APPLICATION OF ANALYTICAL AND NUMERICAL METHODS TO EVALUATE INDUCED CURRENTS IN HUMAN BODIES BY ELF MAGNETIC FIELDS

Shaher A. Mahmoud[1] A. H. Hamza[2]
Nagat M. Abdel-Gawad[2] Samy M. Ghania[2]
[1] Egyptian Electricity Holding Company, Egypt
[2] Faculty of Engineering at Shoubra, Zagazig University, Egypt
*E-mail : shaher_anis@yahoo.com

Abstract: This paper addresses the issue of the interaction of the human body with power frequency (50/60 Hz) magnetic fields. Two human body models are used; a simple spheroid based on an analytical method and an approximate human shape based on finite element method (FEM). The employed human body models are positioned in two magnetic field sources; under a power transmission line and inside an electric power substation representing typical exposure cases. The magnetically induced currents inside human body due to the exposure to power frequency magnetic fields are evaluated. A number of parameters such as human dimensions and proximity to the current-carrying conductors are considered. A comparative analysis of the magnetic induction inside the human body due to the different human models and magnetic field sources is also presented.

INTRODUCTION

In the past few decades, the study of the extremely-low frequency (ELF) magnetic fields came up to the international focus. The purpose of this interest is to clear and investigate the potential health effects due to the exposure to these fields [1]. The magnetic fields are produced in many different environments where carrying-current conductors exist such as in the case of electric power transmission and distribution overhead lines, cables and substations. Many studies were performed to study the magnetic fields produced by the electric power transmission lines and electric power substations [2-5]. In light of these studies, two different human models are developed. The developed human body is simulated analytically as a single prolate spheroid and as a multi-spheroids, and is simulated numerically as a multi-cylinders with spherical head based on Finite Element Method (FEM) to assess the magnetically induced electric fields and currents inside the different human parts of the human body.

PROPOSED HUMAN MODELS

The human body is simulated by different analytical and numerical techniques. The analytical human body model assumes two different shapes; single prolate spheroid and multi-spheroids with spherical head to represent the different human parts. Meanwhile, the numerical human body model assumes the human body as a multi-cylinders with spherical head. Fig.1 presents the analytical human model as a single spheroid with its semi-axes length a " as half height" and b " as half width". Fig.2 presents the analytical human body model as a multi-spheroids with spherical head and each human part is represented by its semi-axes lengths. Fig.3 presents the numerical human body model indicating the dimensions of each human part.

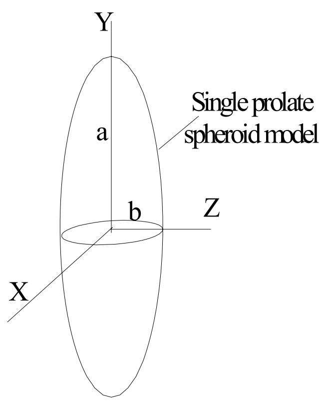

Fig.1 Representation of the modeled human body as a single prolate spheroid.

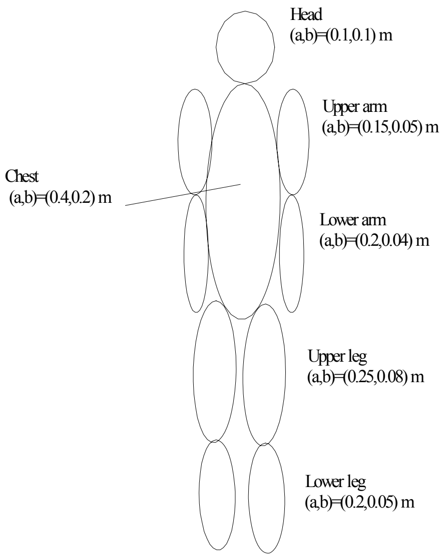

Fig.2 Representation of the modeled human body as a multi-spheroids with spherical head.

