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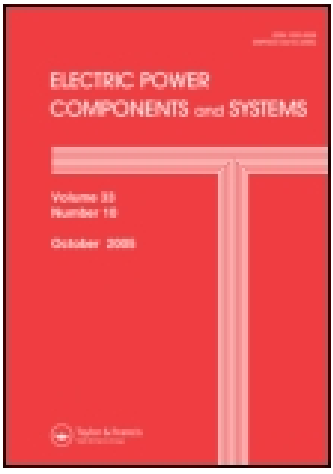

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Interaction of Environmental ELF Electromagnetic Fields with Living Bodies

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The subject of potential environmental hazard due to the exposure to extremely low frequency (ELF) magnetic fields produced by electric power installations is receiving worldwide attention. This paper is a contribution to the assessment of that hazard by evaluating the induced electric fields and currents due to the nonuniform magnetic fields distribution along the height of a human. The effect of magnetic field orientation relative to the body posture is examined and the subsequent variation of the induced electric field in the human body is evaluated. Also, the paper accounts for the electric field coupling of a human in contact with the ground. A comparative study of induced magnetic and electric fields within a grounded human beneath different power lines is made and its results are discussed.

Keywords electromagnetics, magnetic fields, field exposure

1 Introduction

The potential hazards due to exposure to extremely low frequency (ELF) electromagnetic fields emitted by electric power systems and installations have become a major public and environmental concern (Polk and Postow, 1986; Stuchly and Zhao, 1996). Consequently, the interaction of those electromagnetic fields with living forms has become an increasingly important subject.

Living bodies do not possess significant ferromagnetic properties, and thus, they do not distort the applied magnetic field by their presence. In other words, magnetic fields penetrate living body completely. Meanwhile, alternating (AC) magnetic fields—according to Faraday's law—produce an electric field within the body given by

$$\oint_c \overline{E}\,.\overline{dl} = -\frac{\partial}{\partial t}\oint_c \mu_0 \overline{H}\,.\overline{ds}\,.$$

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This field, in turn, produces an AC electric current which circulates within the living body. The induced electric field **E** is generally proportional to the radius of the magnetic field path. Therefore, the outer surface of the living body which has the maximum path radius is expected to carry the largest induced electric field, and therefore, receives the main attention in the present work.

A living body is simultaneously exposed to an electric field in addition to the magnetic field. A time-varying electric field (i.e., AC fields) will induce a time-varying surface charge on the body and hence a time-varying current within the body. These currents will combine with those induced originally by magnetic fields as explained above. Electric fields materializing on the outside body surface are much higher than those present in the absence of the body (Mahdy et al., 1991). On the other hand, the electric field induced on the inner body surface (and thus responsible for body currents) is greatly reduced due to the sharp contrast between the electric properties outside and inside the body (Polk and Postow, 1986). The present work holds a comparative analysis of the magnetic field–induced currents and the electric field–induced currents. While the present paper does not offer a novel field solution to the problem, it utilizes the known spheriod-based model to serve the comparative field objectives of the work.

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2 Magnetically Induced Electric Field and Current

To simplify the analysis, a human body in a standing position is modeled by a prolate spheroid of dimensions **a** and **b**, as shown in Figure 1. The model is used to assess the induced electric fields and currents at different locations inside the body due to externally applied magnetic fields.

Maxwell's equation, which governs the relation between magnetic and electric fields, is

$$\overline{\nabla} \times \overline{E} = -\mu_0 \frac{\partial \overline{H}}{\partial t}.$$

Under AC conditions it can be shown that the internal, circumferencial electric field, $\overline{E}_m$, caused by an external magnetic field, $\overline{H}_o$, takes the form (Takemoto, 1988)

$$\overline{E}_m = \overline{E}_{m1} + \overline{E}_{m2} + \overline{E}_{m3}, \tag{1}$$

