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Electric Field Prediction for a Human Body-Electric Machine System

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A system consisting of an electric machine and a human body is studied and the resulting electric field is predicted. A 3-phase induction machine operating at full load is modeled considering its geometry, windings, and materials. A human model is also constructed approximating its geometry and the electric properties of tissues. Using the finite element technique the electric field distribution in the human body is determined for a distance of 1 and 5 m from the machine and its effects are studied. Particularly, electric field potential variations are determined at specific points inside the human body and for these points the electric field intensity is computed and compared to the limit values for exposure according to international standards.

ELF EMF electric fields effect electric machines human risk factor

1. BRIEF OVERVIEW ON INTERACTIONS OF ELF FIELDS WITH BIOLOGICAL SYSTEMS

The presence of industrial or extremely low frequency electromagnetic fields (ELF-EMF) has implied the need for technological control of their manifestations. Their effects are associated not only with transmission and distribution lines of electrical power systems, but also with occupational environments and office machines, medical and dental apparatuses and instrumentation, illumination sources and home appliances, computer and entertainment systems, and so forth. Most of these facilities are indispensable components of everyday life and work environment in all industrialized countries.

1.1. Physiological Aspects

Magnetic fields interact with biological systems through forces developed by electrical currents associated with physiological functions and through torques exerted on the magnetic moments of molecules and electrons. Many biological processes are affected by electromagnetic fields. Hence internal fields generated by external magnetic fields are expected to affect living tissues [1, 2, 3].

Most of the present interest in the effects of static and low-frequency magnetic fields centers on three topics: first, concerns that 50–60 Hz power distribution fields of 0.2 μT may affect the health of populations, second, that AC fields larger than 1 mT and smaller than 100 mT with frequencies of a few kilohertz may have therapeutic effects, for example, on the healing of bone fractures and soft-tissue injuries and, third, that very large slowly varying fields of the order of 2 T used in magnetic resonance imaging might affect the physiology of patients [1, 4, 5, 6, 7].

The orientation of human red blood cells is affected by the application of magnetic and electric fields. Because of their anisotropic diamagnetism,

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red blood cells orient parallel to strong magnetic fields. The electric orientation of erythrocytes is also caused by electric dipoles induced by an electric field. Thus, all red blood cells orient in the same direction and parallel to both the electric and magnetic fields. Also, flowing red blood cells orient perpendicular to the direction of the flow by the application of the fields. Thus, the orientation of the red blood cells by strong electric and magnetic fields affects the blood flow [8].

The torques that the Earth's magnetic field applies to the ferromagnetic domains of biologically formed magnetite affect the biology of several species. Low-frequency magnetic fields also induce electric fields through the Faraday effect that may have biological consequences. For either the direct magnetic fields or the magnetically induced electric fields to affect the biology of living systems, the interactions with such systems must generally be larger than the interactions with endogenous physiological and thermal noise. This constraint seems to exclude the possibility that the environmental fields less than 1 μT from the electric power distribution system affect health and places important constraints on the fields that can be expected to have therapeutic value [1].

To date, electric and magnetic exposure limits for frequencies below 100 kHz are based on vaguely defined neurobiological responses to electric fields induced in tissues in vivo by magnetic fields and on perceptual responses to external electric fields. Advances in risk assessment methods and biological research on stimulation thresholds and mechanisms are providing new bases for exposure limits. Overviews of reported neurobiological effects of electric and magnetic stimulation can lead to the development of the next generation of electric and magnetic occupational and public exposure guidelines that should be considered in new standards. For magnetic fields, there is stronger evidence for setting exposure limits to protect against adverse effects of nerve stimulation than for protecting against visual magnetophosphenes. Research on sensory perception, spontaneous and evoked potentials, and epidemiological studies of neuropsychiatric conditions in electric and magnetic exposed populations lead to the existent exposure limits [9, 10].

1.2. Medical and Dental Equipment

In recent years a new rising concern is magnetic field effects on dental (oral) tissues, on pulp cells, and dental amalgam by intra-oral release of mercury vapors from amalgam restorations [11]. In the dental work environment such as offices and laboratories, magnetic fields are associated with ultrasonic scalers, amalgamators and composite light curing units, X-rays view boxes, and chair lights [12]. A number of studies have shown that many dental instruments produce radiation with magnetic field higher than 4 mT, at a significant decrease in power of the magnetic field with increasing distance from the source. It has also been reported that instruments of older generations produce stronger magnetic fields than do the new ones [13]. Reported measurements of common household appliances are comparable with measurements in the dental laboratory environment. It is also important to notice that this depends on the distance and the type (model and age) of the dental equipment. In order to avoid the possible effects of magnetic fields the recommendations are to minimize exposure time.

The magnetic field produced in a typical dental laboratory by many bench engines driven by electric motors operated from the standard network of 50 Hz was studied. The magnetic field around each engine operating at full speed as well as the total magnetic field resulting on workplaces from all the installed engines operating simultaneously was measured at different distances from the dental technician position. The results show that at a typical distance from the technician, the magnetic field values are lower than the limits imposed by international standards [14].