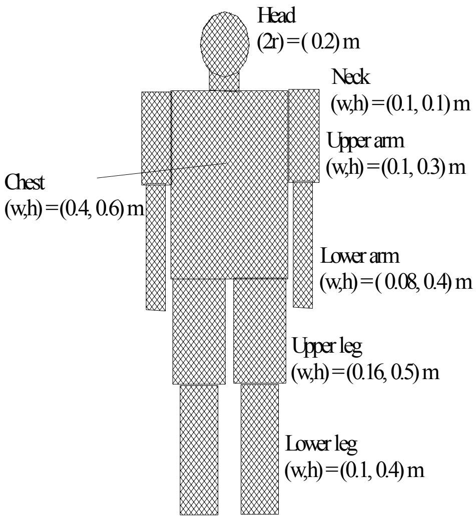

Fig.3 Representation of the modeled human body as a multi-cylinders with spherical head.

THE DIFFERENT CALCULATION TECHNIUES

The induced electric field E due to the exposure to magnetic field H is calculated Based on Maxwell's equation.

$$\vec{\nabla} \times \vec{E} = \mu_o \frac{\partial \vec{H}}{\partial t} \quad (1)$$

For the analytical human model simulated as a spheroid model with its semi-axes as a and b [6]:

$$\frac{x^2}{b^2} + \frac{y^2}{a^2} + \frac{z^2}{b^2} = 1 \quad (2)$$

$$\left(\frac{b}{a}\right)^2 = k \quad (3)$$

$$\vec{E}_{mx} = j\omega\left(\frac{zB_y}{2} - \frac{kyB_z}{1+k}\right) \quad (4)$$

$$\vec{E}_{my} = j\left(\frac{\omega}{1+k}\right)\left(xB_z - zB_x\right) \quad (5)$$

$$\vec{E}_{mz} = j\omega\left(\frac{kyB_x}{1+k} - \frac{xB_y}{2}\right) \quad (6)$$

$$E_m = \sqrt{E_{mx}^2 + E_{my}^2 + E_{mz}^2} \quad (7)$$

$$\vec{J} = \sigma.\vec{E}_m \quad (8)$$

where:
σ is the electrical conductivity of the human tissues.
ω is the frequency of the magnetic field.

For a single prolate spheroid, a single value of a and b are chosen to represent the human half height and width, respectively. While for a multi-spheroids model, different a and b are assumed to represent the different human parts. For each case, a program is developed to simulate the human body for the purpose of calculating the magnetic induction inside the human body.

For the numerical human model, with the help of MATLB software using the Partial Differential Equation (PDE) toolbox, a program is developed based on Finite Element Method (FEM) using the cylindrical coordinates to simulate the human model. The FEM is used for modeling a wide class of problems by breaking up the computational domain into elements of simple shapes with its shape function. Once the shape functions are chosen, it is possible to program the computer to solve complicated geometries by specifying the basis functions. The Maxwell's equations are expanded into two dimensions to cover each human part cross section area which is bounded by the boundary segment conditions of each human part borders as a rectangular or a circular segment for the cylindrical coordinates. Fig.4 presents the triangular mesh inside bounded area. At each triangle head the induced electric field and hence the induced electric current is evaluated.