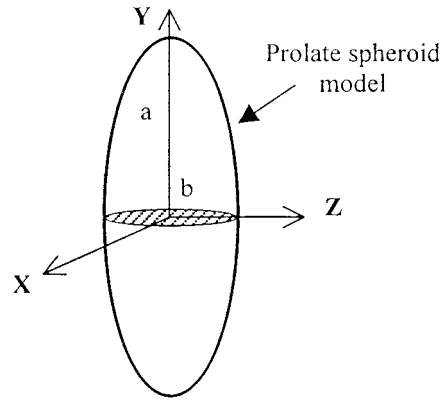

Figure 1. Representation of a living body (a human).

where $\overline{E}_{m1}$, $\overline{E}_{m2}$, and $\overline{E}_{m3}$ circumferential induced electric fields due to x, y, and z directed horizontally polarized magnetic fields, respectively,

$$\overline{E}_{m1} = -j\omega\mu_o H_{ox} \frac{\left[z\hat{y} - \left(\frac{b}{a}\right)^2 y\hat{z}\right]}{1 + \left(\frac{b}{a}\right)^2}, \tag{2}$$

$$\overline{E}_{m2} = -j\omega\mu_o H_{oy} \frac{(x\hat{z} - z\hat{x})}{2}, \tag{3}$$

$$\overline{E}_{m3} = -j\omega\mu_o H_{oz} \frac{\left[\left(\frac{b}{a}\right)^2 y\hat{x} - x\hat{y}\right]}{1 + \left(\frac{b}{a}\right)^2}, \tag{4}$$

where, $\hat{x}$, $\hat{y}$, and $\hat{z}$ are unit vectors in x, y, and z directions, respectively. Let

$$\mu_o H_o = B \text{ and } \left(\frac{b}{a}\right)^2 = k.$$

Then, the three field components may be rewritten as

$$\overline{E}_{m1} = -j\left(\frac{\omega z B_x}{1+k}\right)\hat{y} + j\left(\frac{\omega k y B_x}{1+k}\right)\hat{z},$$

$$\overline{E}_{m2} = -j\left(\frac{\omega x B_y}{2}\right)\hat{z} + j\left(\frac{\omega z B_y}{2}\right)\hat{x},$$

$$\overline{E}_{m3} = -j\left(\frac{\omega k y B_z}{1+k}\right)\hat{x} + j\left(\frac{\omega x B_z}{1+k}\right)\hat{y}.$$

Substituting by $\overline{E}_{m1}$, $\overline{E}_{m2}$, and $\overline{E}_{m3}$ in equation (1) gives

$$\overline{E}_m = \left[j\omega\left(\frac{zB_y}{2} - \frac{kyB_z}{1+k}\right)\right]\hat{x} + \left[j\left(\frac{\omega}{1+k}\right)(xB_z - zB_x)\right]\hat{y} + \left[j\omega\left(\frac{kyB_x}{1+k} - \frac{xB_y}{2}\right)\right]\hat{z}.$$

Hence,

$$\overline{E}_{mx} = j\omega\left(\frac{zB_y}{2} - \frac{kyB_z}{1+k}\right), \tag{5}$$

$$\overline{E}_{my} = j\left(\frac{\omega}{1+k}\right)(xB_z - zB_x), \tag{6}$$

$$\overline{E}_{mz} = j\left(\frac{kyB_x}{1+k} - \frac{xB_y}{2}\right) \tag{7}$$

and

$$E_m = \sqrt{E_{mx}^2 + E_{my}^2 + E_{mz}^2}. \tag{8}$$

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2.1 Induced Current Density

The electric current density, $\overline{J}$, produced by the internal field may be expressed as

$$\overline{J} = \sigma.\overline{E_m}, \tag{9}$$

where σ is the conductivity of the body tissues.

3 Results and Discussion

The prolate spheroidal model representing a standing human has $a = 0.9$ m (for a human height of 1.8 m) and $b = 0.15$ m (for a human maximum diameter of 0.3 m).