1.3. Occupational ELF-EMF From Power Installations

In recent decades, the potential environmental hazard due to exposure to ELF-EMFs produced by electric power installations has received worldwide attention. The assessment of that hazard by evaluating the induced electric fields and currents due to the non-uniform magnetic fields distribution along the height of a human have been reported. The effect of magnetic field orientation relative to the body posture and the variation of the induced electric field in the human body were evaluated [15]. Also, there are numerous studies and reports dealing with high voltage transmission lines or wiring code data [16]. Electric and magnetic fields at all points near high-voltage transmission lines, the total axial current, the current and power densities in the interior of a human body were determined when the body was standing on the ground under or near the line, was in an elevated basket under the line, or was reclining in bed near the height of the line. The obtained results for field values are weak and the current and power densities are small so that the thermal effects are ignorable, but not necessarily the possible effects on nerve action, on the functioning of cells, or on certain secretions [17].

One important characteristic of ELF-EMFs is that magnetic and electric fields can be studied independently. Thus, the electric field can be studied separately from the magnetic field, based on the negligible correlation between the two fields at low frequencies such as 50 Hz [18].

Most of the papers focus on the magnetic field, because it is considered to be most likely correlated to cancer and because it may reach significant values even at non-industrial places, around common sources where the general public lives or works. On the other hand, the electric field is more predictable under the notion that large intensities are expected only near high voltage sources, and simple shielding can be used to limit the field. Nonetheless, the electric field is no less important under the bioelectromagnetic aspect and can produce direct effects on biological material. Its indirect effects such as the induced current densities generate magnetic fields and, thus, the study of the electric field can provide better understanding of the way the magnetic field interacts with living matter. Few papers refer to the electric field caused by specific home appliances, and even fewer deal with industrial electrical equipment.

Despite the broad scientific research for more than two decades on the potential biological impact of ELF-EMFs and their correlation to certain cancer types, the results are still considered controversial. Hundreds of epidemiological studies, in vivo and in vitro studies, and also theoretical analyses have so far not yielded a generally acceptable outcome [19, 20]. Many researchers and policy makers regard the mere failure to prove a positive correlation as a negative result, or even a waste of time and research funds. The dispute, however, has made engineers more careful in designing all kinds of electric equipment. Field analyses and measurements are nowadays commonly carried out to determine field distributions around various installations and equipment, particularly in the proximity of the general public [16, 21, 22, 23 24]. Some of the benefits of these studies are risk estimation of exposure to EMF, better design of artificial human implants, estimation of the influence of external fields to such implants, and proper design of electric appliances and medical apparatuses with the radiation criteria taken into consideration.

The magnetic field distribution in a human body standing close to a 3-phase induction machine operating as a motor in an electrical installation has been reported in a previous publication [25]. This reported human body-electric machine system represents many real situations of operators of electric machineries of all kinds. In the following, the same authors present the electric field distribution in a human body standing close to a medium-sized 3-phase induction machine operating as a motor. To determine the electric field distribution and the electric field intensity, a mathematical model is developed and solved using numerical analysis and the discrete element method. Also, the electric potential in vital human body regions such as the brain, the heart, and the lungs is deduced and the obtained results are discussed.

2. FIELD PROBLEM ANALYSIS

2.1. Numerical Analysis

The numerical analysis of the electric field problem involves the following phases (Figure 1):

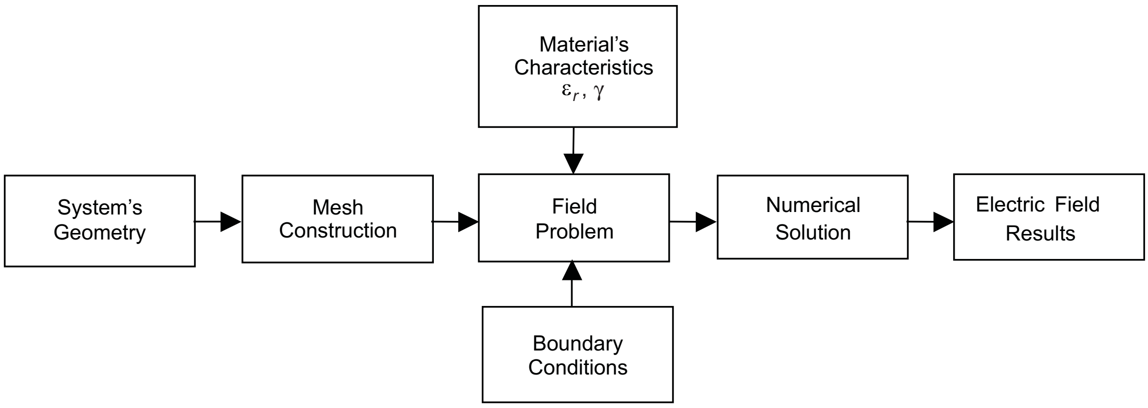

Figure 1. Phases for solving the field problem using the finite element method.

System's geometry description. The description involves the geometry of all present bodies in the electric field under study. The approach is the use of simple contours such as triangles, squares, circles, arrows. Two objects are considered: an electric machine and a human body.