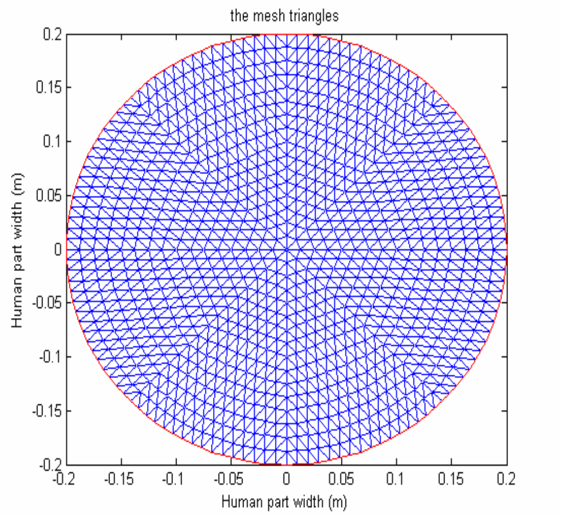

Fig.4 Representation of bounded area with triangular mesh elements

INDUCED ELECTRIC FIELD AND CURRENT DENSITY INSIDE HUMAN BODY DUE TO 1 µT

Initially, the electric fields and current densities inside the human body modeled as a single spheroid are evaluated due to the exposure to a magnetic field of 1 µT taking into the consideration the effect of the human body size and the incident angle of the externally applied magnetic field. An average electrical conductivity of 0.04 S/m for the human body tissues is used. Fig.5 presents the induced electric field and current density along a human with height of 180 cm and variable width from 30 cm to 50 cm when exposed to vertical downward magnetic field of 1 µT.

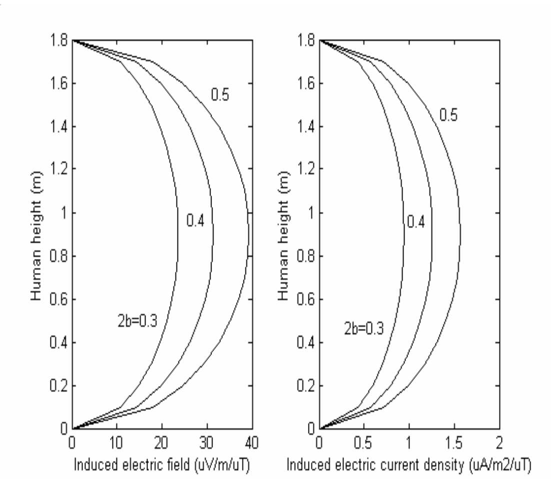

Fig.5 Induced electric field and current density along human height of 180 cm and with variable width

The induced electric fields and current densities reach their maximum at the middle human height and their values are (23.552 µV/m/µT, 0.942 µA/m^2/µT), (31.421 µV/m/µT, 1.257 µA/m^2/µT) and (39.251 µV/m/µT, 1.570 µA/m^2/µT) for the widths 30 cm, 40 cm and 50 cm, respectively.

To account for the effect of the incident angle of the applied external magnetic field, a human with height of 180 cm and width of 40 cm is exposed to 1 µT with different incident angles (0^0 "horizontal", 30^0, 45^0 and 90^0 "vertical"). Fig.6 presents the induced electric field and current density inside the human with height of 180 cm and width of 40 cm and exposed to 1 µT with different incident angles. The maximum induced internal electric fields and current densities increase as the incident angle increases from 0^0 (i.e horizontal) to 90^0 (i.e vertical). While the maximum induced electric fields and current densities occur at the human mid-height, they tend to occur at the lower body sections as the incident angle decreases. So that, for the others two models the 90^0 (vertical) incident angle will be considered since it gives the highest level of induction.

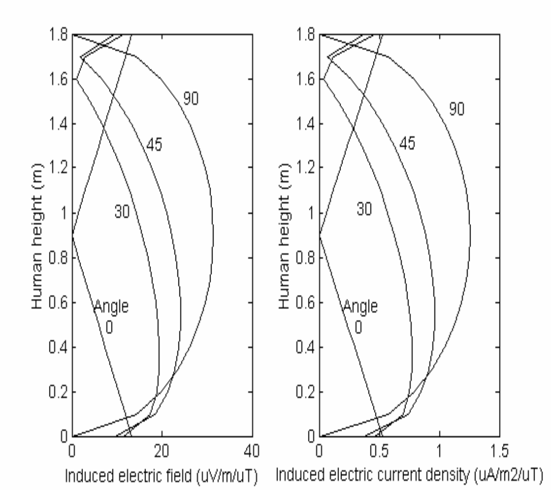

Fig.6 Induced electric field and current density along human height of 180 cm and 40 cm width with different incident angles.