Figure 2 shows the variation of induced (internal) circmferential electric field along the height of the human exposed to an incident vertical magnetic field which gradually varies in magnitude along the human height. The magnetic field maximum value is 1 μT at human model's top. The magnitude of the incident magnetic field is assumed to decay from top to bottom at different rates, namely, 0% (i.e., uniform), 10%, 20%, or 30%.

In case of nonuniform incident magnetic field along the standing model, as the degree of nonuniformity increases, the peak value of the induced electric field shifts further away from the mid-height toward the upper body. It is clear that uniform incident magnetic field produces higher induced electric field values, compared with those of nonuniform incident magnetic fields.

Assuming the human body to have uniform conductivity of 0.04 S/m (which can be related to fat tissues of humans), the induced current is evaluated. Figure 3 shows the variation of the induced current density with height.

3.1 Effect of Incident Angle of Magnetic Field

Figure 4 demonstrates the effect of variations in the incident angle of an externally applied magnetic field on the induced electric field. It can be seen that while the

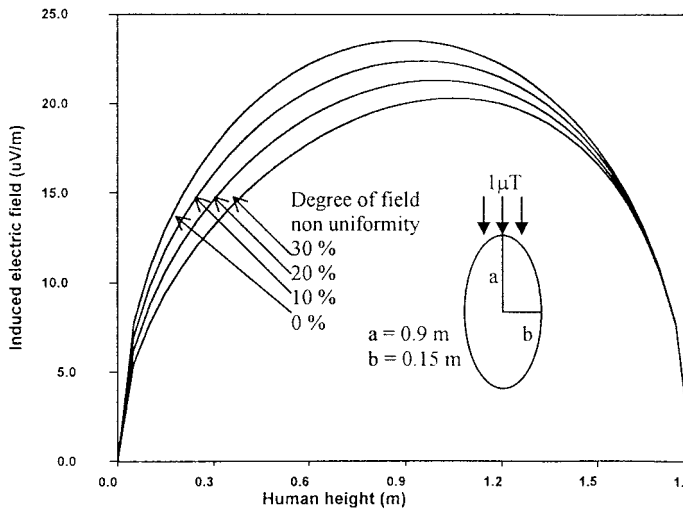

Figure 2. Variation of induced electric field with height for human exposed to a varying, vertical magnetic field of 1 μT (at head).

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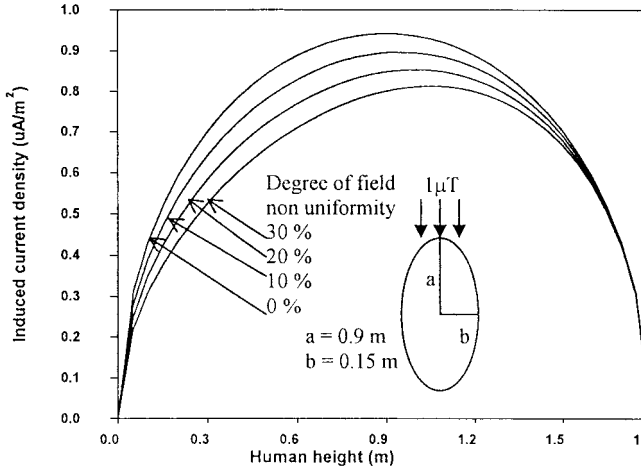

Figure 3. Variation of induced current density with height for a human exposed to a varying, vertical magnetic field of 1 μT (at head).

induced electric field reaches its maximum at mid-height under a vertical external magnetic field, it reaches its minimum at that position in case of a horizontal external magnetic field.

3.2 *Elliptic Polarization*

The three-phase alternating currents produce a magnetic field identified by a rotating vector which varies in amplitude and whose tip traces an elliptic locus (elliptic polarization). The induced electric field within the body varies accordingly.

