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Several Aspects of Human Exposure to Low Frequency Fields; Incident and Internal Field Dosimetry Procedures and Related Legal Issues

Dragan Poljak, Tonko Garma, and Zorica Novakovic Šesnić

***Summary* — The paper deals with simple and efficient dosimetry procedures for human exposure to low frequency (LF) electric and magnetic fields at single and multiple frequencies, respectively. The electromagnetic interference (EMI) sources of interest are overhead power lines and transmission substations. Electric and magnetic fields due to EMI sources are either calculated or measured. Theoretical dosimetry is based on scalar potential integral equation (SPIE) for the case of the electric field assessment while the magnetic fields are computed by means of the Biot-Savart law. The internal fields in the human body are determined by using the canonical body models (disk model and cylindrical model). The obtained results are compared to exposure limits proposed by national and international legislation, respectively (National Gazette No 146/2014, 31/2019, 59/2016) and ICNIRP International Commission on Nonionizing Radiation protection). Finally, legal issues pertaining to human exposure to LF fields are addressed.**

***Keywords* — Human exposure, low frequency fields electromagnetic dosimetry, legal issues.**

I. Introduction

Human exposure to low frequency (LF) fields may cause some non-thermal effects, mostly pertaining to excitable tissue [1]. Such effects are quantified in terms of electric fields induced inside the body. Prerequisites for the assessment of internal electric field is the knowledge of external fields which can be determined by calculations and/or measurements. Assessment of external fields is a task of incident field dosimetry, while internal dosimetry deals with the assessment of internal fields. [2]. Incident field dosimetry is a well-established engineering discipline and involves standard analytical/numerical approaches for the calculation of field levels and related measurement procedures. Dosimetry of internal fields is far more demanding as highly irregular geometry and heterogeneous structure of the human body must be taken into account. Thus, the analysis within the framework of the internal field dosimetry can be carried out by using realistic, anatomically based models or simplified canonical body representations. Review of some commonly used models could be found elsewhere, e.g. in [2] In many scenarios human being is located far enough from electromagnetic interference (EMI) source and the use of simplified canonical models is possible.

This paper is an extended version of conference papers [3, 4] and reviews some incident and internal field dosimetry procedures using simplified body models and also addresses some legal issues pertaining to the national/international legislation that proposes exposure limits.

The paper is organized, as follows; Section II deals with the incident dosimetry procedures for the assessment of external electric and magnetic fields. In addition to a most often single frequency case, a scenario involving simultaneous exposure to multiple frequencies (which is studied in somewhat lesser extent) is addressed. Typical 110 kV transmission substation as well as 110 kV overhead power line (fir tree mast) are considered as the most common LF source. In Section III internal dosimetry procedures are outlined, in particular cylindrical body model for the exposure to electric field and disk model of the torso for the exposure to magnetic fields.

Obtained illustrative results for external electric and magnetic fields and internal electric fields compared against national and international exposure limits [1, 5], respectively, are presented in Section IV.

Some legal issues pertaining to national/international legislation and proposed exposure limits are reviewed in Section V.

Finally, some concluding remarks and guidelines for future work are given.

II. Incident field dosimetry – Theoretical and Experimental Procedures

This section deals with computational and measurement procedures for the assessment of external electric and magnetic fields generated by LF sources. Of particular interest are power lines and transformer substations.

According to [1], for biological effects at frequencies up to 10MHz, simultaneous exposure to LF fields of multiple frequencies requires following conditions to be satisfied for external field levels:

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$$\sum_{j=1\text{Hz}}^{10\text{MHz}} \frac{E_j}{E_{R,j}} \leq 1 \tag{1}$$

$$\sum_{\boldsymbol{j}=\mathbf{1}\text{Hz}}^{10\text{MHz}} \frac{\boldsymbol{H_j}}{\boldsymbol{H_{R,j}}} \leq \mathbf{1} \tag{2}$$

where: E_j and H_j is the electric and magnetic field intensity, respectively, while $E_{R,j}$ and $H_{R,j}$ is the reference level of the electric and magnetic field, respectively, at *j-th* frequency.