Fig.7 presents the induced electric field and current density inside the different human parts of a multi-spheroids model due to exposure to an external magnetic field of 1 µT at 90° incident angle and with 0.04 S/m electrical conductivity. The maximum induced electric field spans a range from 6.28 µV/m/µT to 31.4 µV/m/µT, while the maximum induced current density spans a range from 0.251 µA/m^2/µT to 1.256 µA/m^2/µT.

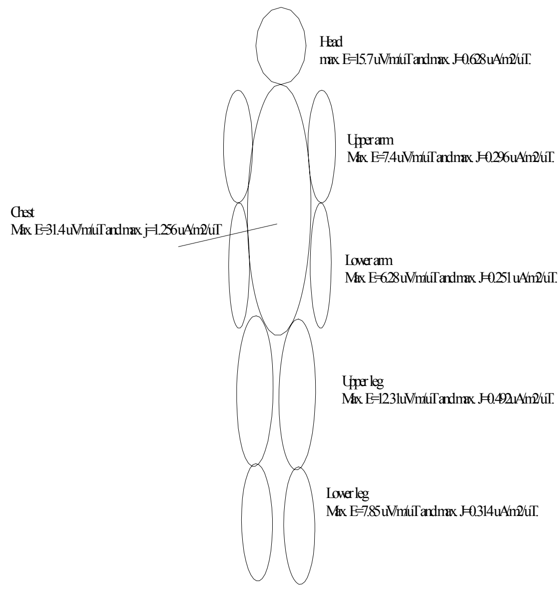

Fig.7 Maximum induced electric field and current density inside the different human parts with 1 µT exposure at 90° incident angle and with 0.04 S/m electric conductivity.

Table 1 presents the maximum and average induced electric field (µV/m/µT) and the corresponding induced current density (µA/m2/µT) inside different human parts with 0.04 S/m electric conductivity and 1 µT magnetic field external exposure. Concerning the average induction, the maximum average values are 20.903 µV/m/µT and 0.836 µA/m^2/µT found at the chest, while the minimum average values are 3.43 µV/m/µT and 0.137 µA/m^2/µT found at the lower arms. The average to maximum induced electric current density for different human parts spans a range from 0.5 to 0.665.

For the numerical human model, Fig.8 presents the induced electric field distribution over the chest horizontal cross section area when exposed to 1 µT external magnetic field. The induced electric field contour lines are circular in shape and their values increase till reaching a maximum of about 31.4 µV/m/µT at the outer section edge. Fig.9 presents the induced current density over the chest horizontal cross section area. The maximum induced current density is about 1.25 μA/m^2/μT and is reached at the outer edge.

Table 1 Maximum and average induced electric field and current density inside the different human parts (multi-spheroids model) with 1 μT exposure and 0.04 S/m electrical conductivity.

Human part name	(a/b) ratio	E max (uV/m/uT)	E avg (uV/m/uT)	J max (uA/m2/uT)	J avg (uA/m2/uT)	J avg / J max
Head	0.1/0.1 (1)	15.7	9.6	0.62	0.38	0.61
Chest	0.4/0.2 (2)	31.4	20.9	1.25	0.83	0.66
Upper arm	0.15/0.05 (3)	7.4	3.7	0.29	0.14	0.5
Lower arm	0.2/0.04 (5)	6.28	3.43	0.25	0.13	0.54
Upper leg	0.25/0.08 (3.125)	12.31	7.45	0.49	0.29	0.60
Lower leg	0.2/0.05 (4)	7.85	4.28	0.31	0.17	0.54