Figures 5 to 7 show the variation of induced electric field over the power frequency period (2π radians or 360 degrees) at mid-height in three different cases of elliptic polarization representing three respective typical situations, namely beneath the center line, under the outer phase conductor, and on the border of the

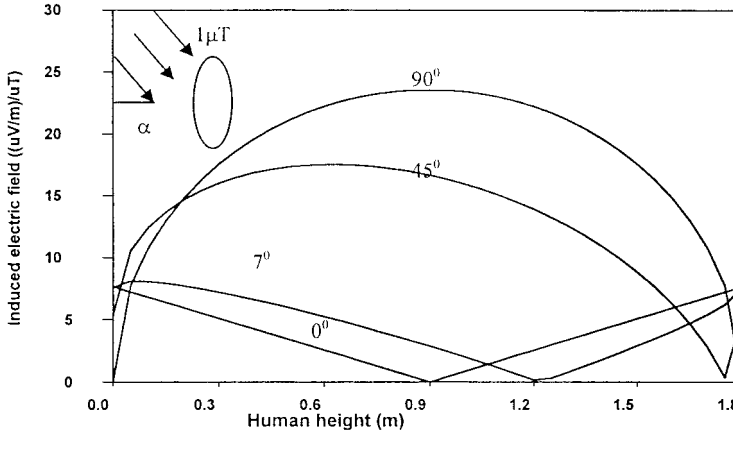

Figure 4. Variation of induced electric field with height for a human at different incident angles of magnetic field to the body.

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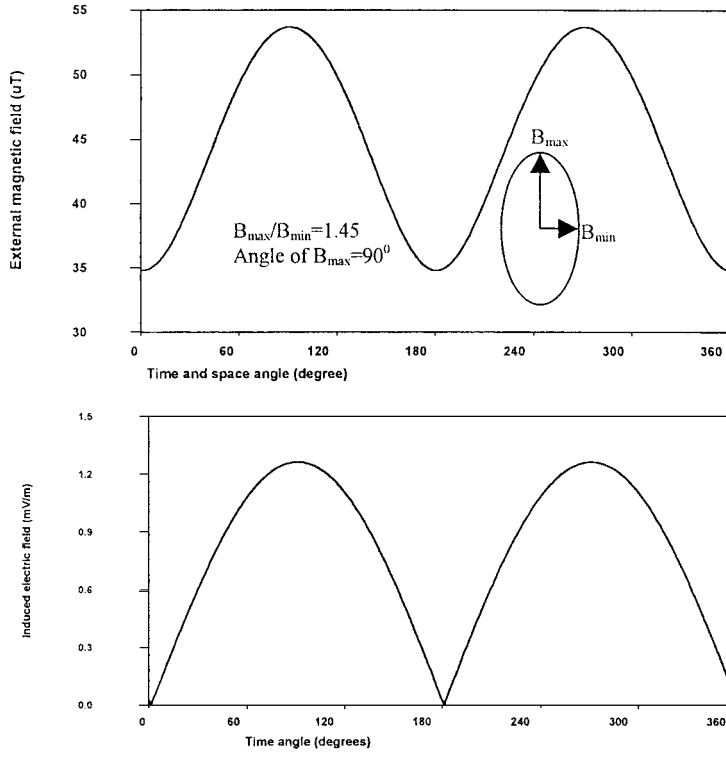

Figure 5. Time-variation at induced electric field at mid-height of a human model beneath center line of a 500 kV line.

right-of-way at mid-span of a 500 kV line carrying a rated current of 2000 A. The line conductors have bundle sizes 3 × 30.6 mm with 45 cm subconductor spacing and 9.0 m clearance-to-ground. The heights of the outermost phases and the middle phase at the tower are 22 m and 24.35 m, respectively. The variations in the incident magnetic field and the induced electric field are not uniquely related. The highest instantaneous incident magnetic field magnitudes do not necessarily produce the highest induced electric field magnitudes, as shown in Figure 6. At the human's mid-height, the maximum induced electric field reached about 1.27 mV/m.

4 Electrically Induced Current Density

A human under a power line is not exposed only to a magnetic field (produced by the line current), but also to an electric field (produced by the line voltage). The electric field strength in the absence of the human body may be referred to as the unperturbed field. Because of the finite electrical conductivity of the human body, its presence will perturb the field significantly. The field is enhanced near surfaces which are normal to the original direction of the electric field. A time-varying electric field will induce a time varying surface charge on the body and, in turn, time varying currents will flow within the body.