A. Electric Field Calculation

Electric field in the vicinity of a wire configuration of interest is determined in two steps. First, one needs to evaluate the scalar potential around the wire structure of interest and once the potential distribution is known it is possible to obtain the electric field. The scalar potential distribution can be determined if the linear charge density over conductors is known. The linear charge density is governed by the *scalar potential integral equation* (SPIE) [2, 3]. Finally, the desired electric field distribution in the vicinity of the LF EMI source is obtained by means of the gradient operator. It is worth noting that SPIE can be solved via the Galerkin-Bubnov variant of the indirect Boundary Element Method (GB-IBEM), while the gradient operator is usually approximated by using the finite difference approximation. In particular, for the case of an arbitrary wire structure above a finitely conducting ground the impact of the ground is taken into account via the theory of images, as indicated in Fig1.

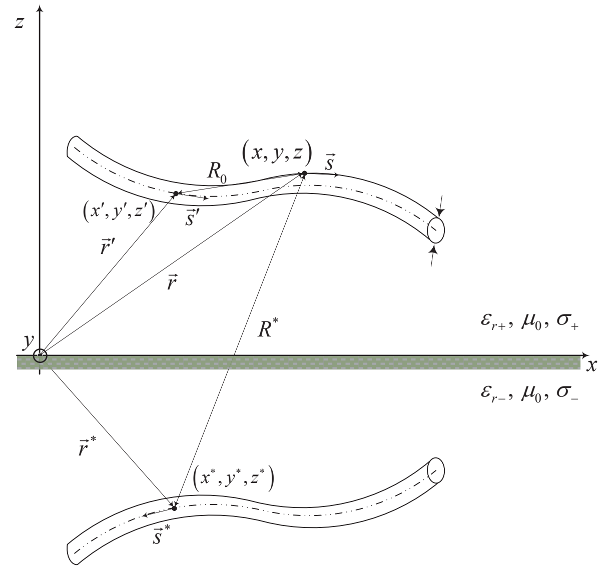

Fig. 1. Arbitrary wire configuration (The source and image wire)

It is worth noting that attenuating impact of the ground can be taken into account via corresponding reflection coefficient [5]. A general expression for a scalar potential in the vicinity of a wire configuration of length l and arbitrary shape obtained by quasi-static approximation and reflection coefficient arising from the *Modified Image Theory* is of the form

$$\varphi(\vec{r}) = \frac{1}{4\pi\varepsilon_0}\int_l \left(\frac{1}{|\vec{r}-\vec{r}'|} - \Gamma_{ref}^{MIT}\frac{1}{|\vec{r}-\vec{r}*|}\right)\rho_l(\vec{r}')ds' \tag{3}$$

Where ρ_l denotes the unknown linear charge density along the wire configuration, $\vec{r}'$ is a radius vector of a source point, $\vec{r}$ is a radius vector of an observation point, $\vec{r}^*$ stands for a point at the image source, and Γ_{ref}^{MIT} is a reflection coefficient arising from the modified image theory [2, 3] and is given by

$$\Gamma_{ref}^{MIT} = \frac{\varepsilon_{eff}-\varepsilon_0}{\varepsilon_{eff}+\varepsilon_0} \tag{4}$$

where $\varepsilon_{eff} = \varepsilon_r - j\frac{\sigma}{\omega}$ is the complex permittivity of the ground.

Unknown linear charge density can be obtained by numerically solving corresponding SPIE [2, 3]. Provided the potential at the wire surface is known $\varphi_l(\vec{s}')$ SPIE takes form

$$\varphi_l(\vec{s}') = \frac{1}{4\pi\varepsilon_0}\int_l \left(\frac{1}{R_l} - \Gamma_{ref}^{MIT}\frac{1}{R_l^*}\right)\rho_l(\vec{r}')ds' \tag{5}$$

where R_l and R_l* is the distance from the axis of wire in the air and image wire, respectively, to the point at the surface of the wire in the air.