Table 2 presents the maximum and average induced electric field (μV/m/μT) and the corresponding induced current density (μA/m2/μT) inside different human parts with 0.04 S/m electric conductivity and 1 μT magnetic field external exposure. The maximum induced electric current density is about 1.25 μA/m^2/μT and occurs inside the chest part while the minimum value is 0.251 μA/m^2/μT and occurs inside the lower arm part. The average to maximum ratio of the induced current density is about 0.678 on average

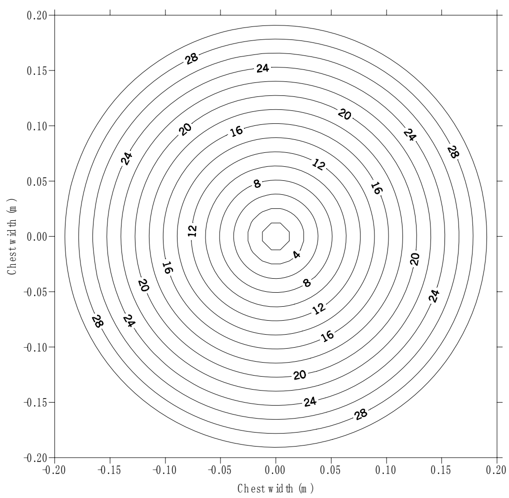

Fig.8 Induced electric field (μV/m/μT) over the chest horizontal cross section inside the human body with 40 cm width.

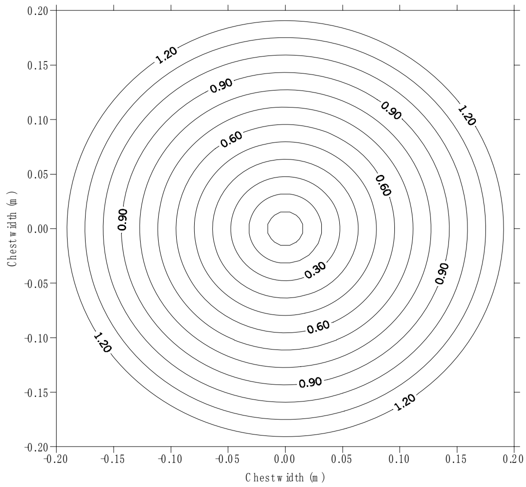

Fig.9 Induced current density (μA/m^2/μT) over the chest horizontal cross section inside the human body with 40 cm width.

Comparing the obtained results for the induced electric field and the current density inside the different human parts for the multi-spheroids analytical model and the multi-cylinders numerical model, the maximum values are the same as the exposed area is the same while the average values are little different due to the difference between the shapes of spheroids and cylinders.

Table 2 Maximum and average induced electric field and current density inside the different human parts (multi-cylinders model) with 1 μT exposure and 0.04 S/m electrical conductivity.

Human part name	(w/h) ratio	E Max (uV/m/uT)	E avg. (uV/m/uT)	J max .(uA/m2/uT)	J avg. (uA/m2/uT)	J avg / J max
Head	0.2/0.2 (1)	15.7	10.616	0.62	0.42	0.68
Chest	0.4/0.6 (0.67)	31.4	21.23	1.25	0.84	0.69
Upper arm	0.1/0.3 (0.34)	7.8	5.308	0.312	0.21	0.67
Lower arm	0.08/0.4 (0.2)	6.28	4.246	0.251	0.17	0.67
Upper leg	0.16/0.5 (0.32)	12.5	8.429	0.503	0.34	0.67
Lower leg	0.1/0.4 (0.25)	7.85	5.32	0.314	0.21	0.67

INDUCED ELECTRIC FIELD AND CURRENT DENSITY INSIDE HUMAN BODY DUE TO TYPICAL MAGNETIC FIELD

Table 3 presents the maximum measured magnetic field values inside the accessible locations in a typical 220/66 kV substation [4] while Table 4 presents the maximum magnetic field values evaluated nearby 500 kV and 220 kV power transmission lines [2]. The human body models are exposed to these typical magnetic field values for the purpose of evaluating the induced electric field and current density inside the human body.