In this paper, the charge simulation method (CSM) is applied to the prolate spheroidal grounded human model (Singer et al., 1974). Ring charges are used to

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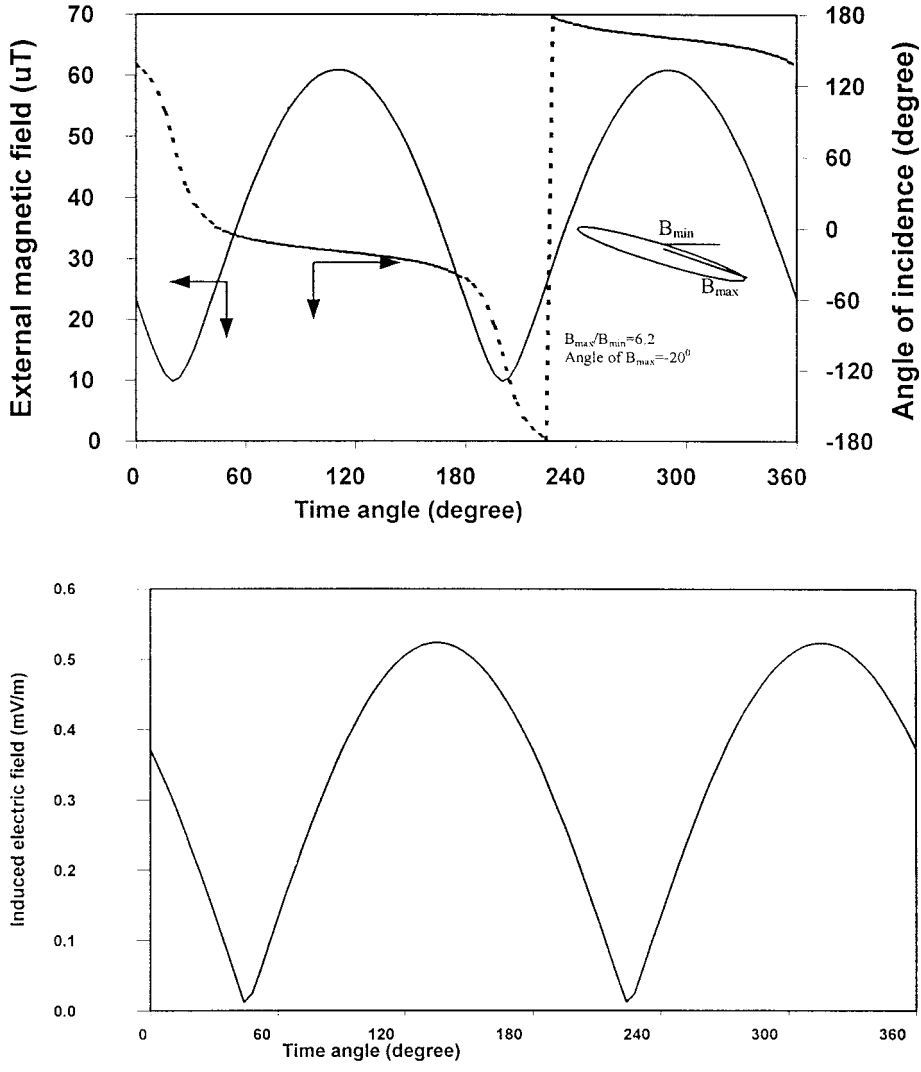

Figure 6. Time-variation at induced electric field at mid-height of a human model under outer phase conductor of a 500 kV line.

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simulate the human body surface charges, and finite line charge segments are used to produce a uniform field from a parallel plane arrangement of sufficiently large width.