The construction of the mesh. The space around the two objects is divided into small triangular elements with a smaller surface in the area of high field variations and a bigger surface in the area of small field variations. In this manner the total number of triangular elements and the degree of complexity of the problem are held at a low level.

Boundary conditions. The space around the two objects under study must be considered very large to approximate the boundary condition of zero field value at its limits. Also, the source of electric voltage supplying the electric machine is input to the problem.

Description of all materials used in the system. At this phase the electric conductivity and the relative permittivity of the electric machine and of the human body are inputted.

Field problem analysis. After all data previously described has been inputted into the model, the problem is uniquely described and it can be analyzed and solved.

Numerical solution. The solution is obtained from the computation of the energy of the electric field followed by its minimization. The output is the electric field potential in all triangular elements of the mesh.

Electric field results. The results concerning the electric field potential can be computed on closed contours according to our selection. Then, the electric field intensity is computed.

The system under study consisted of a human body of 1.75 m in height and a 3-phase induction machine operating as a motor (Figure 2). Two cases were studied, one for the human model placed at 1 m and one for the human model placed

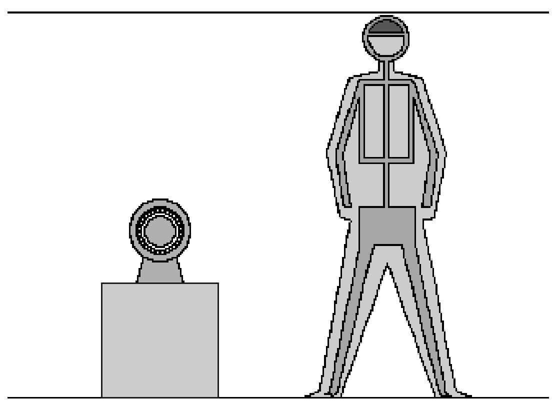

Figure 2. System geometry. The electric machine is on the left and the human body on the right (the left arm is closer to the machine than the right arm).

at 5 m from the machine. Thus, the influence of the distance over the electric field distribution and electric field values could be estimated.

2.2. Human Body Model

Electrical properties such as electrical conductivity and relative permittivity of tissues at low frequencies when a uniform electric field was applied to tissue were studied starting from the first decades of the 20th century, both by experimental measurements and by using parametric models and, then, reported in many publications [26, 27, 28, 29, 30, 31, 32, 33, 34].

Many fundamental publications, literature reviews, reported experimental tests and measurements, as well as results from parametric models were assessed by the authors of this paper in order to decide on a better approximation of the relative permittivity and of the electric conductivity of the human tissues [33, 35, 36, 37, 38]. Most of the published data correspond with other values in the body of data from the relevant literature. However, most of the published data have a high degree of uncertainty. Thus, a resulting uncertainty is detected which depends on the parametric model used, the mathematical approach for the behavior of the tissues, the experimental technique used for measurements, the source of materials used such as excised animal tissues, human autopsy materials. Only in very rare cases were the studied materials in vivo human tissues. Another source of uncertainty is the interpolation between frequencies ranges as most of the available data were tabulated or logarithmically plotted versus frequency (with a mantissa of 10 and an integer number such as 1, 2, 3, … as an exponent, thus giving the tissues values at frequency coordinates such as 10^1, 10^2, 10^3, … , 10^7, … Hz). As a consequence, many of the results reported vary by a factor larger than 10 [30] or present a spread of value ranges from ±5 to 10% above 100 MHz and up to ±15–25% at the frequency range under 1 kHz [38]. As a result, despite all precautions taken to eliminate all known sources of systematic errors, it is possible that the dielectric parameters below 1 kHz may be undercorrected up to a factor of 2 or 3 [38].

For the needs of this analysis the dielectric properties of tissues were studied from research in the worldwide available literature and the most significant values were selected and used in our computations. In our analysis we considered the following approach: the human body model consists of three separate materials with different electric properties (Figure 3a): the skeletal system (bones), the brain, and skeletal muscles. The dimensions and geometry of these three materials approximate physical human dimensions, whereas at the same time the model's complexity is kept manageable. Table 1 presents selected values used in our numerical analysis for the relative permittivity ε_r and the electric conductivity γ of the three tissues [30, 33, 35]. These values were obtained using an approximation procedure because no published reference gives the exact values of the three tissues at 50 Hz frequency.

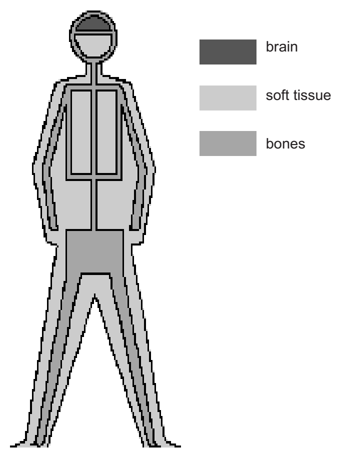

Figure 3a. Human body geometry and model. The body is modeled as consisting of three different materials: bones, soft tissues and brain.