Table 3 the maximum measured magnetic field values (µT) inside the accessible locations of 220/66 kV substation

Accessible locations	Maximum magnetic field value (µT)
Under 220 kV busbar	12.14
Under 66 kV busbar	23
Near transformers	4.5

Table 4 the maximum magnetic field values nearby 500 kV power transmission line.

Human positions	Magnetic field values (uT)	
	In front of tower	In front of mid-span
Under the line	8.65	17.5
At ROW	3.75	4.5
At 2ROW	1.8	2

Fig.10 shows the distribution of induced electric fields and current densities over the human height while the human is located at different positions inside the substation corresponding to the maximum magnetic field values resulted from the measurements. The maximum induced electric fields and current densities are (120 µV/m, 4.8 µA/m^2) near the transformers, (381 µV/m, 15.25 µA/m^2) under 220 kV busbar and (722 µV/m, 18.89 µA/m^2) under 66 kV busbar, respectively.

Comparatively, the corresponding induced values when the human(for multi-spheroids and multi-cylinders) is placed at the ground level directly under the center phase of 500 kV power line of 8.65 µT/kA are 135.8 µV/m and 5.432 µA/m^2, respectively while being in front of mid-span the induced electric field and current density are 274.74 µV/m and 10.98 µA/m^2, respectively.

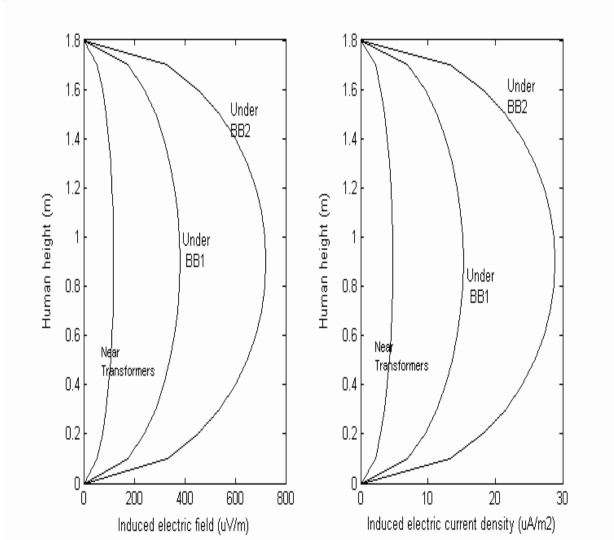

Fig.10 The distribution of induced electric fields and current densities over the human height at different positions inside the substation due to the measured maximum magnetic field values (human dimension: height 1.8 m and width 0.4 m).

CONCLUSIONS

(1) Based on an analytical technique, a single prolate spheroid human model with height 1.8 m, width 0.3 m and with 0.04 S/m average electric conductivity of the human tissues exposed to 1 µT with 90° incident angle will result in an induced electric field of 23.55 µV/m/µT and an induced current density of 0.942 µA/m^2/µT.

(2) For the analytical human model under study, the maximum induced electric field or current density increases by about 33 % as the human body width increases from 0.3 to 0.4 m, and by about 45 % as the human body width increases from 0.3 to 0.5 m.

(3) By considering the human exposure to magnetic fields inside a typical 220/66 kV substation, the average to maximum induced electric current density reaches 0.37, 0.4 and 0.34 over the human height as the human position changes from the 220 kV busbar, 66 kV busbar and near the transformers, respectively

(4) Based on an analytical technique as a multi-spheroids human model and numerical human model as a multi-cylinders with 0.04 S/m average electric conductivity of the human tissues exposed to 1 µT with 90° incident angle will result in an induced electric field of 31.4 µV/m and an induced current density of 1.256 µA/m^2 in the chest. The minimum induction is found in the lower arm where the induced electric field and current density are 6.28 µV/m and 0.251 µA/m^2, respectively.

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