The human model with the sets of simultating charges used in the present work is indicated in Figure 8, where G is the air medium width, H is the human height, N_L is the number of finite line charge segments, and N_R is the number of ring charges. Using CSM to solve the potential boundary problem of the human model, the values of the simulating charges can be obtained.

Gauss's low states that the surface integral of the normal component of the electrical field over a closed surface is equal to the total charge enclosed by the surface of integration divided by the permittivity of the empty system space ϵ_o.

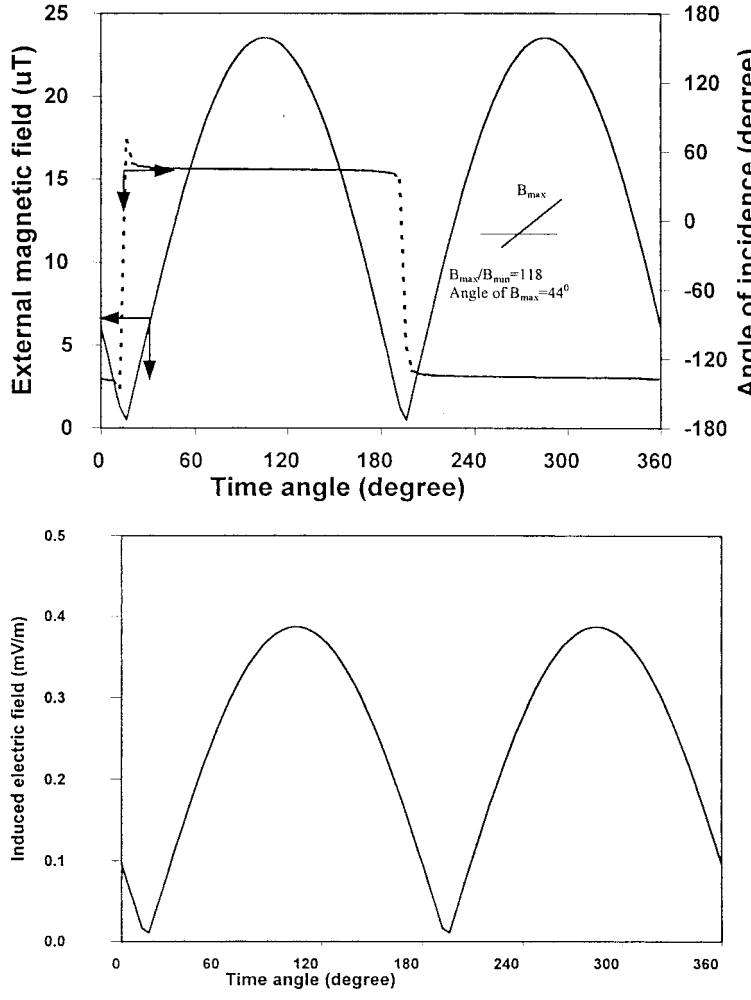

Figure 7. Time-variation at induced electric field at mid-height of a human model at ROW edge of a 500 kV line.

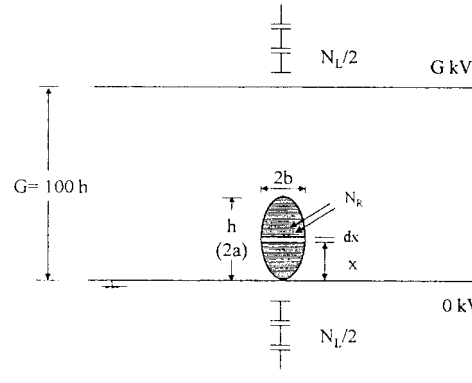

Figure 8. Simulation of grounded human in uniform electric field.

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This leads to the following steady state flow system equation at any point in the space including the body.

$$\overline{\nabla}.\overline{J} = 0, \tag{10}$$

where $\overline{J}$ is the current density.