As already mentioned, integral equation (5) can be numerically solved by means of GB-IBEM [6]. Once the linear charge density is known is known ρ_l it is possible to determine the potential in the vicinity of the wire structure. Finally, in accordance to the quasi-static approximation the corresponding electric field can be obtained as a gradient of scalar potential

$$\vec{E} = -\nabla\varphi \tag{6}$$

Equations (3) to (6) are general and valid for arbitrarily shaped wires which is of particular interest in the analysis of substation transformers [2-4]. On the other hand, if power lines with negligible sag are analyzed an approximation with straight conductors could be used and relations (3) and (5) could be simplified appreciably. Finally, the ground influence can be often neglected, as well [1]. Namely, the wire structure is assumed to be insulated in free space [1] and, consequently, the straight wire geometry of length 2*L*, shown in Fig. 2., is considered.

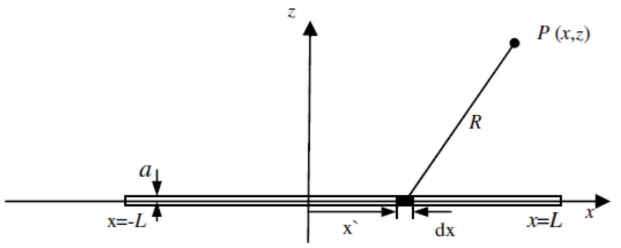

Fig. 2. Straight conductor of length 2L in rectangular coordinate system

Now the Electric scalar potential in an arbitrary point *P(x,z)* due to a straight wire segment with linear charge density ρ_l is given by expression [1]

$$\varphi(x,z) = \frac{1}{4\pi\varepsilon_0}\int_{-L}^{+L}\frac{\rho_l(x')dx'}{R} \tag{7}$$

where *R* is the distance from the source point at the straight wire to the arbitrary observation point *P*.

Provided the potential along the straight wire ϕ_l is known integral expression (5) becomes an integral equation of the form

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$$\varphi_l = \frac{1}{4\pi\varepsilon_0}\int_{-L}^{+L}\frac{\rho_l(x')dx'}{\sqrt{(x-x')^2+a^2}}, \tag{8}$$

where a is the wire radius.

Solving the integral equation (6) via GB-IBEM algorithm yields the linear charge density distribution along the wire configuration. Mathematical details are available elsewhere, e.g. in [1].

Once the charge density is determined it is possible to compute the scalar potential distribution in the vicinity of the wire configuration from (5). Finally, the corresponding electric field in an observation point of interest is obtained as a gradient of the scalar potential [5]:

$$E_{xi} = -\frac{\partial\varphi}{\partial x}, \qquad E_{zi} = -\frac{\partial\varphi}{\partial z} \tag{9}$$

It is worth mentioning that, due to the radial symmetry, reducing the domain of interest to XZ plane can be carried out without any loss of generality.

B. Magnetic field calculation

Calculation of LF magnetic field generated by arbitrary wire configurations is, in principle, less demanding compared to the electric field calculation, as the current flowing along the conductor configuration is known input parameter. The magnetic field of an arbitrary wire configuration is usually obtained by using Biot-Savart law for curvilinear current element, as shown in Fig 3.

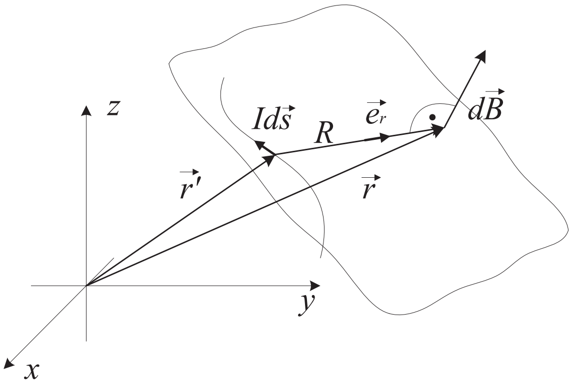


Fig. 3. Curvilinear current element

Magnetic flux density $\vec{B}$ in an arbitrary observation point due to contribution of all infinitesimal contributions $id\vec{s}'$ along the wire structure according to Biot-Savart law is expressed by integral

$$\vec{B} = \frac{\mu_0}{4\pi}\int_l \frac{id\vec{s}'\times(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|^3} = \frac{\mu_0}{4\pi}\int_l \frac{id\vec{s}'\times\vec{e}_R}{R^3} \tag{10}$$

where $R = |\vec{r}-\vec{r}'|$ is the distance from the source to observation point, respectively.