TABLE 1. Selected Values for Electric Properties of Tissues

Human Body Model Materials	Relative Permittivity ε_r	Electric Conductivity γ (S/m)
Bones	$10 \cdot 10^3$	0.01
Brain	$1.3 \cdot 10^3$	0.12
Skeletal Muscles	$1 \cdot 10^3$	0.52

2.3. Electric Machine Model

The technical data of the electric machine involved in this study are given in Table 2.

TABLE 2. Technical Specifications of Electric Machine

Machine Specifications	Cage Induction Motor
Number of poles	4
Number of phases	3
Connection type	Δ/Y
Input voltage	220/380 V AC
Input frequency	50 Hz
Rated current	17 A
Rated Speed	1400 r/min
Rated Power	11 kW

The laboratory induction machine considered consisted of a stator and a rotor mounted on bearings and separated from the stator by an air gap. Electromagnetically, the stator consisted of a core made up of laminations carrying slot-embedded conductors. These conductors were interconnected and constituted the armature windings. Alternating current was supplied to the stator windings and the currents in the rotor windings were induced by the rotating magnetic field produced by the stator currents. The cage-type rotor of the induction machine was cylindrical and carried conducting bars short-circuited at both ends. This machine had an elementary 4-pole 3-phase distributed stator winding confined in the ferromagnetic machine yoke and carrying 3-phase symmetrical currents (Figure 3b). The copper wires construct the distributed stator winding. Each of the 24 wires was applied a voltage and carried a current according to its phase (R, S, or T) and angular displacement.

The stator windings were connected to a 3-phase, 220 V, 50 Hz power supply, and the machine operated as a motor at its nominal power of 11 kW at the full speed of 1400 r/min. This machine model provided accurate results due to the following:

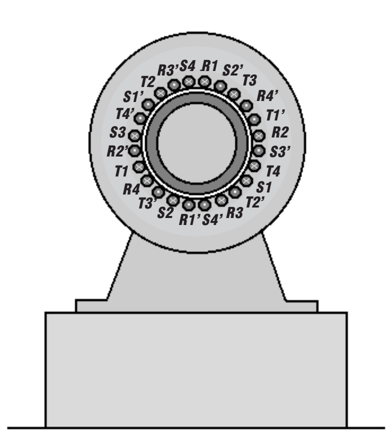

Figure 3b. Electric machine geometry and model. *Notes.* Each conductor of the stator winding is assigned the proper phase of the 3-phase supply and the correspondent angular displacement. Phase 1: $R_1 - R_1' - R_3 - R_3' - R_2 - R_2' - R_4 - R_4'$. Phase 2: $S_1 - S_1' - S_3 - S_3' - S_2 - S_2' - S_4 - S_4'$. Phase 3: $T_1 - T_1' - T_3 - T_3' - T_2 - T_2' - T_4 - T_4'$.

- Eddy currents induced in the stator and the rotor were considered,
- The model resembled real situations and the field could be calculated at any distance from the machine.

Our analysis aimed to study the case of the operator of the electric machine exposed to risk conditions such as poor or failing grounded equipment. The non-grounded electric motor increases the produced electric field in the human body and, also, as it is already known, it can be a source of the risk of electrocution [39]. On the other hand, in the case of a grounded electric machine, zero voltage and zero potential everywhere throughout the operator's body will result because the stator core is forced to zero voltage and, thus, minimal electric field is leaked outside the machine.

2.4. The Electric Field Analysis

The electric field analysis was carried out using the finite element numerical method in 2-D [40]. The mesh consisted of 1,292 nodes and 2,536 triangular elements, and was constructed dense in the region of interest (around and inside the human body and the machine) and sparse at the ends of the area under study. To resemble infinity, the area studied spread to 15 m in height and 40 m in width.

The basic assumptions for the field analysis were as follows: source currents were balanced 3-phase and confined to the metallic current paths, conductivity of the soil was considered infinite, and the field equaled zero at infinity. Assumed boundary conditions for the numerical analysis were zero potential at infinity and zero potential at the ground.

3. NUMERICAL SOLUTION AND RESULTS

The problem of the human body-electric machine system, as formulated in the previous section, was solved using Magnet software [41]. Figure 4 presents the computed equipotential lines of the resulting electric field in the human body standing on the right and at a distance of 1 m from the electric motor.

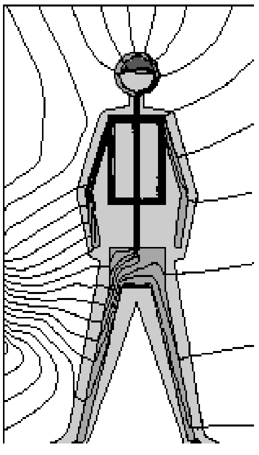

Figure 4. Electric field produced in the human body by the electric motor in operation. The equipotential lines of the computed electric field are shown.

Two cross-sections of the human body were studied in detail, one at the head and one at the thorax level, chosen because they enclose vital organs such as the brain, the lungs, and the heart. The electric field computed along contours passing through these areas provides information on the expected field values on these organs.