From the above relation, the governing equations which describe the system are

$$\overline{\nabla}.(\sigma_o + j\omega\epsilon_o)\overline{E}_o = 0. \tag{11}$$

At the space outside the body, σ_0 and ϵ_0 are the conductivity and permittivity of the air, E_o is the field in space outside the object. Assuming that the body does not carry any internal chargsse, then

$$\overline{\nabla}.(\sigma_i + j\omega\epsilon_i)\overline{E}_i = 0. \tag{12}$$

The subscript "o" refers to external quantities, and "i" refers to internal quantities. At the surface of discontinuity,

$$(\sigma_o + j\omega\epsilon_o)\overline{E}_{no} = (\sigma_i + j\omega\epsilon_i)\overline{E}_{ni}, \tag{13}$$

where at power frequency $\sigma_o \langle\langle \omega\epsilon_o$ and $\sigma_i \rangle\rangle \omega\epsilon_i$, thus equation (13) is rewritten as

$$j\omega\epsilon_o\overline{E}_{no} = \sigma_i\overline{E}_{ni}. \tag{14}$$

Then, the surface electric field $\overline{E}_s$, the induced charge density $\overline{q}$, and the density of the current collected by the body $\overline{J}$ are related by

$$\overline{J} = j\omega\epsilon_o\overline{E}_s = j\omega\overline{q}. \tag{15}$$

It should be mentioned that although the conductivity of living bodies is finite, which implies that the electric field is not exactly normal to the body surface, the angle of inclination to surface remains very close to 90°.

4.1 Interaction Between Electrically and Magnetically Induced Body Currents

The following relationships exist between the magnetically induced and the electrically induced electric fields within a living body.

(1) Vectorial Relationship. The electric field induced within the body by an external electric field is nearly normal to the body surface. On the other hand, the external magnetic field produces within the human body circumferential electric fields E_{m1}, E_{m2}, and E_{m3} in planes normal to the x, y, and z components of the external magnetic field, respectively.

(2) Phasor Relationship. The following set of facts contribute to alteration in the phasor relationship between the two internally induced electric fields; one originally derived from the external electric field, and the other is induced inside the body by the external magnetic field:

a) The line current (and hence magnetic field) and voltage (and hence electric field) are interrelated by the transmission line power factor.

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b) The electrically induced electric field at the body's surface is out of phase with the line voltages.
c) The external electric field is converted into electric field inside the body. The induced electric field lags by 90° behind the external magnetic field as the displacement current outside the body is converted into a conduction current inside the body.
d) From Faraday's law of magnetic induction, the external magnetic field is converted into electric field inside the body. The induced field lags 90° behind the external field:

$$\overline{\nabla} \times \overline{E} = -\frac{\delta \overline{B}}{\delta t}.$$

Furthermore, the induced current density is in-phase with the induced electric field:

$$\overline{J} = \sigma \overline{E}.$$

(3) Location Relationship. The external magnetic field induces electric field within all sections of the body. However, as mentioned earlier, only those fields induced at the outer layer which has the largest path radius are considered because of the expected higher levels of induction. It is also at those regions that external electric field–induced conductive current densities enter the body.

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4.2 Results and discussion

Figure 9 shows the variation of both surface electric field and induced current density along the height of a human (assumed to be 180 cm tall) when the human is grounded and exposed to an unperturbed uniform vertical electric field of 1 kV/m. It can be seen that the surface electric field monotonically increases along the height. The peak value of surface electric field reaches 15 kV/m (i.e., an enhancement factor (E_s/E_o) of 15). The induced current density is directly proportional to the surface electric field everywhere along the height. The peak value of induced current density is 41.8 ($\mu A/m^2$)/(kV/m). The cumulative current flowing across a certain section

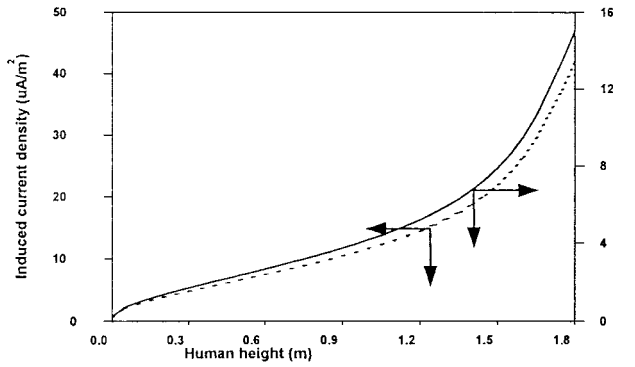

Figure 9. Variation of surface electric field and current density with height for a grounded human exposed to an unperturbed, uniform, vertical electric field of 1 kV/m.

