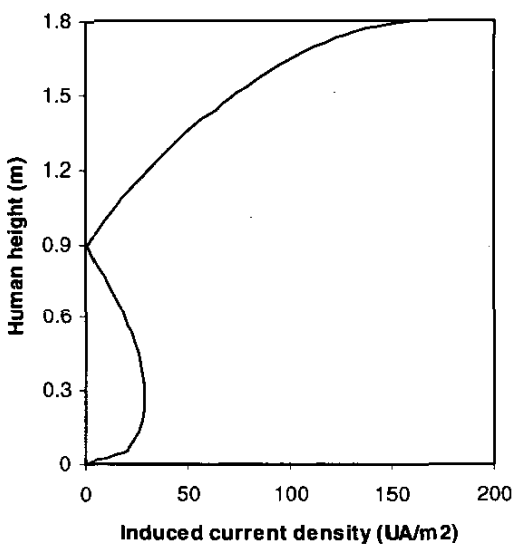

Fig.6 Induced current density in human model at outermost conductor

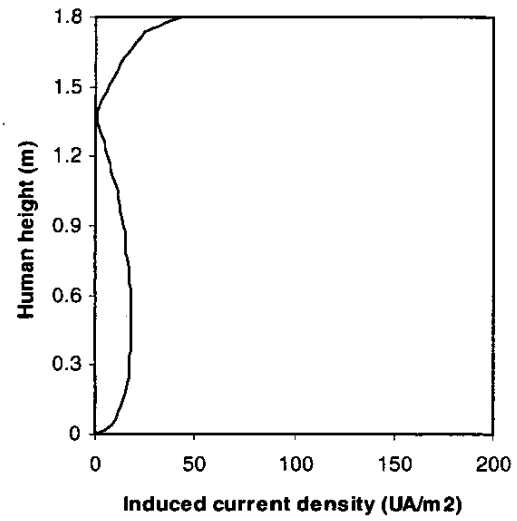

Fig.7 Induced current density in human model at the edge of right-of-way

II.2.2 Specific absorption rate

The specific absorption rate (SAR) is the mass-normalized rates of electromagnetic energy absorption, i.e. the energy per unit mass, and is given by

$$SAR = \frac{\sigma |E|^2}{\rho_m} \qquad [8]$$

Where, ρ_m is the mass density of the material in the cell in question.

The question of how much energy is absorbed by the humans should be answered as quantitatively as possible. The SAR of an field-exposed organ of the human body indicates the rate of magnetic energy absorption by that organ. This quantity helps in assessing the environmental impact of the magnetic fields.

For the present calculations, ρ_m is taken as 10^3 kg/m^3. Also the results were made assuming a uniform human body model conductivity of 0.1 S/m. The actual SAR can be obtained simply by multiplying the values by the ratio of the actual organ conductivity to that of the model.

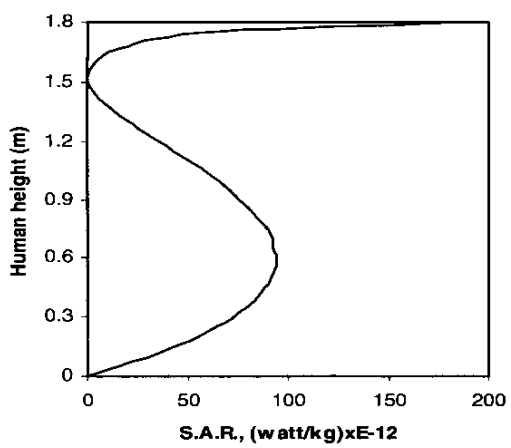

Fig.8 SAR for human at center line

The SAR along the outer tissues of the human body placed beneath a power line and at its center line, under the outermost conductor and at the edge of the right-of-way of the 500 kV line are shown, respectively, in Figs.8, 9 and 10.