Using the discrete element method, the electric field potential P (absolute voltage value) was calculated for each element of the mesh. For the two selected contours, one in the head and one in the thorax, the computed electric field potential is presented in Figures 5a and 5b, respectively. At a 1-m distance, the computed electric voltage at the external contour of the cranium was $\Delta P_{ext} = 24.4$ mV, whereas in the internal contour of the cranium, which corresponds to the brain, was $\Delta P_{int} = 22.84$ mV. Also, at a 5-m distance from the machine, the computed values for the electric voltage at the external and internal contour of the cranium were $\Delta P_{ext} = 1.01$ mV and $\Delta P_{int} = 1$ mV, respectively. The electric voltage applied to the heart was computed as $\Delta P \approx 5.55$ mV and to the lungs at about $\Delta P \approx 9.25$ mV.

By differentiating the curves shown in Figures 5a and 5b, the electric field intensity E was computed. The results are illustrated in Figures 6a and 6b for the head and the thorax, respectively. Table 3 summarizes the computed values of the electric field intensity for the studied body regions. The head, the left and right cranial bones bear the highest electrical stress, and the equipotential lines concentrate mostly in these regions. The highest computed values of the electric field intensity in the human body occurred in the neck, and were 1.13 V/m for 1-m and 0.08 V/m for 5-m distance from the machine.

TABLE 3. Electric Field Intensity (*E*) in the Human Body

Body Region	*E* (V/m) 1 m From Machine	5 m From Machine
Neck	1.130	0.080
Left arm	0.681	0.072
Left costal bones	0.400	0.038
Left cranial bones	0.275	0.042
Vertebral column	0.250	0.025
Right cranial bones	0.138	0.013
Heart	0.078	0.003
Right costal bones	0.063	0.022
Lungs	0.048	0.003
Brain	0.047	0.003
Right arm	0.038	0.003

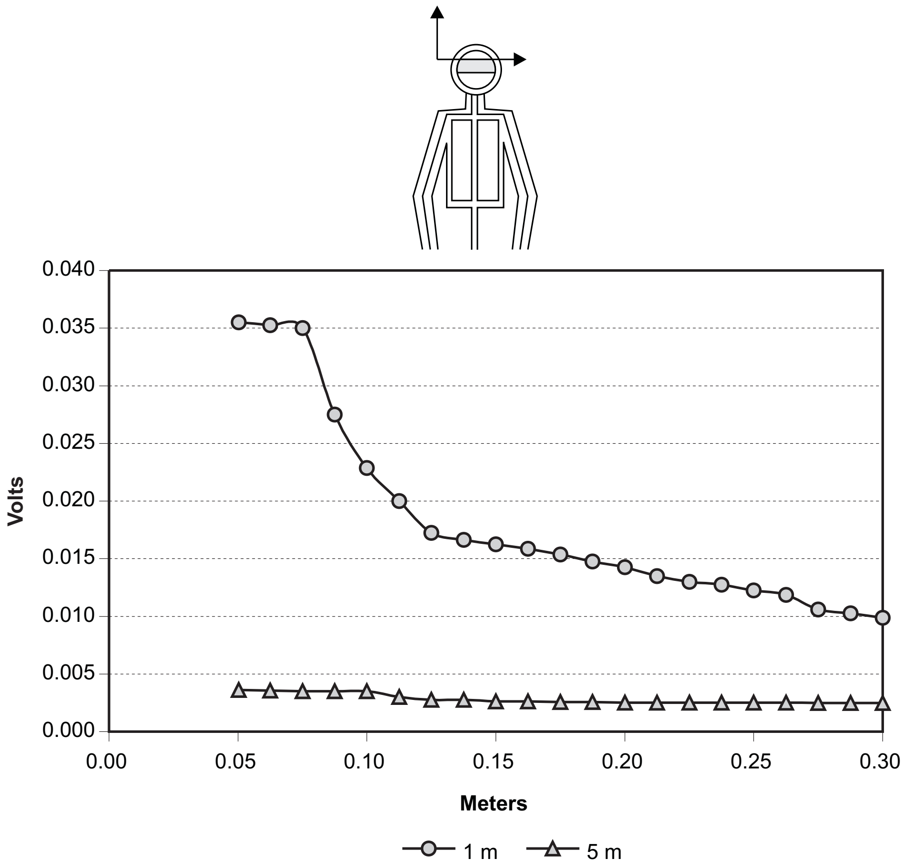

Figure 5a. Electric field potential at head for 1- and 5-m distance from electric motor.