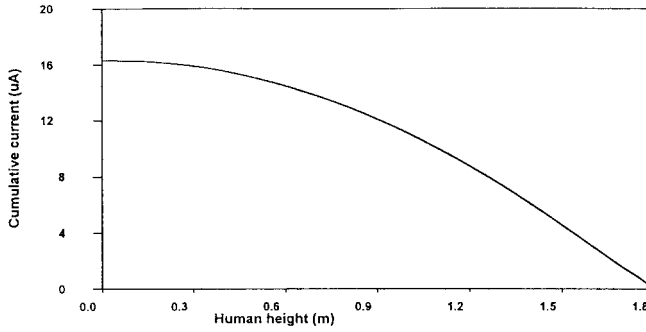

Figure 10. Variation of cumulative current with height for a grounded human exposed to an unperturbed, uniform, vertical electric field of 1 kV/m.

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along the human height is the sum of all currents emanating at all preceding body parts starting from the top of human. The variation of cumulative current with height is indicated in Figure 10. The current flowing from the body to ground (the short circuit current) is about 16.3 μ A/(kV/m).

4.3 Comparative Induction

A live body beneath a power line is exposed to both magnetic and electric fields emanating from that line. At a given spot on the live body, the comparative level of induction, magnetic-based versus electric-based, under a given power line depends on the following factors:

1. The line loading (or current).
2. The position of the living body with respect to the power line.
3. The electric properties of earth.
4. The body dimensions.
5. The conductivity of the body.

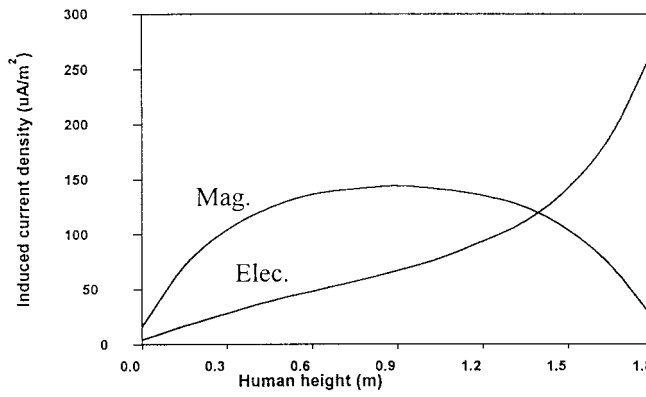

Figure 11. Relative induction assessment from magnetic and electric fields at different heights of a grounded human beneath center line at mid-span of a 500 kV line carrying 2000 Ampere. Note: angle of incident magnetic field = (60°–54°).

Figure 11 depicts the comparative induction along the height of a human positioned under the center line of a power line and at its mid-span. It should be noted that in preparing those figures the following assumptions were made:

1. Rated currents are flowing.
2. The human is 180 cm tall and has a maximum width (diameter) of 0.3 m.
3. The body has an average conductivity of 0.1 S/m.
4. Earth is a pure conductor.

5 Conclusions

1. Along the human height, the maximum intensities of induced currents of magnetic origin occur at locations different from those of electric origin. Peak values of magnetic induction occur at locations near mid-height while those of electric induction occur at the top of the body.
2. For all power lines, magnetic-based induction exceeds electric-based induction, particularly at lower sections of the human body.
3. As the transmission voltage decreases, more human sections become of higher magnetic induction relative to the electric induction. This leads to the expectation that at low voltage level, the magnetic induction becomes completely more hazardous than the electric induction.

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