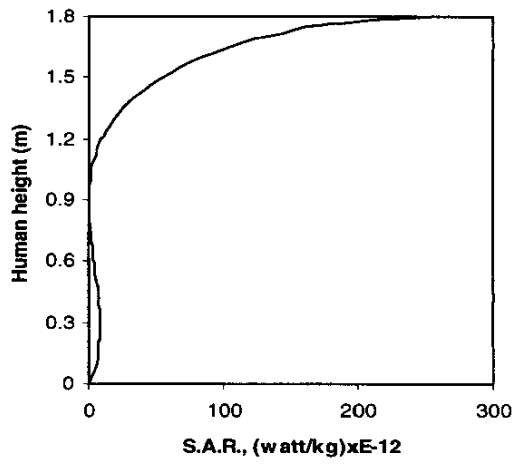

Fig.9 SAR for a human beneath the outermost conductor

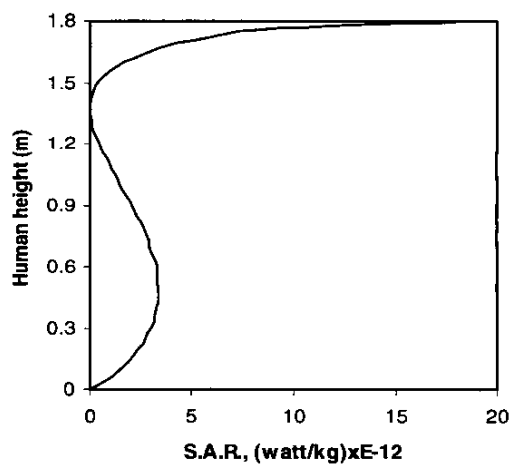

Fig.10 SAR for a human at the edge of right-of-way

III. Live Line Maintenance Exposure

Live line maintenance is an activity, which leads to considerable field exposures, associated with acute effects on the one hand, and which contributes to an increase in possible long term effects on the other hand. Two positions which a lineman may assume on a single-circuit EHV power line phases are considered. The first position is adjacent to the middle phase conductor, while the other position is near the outermost phase conductor, as shown in Fig.11.

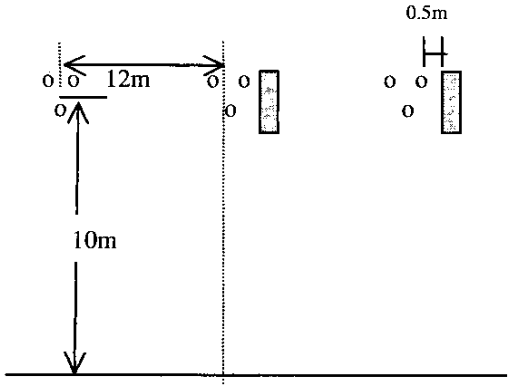

Fig.11 Live line maintenance positions

III.1 Magnetic Field Distribution

Figs.12 and 13 show the equi-field contours inside a rectangle containing the human body model section at the two lineman positions considered above. When the lineman is near the outermost phase conductor the magnetic field varies from about 200 μT to about 460 μT along the human model. At a position near the middle phase conductor the magnetic field varies from about 220 μT at the feet to about 480 μT at the head.

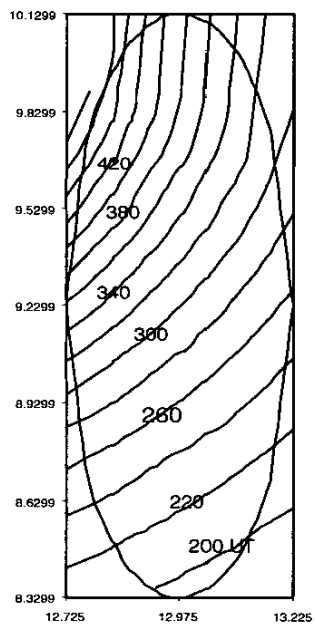

Fig.12 Equi-field contours nearest the outermost phase conductor

III.2 Current Density Distribution

The contours of equal current density induced in the body due to power-frequency magnetic fields are shown in Figs. 14 and 15 for a lineman located, respectively, by the central phase conductor and the outer phase conductor. The current density contours on the cross-sectional plane of symmetry through the spheroidal model.

It is noticed that the distribution of the induced current density is generally non-uniform, with its largest value

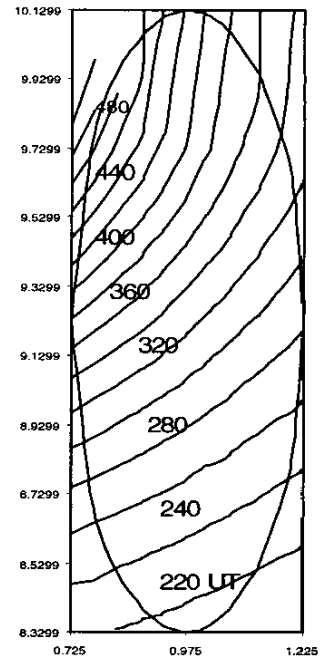

Fig.13 Equi-field contours near the middle phase conductor

found at the top of the model. The non-uniformity of current distribution is much more significant when the lineman is by the central phase conductor than that at the outermost phase conductor. Current densities inside the human model varied between 0.1 and 1.0 mA/m^2 by the central phase conductor, while it varies between 0.2 and 2.3 mA/m^2 by the outermost phase conductor. This means more potential risk of exposure to magnetic fields in the latter case.