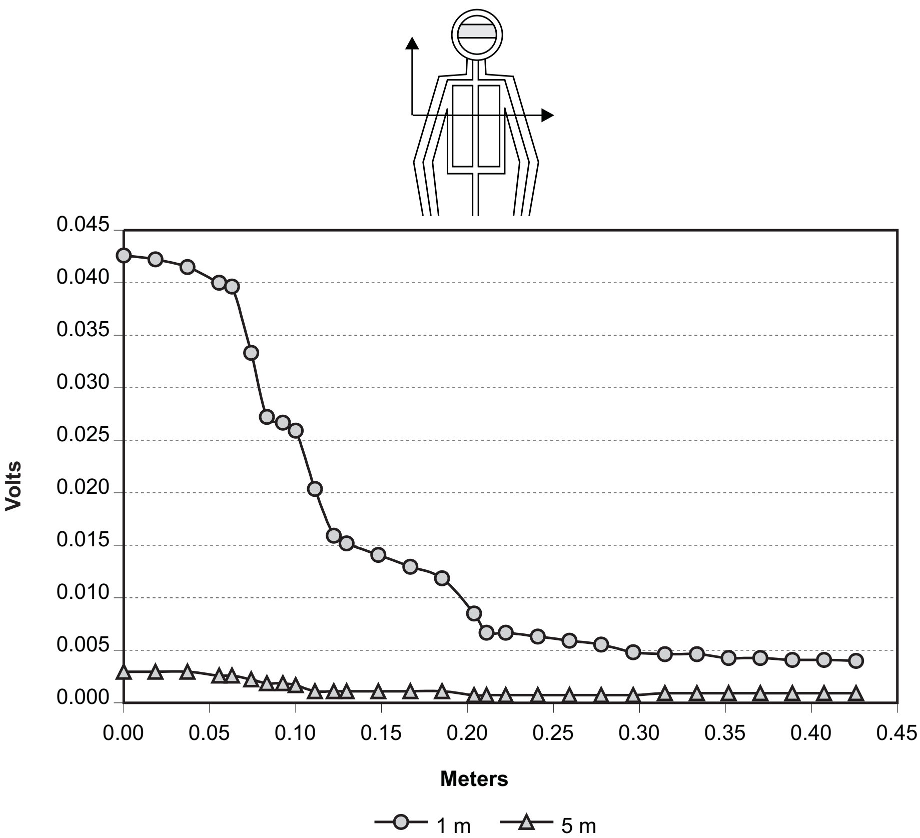

Figure 5b. Electric field potential at thorax for 1- and 5-m distance from electric motor.

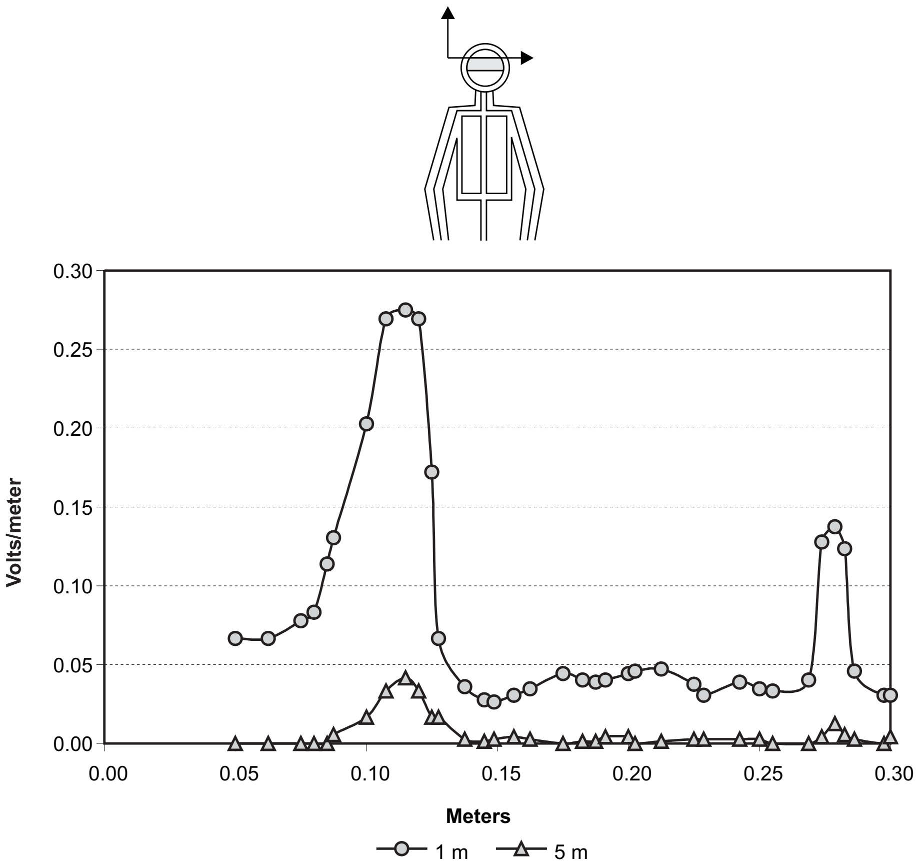

Figure 6a. Electric field intensity at the head for 1- and 5-m distance from electric motor.

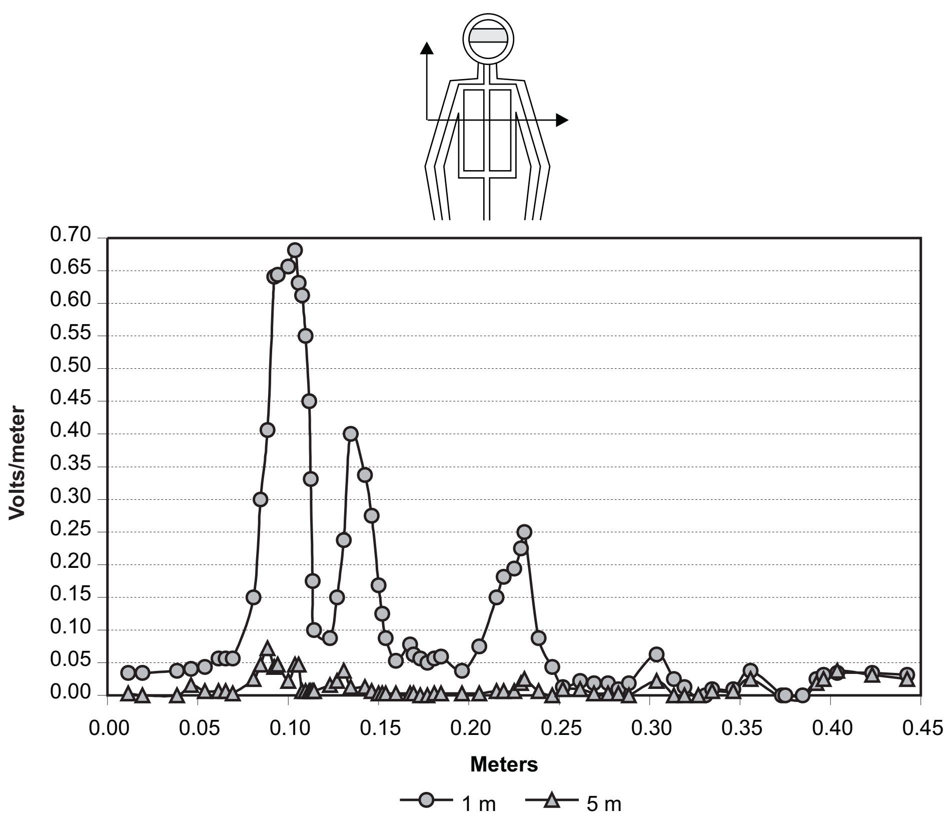

Figure 6b. Electric field intensity at the thorax for 1- and 5-m distance from electric motor.

At the left side of the cranium, which was closer to the machine, the electric field intensity was computed at 0.275 and 0.042 V/m for 1- and 5-m distance, respectively. At the right side of the cranium, the electric field intensity was 0.138 V/m for 1-m and 0.013 V/m for 5-m distance from the machine. Inside the cranium, where the brain resides, the electric field intensity was computed to be 0.047 V/m for 1-m and 0.003 V/m for 5-m distance from the electric machine.

At the thorax level, the maximum intensities of electric field were 0.681 V/m for 1-m and 0.072 V/m for 5-m distance and occurred in the left arm bones, which were closer to the machine. In the left costal bones the corresponding values were 0.400 and 0.038 V/m, respectively, whereas the electric intensity in the vertebral column was 0.250 and 0.025 V/m for 1- and 5-m distance from the electric machine.

At the soft tissues inside the thorax (the lungs and the heart) the electric field intensity was computed as follows: at the heart it was 0.078 V/m for 1 m and 0.003 V/m for 5 m, at the lungs it was 0.048 V/m at 1 m and 0.003 V/m at 5 m. All the aforementioned results obtained from the computations of electric field intensity are summarized and depicted in Figure 7.

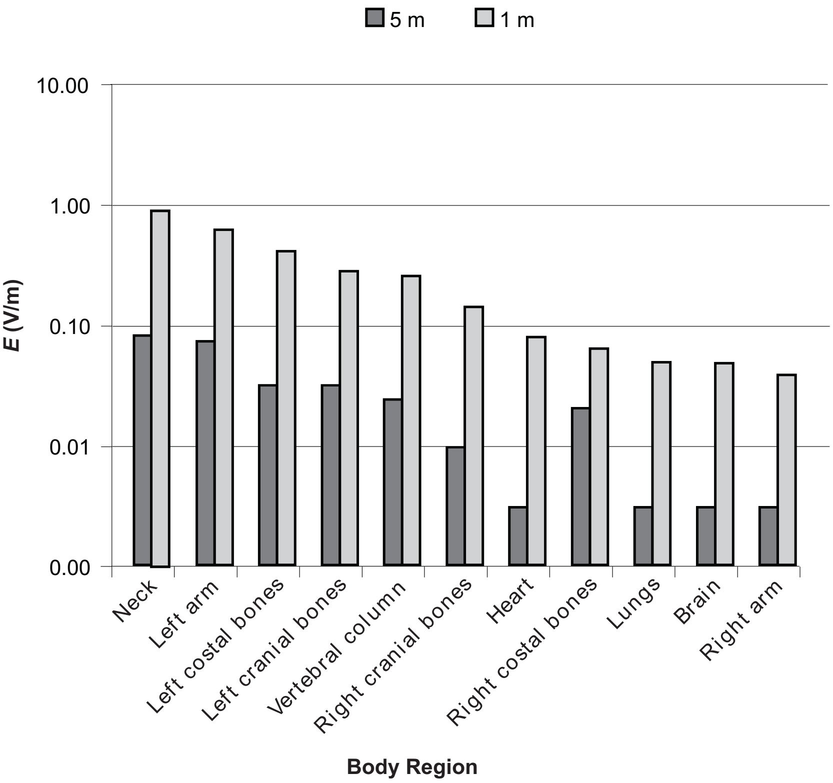

Figure 7. Comparative representation of electric field intensity produced in different regions of the human body by an electric machine operating as motor at distances of 1 and 5 m from the operator.