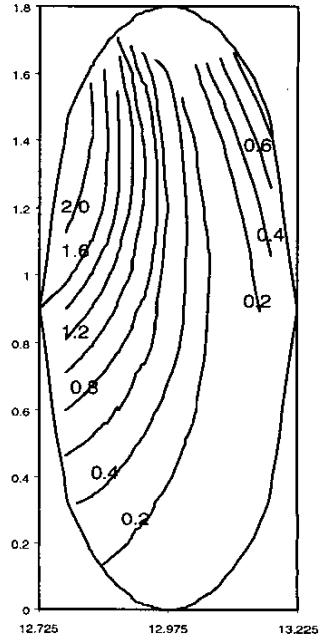

Fig.14 Equi-induced current density contours (mA/m^2) near the central phase conductor.

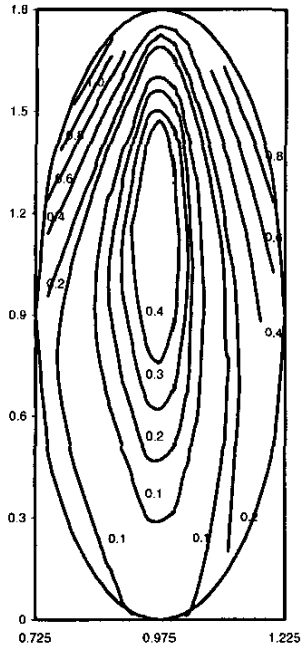

Fig.15 Equi-induced current density (mA/m^2) near outermost phase conductor

III.3 SAR Distribution

The contours of equal specific absorption rate (SAR) over the cross sectional plane of symmetry along a human by the outermost phase conductor are shown in Fig.16. The highest values appear to take place on the side nearer to the conductor. Typical SAR values reach as high as 52.9x10^{-9} watts/kg at the top of the right side of the

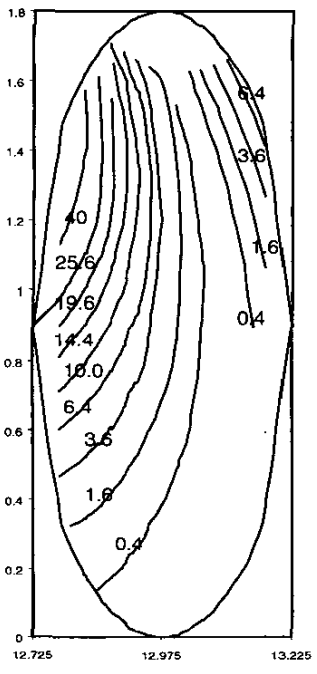

Fig.16 Equal specific absorption rate contours (watts/kg x10^{-9}) in a man situated by the outermost phase conductor

model. Such values are about three orders of magnitude higher than those encountered in a human body located on the ground beneath the power line as indicated from Figs. 8 through 10.

Conclusions

Magnetic fields beneath- and in the vicinity of the- phase conductors of extra-high voltage power lines were evaluated. Using a human body model in the form of a prolate spheroid and using real characteristics of biological bodies, it is possible to deduce the induced currents distribution inside the bodies and subsequently the specific absorption ratio (the mass-normalized energy absorption).

For human locations underneath the power line, the maximum induced current density is at the head of the model with another smaller peak near the lower abdomen. The current density distribution along the human model is strongly dependent on the orientation angle of the incident magnetic field, which in turn depends on the model location. Maintenance linemen are exposed to higher magnetic fields that those on the ground, which in turn induce high current densities inside the body –and subsequently specific absorption rates- three orders of magnitude higher than those in bodies on the ground. The current density inside the body of a lineman can be as high as 2.3 mA/m^2 , and the specific absorption rate can reach 52.9x10^{-9} watt/kg near the outermost conductor.

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