4. DISCUSSION

The electric field values computed with our method for the chosen model of the human body-electric machine system are small, many times lower than the limits of related standards and guidelines [42, 43, 44, 45], and should not be expected to produce any harmful macroscopic and microscopic biological effects. The limits for exposure to ELF fields as established by international standards are different in different countries and concern general public exposure and occupational exposure as well (Table 4).

CENELEC proposed the electric field exposure limits for the European standard supply frequency 50 Hz at 10 kV/m for general public

TABLE 4. Limit Values for Exposure to Electric Fields According to Different Standards

Standards	General Public Exposure	Occupational Exposure
Comité Européen pour Normalisation Electrotechnique (CENELEC)	0–0.1 Hz, 14 kV/m 0.1–50 Hz, 10 kV/m 50–1500 Hz, 600/*f* kV/m 1.5–10 kHz, 0.4 kV/m	0–0.1 Hz, 42 kV/m 0.1–50 Hz, 30 kV/m 50–1500 Hz, 1500/*f* kV/m 1.5–10 kHz, 1 kV/m
International Commission on Non-Ionizing Radiation Protection (ICNIRP)	60 Hz, 4.2 kV/m	60 Hz, 8.3 kV/m
American Conference of Governmental Industrial Hygienists (ACGIH)	Ceiling value: 60 Hz, 25 kV/m	

Notes. *f*—frequency. The standard supply frequency in Europe is 50 Hz and 60 Hz in the North America.

exposure and at 30 kV/m for occupational exposure. The ELF exposure limits of the American Industrial Hygiene Association (AIHA), of the American Conference of Governmental Industrial Hygienists (ACGIH), and of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) are based on avoiding the effects first noticed as current densities increase above endogenous levels (10 mA/m^2), such as magnetophosphenes, electrophosphenes, direct nerve and muscle stimulation, and changes in brain cognitive function. For power-frequency fields in North America, where the standard supply frequency is 60 Hz, the ACGIH exposure limits for the electric field are 25 kV/m. These ACGIH exposure limits are ceiling values. For power-frequency fields, ICNIRP has established guidelines for both occupational and general public exposures to both electric and magnetic fields. For 60 Hz fields, the ICNIRP electric field guidelines for residential and occupational exposures are 4.2 and 8.3 kV/m, respectively.

Until now, minimum distances between electric machines and operators have not been established yet. Also, no legislation mentions specific guidelines or limits for operation with exposure to ELF fields produced by groups of electric machines working together.

Some data derived from computations give rise to questions on problems and future trends. Thus, the legislation on the specific requirements for occupational ELF levels must be updated concerning safety distances for operation of electric machines. Some on-going projects for standardizations can be found from research on the following Internet sites:

- American Industrial Hygiene Association (AIHA): http://www.aiha.org,
- European Committee for Electrotechnical Standardization (CENELEC): http://www.cenelec.org,
- Commission on Non-Ionizing Radiation Protection (ICNIRP), EMF Publications: http://www.icnirp.org/pubEMF.htm,
- Institute of Electrical and Electronics Engineers (IEEE): http://www.ieee.org/ieeexplore.

Furthermore, the impact of ELF produced by electric equipment must include not only the implementation of the regulation, but also monitoring, training, and information aspects addressed to operators and other employees as well. Improvements and problems, achievements and difficulties are of interest to small and medium-sized private enterprises and to educational laboratories in universities as well.

5. CONCLUSIONS

A numerical solution for the electric field produced by an electric machine operating at nominal power and at full speed in an operator's body was found. The conductive materials of the machine stator core limit the electric field outside it. However, there is a small field leak due to machine design and to the finite conductive properties of machine materials.

The results show that the electric field produced in the human body decreases with the increase of the distance from the machine. It was found that the maximum intensity produced by the electric field in the human body occurs in the neck and specifically in the cervical skeletal bones. Also, significant intensities are produced in the cranium bones, in the vertebral column, and in the costal bones. These bones present a shielding behavior for vital human organs such as the heart, the lungs, and the brain.

In all cases, the computed electric field level was lower than the limits imposed by the existent international standards. However, the computed values of electric field can become much higher in other types of electric machine configurations, such as

- in large industrial installations with groups of machines working together, either generators or motors,
- in electric drives involving frequency converters (Pulse Width Modulation-based inverters), which supply electric machines with higher voltage and frequency than 380 V and 50 Hz,
- in high voltage equipment,
- in electric power stations with many installed generators of hundreds of kilowatts or megawatts.

The same method described in this article can be used in multimachine installations and also for electric drives with power supplies of variable voltage-variable frequency. In all cases the resulting fields must be superimposed.

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