Integral (8) can be significantly simplified if an arbitrary curved structure is considered as superposition of straight wire segments, as shown in Fig. 4.

Performing some simple mathematical manipulations ϕ-component of the magnetic field generated by straight wire segment, Fig. 4., is obtained

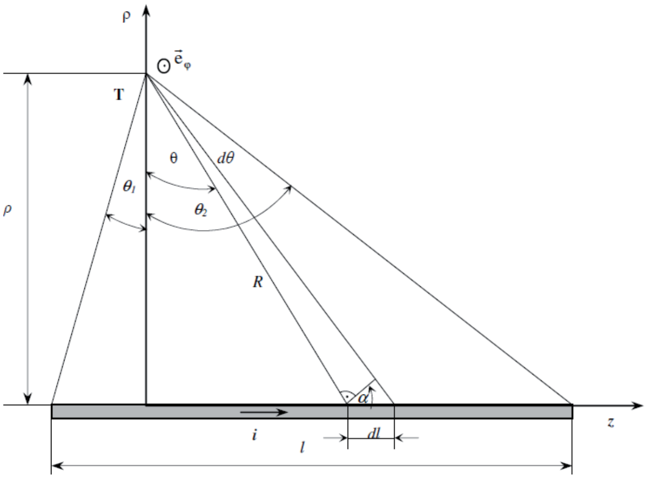


Fig. 4. Straight wire segment

$$\vec{B} = \vec{e}_\phi\frac{\mu_0 i(t)}{4\pi\rho}\int_{\theta_1}^{\theta_2}\cos\theta\, d\theta = \vec{e}_\phi\frac{\mu_0 i}{4\pi\rho}(\sin\theta_1+\sin\theta_2) \tag{11}$$

where ρ is the variable of cylindrical coordinate system, while Θ is the auxiliary angle, as depicted in Fig. 4.

More mathematical details on the application of Biot-Savart law to the calculation of LF magnetic fields can be found elsewhere, e.g. in [2].

C. Electric and magnetic field measurement

Measurements are carried out by Aaronia Spectran NF-5030 spectrum analyzer, equipped with high performance DSP and 3D magnetic- and electric-field sensor. Prior to being adjusted to detect first and higher field harmonics (up to 7th), the analyzer was placed on insulated tripod enabling adjustable measurement height. During the entire measurement process, obtained data were transferred to laptop PC for post-processing and further in-depth analysis. Typical 110 kV transmission substation as well as 110 kV overhead power line (fir tree mast), is considered, respectively, as the most common LF source for the worst case scenario, see Fig. 5.

Fig. 5. Magnetic field measurement configuration in case of 110 kV overhead power line (fir tree mast)

III. INTERNAL DOSIMETRY PROCEDURES

This section outlines dosimetry procedures for the assessment of internal electric field induced inside the human body due to the exposure to either electric or magnetic external field, respectively.

Contrary to ICNIRP 1998 guidelines [7] in which induced current density represents the basic restriction at LF exposures in ICNIRP 2020 guidelines 2010 [1] the induced field is the basic restriction. These two quantities are simply related through the Ohm law in a differential form

$$\vec{E} = \frac{\vec{J}}{\sigma} \qquad 12)$$

where σ is the conductivity of a tissue.

For the case of simultaneous exposure to different frequencies, as the internal field is the basic quantity up to f=10MHz, the accumulative nature of these fields is taken into account, as follows [1]

$$\sum_{j=1\text{Hz}}^{10\text{MHz}} \frac{E_j}{E_{L,j}} \leq 1 \qquad (13)$$

where $E_{i,j}$ is the internal field value at a given frequency and $E_{L,j}$ is the assigned limit at the same frequency.

This subsection deals with simple and efficient internal dosimetry procedures for the assessment internal fields, i.e. the electric and magnetic fields induced inside the human body. Cylindrical body model is used for the exposure to axial electric field and the disk body model is used for the exposure to the magnetic field perpendicular to the body.

A. CYLINDRICAL BODY MODEL

When the human body is exposed to the LF electric field being axial to the body it is possible to use a simple cylindrical representation of the human being as shown in Fig. 6. Note that the body is dominantly conducting at low frequencies [8-9].

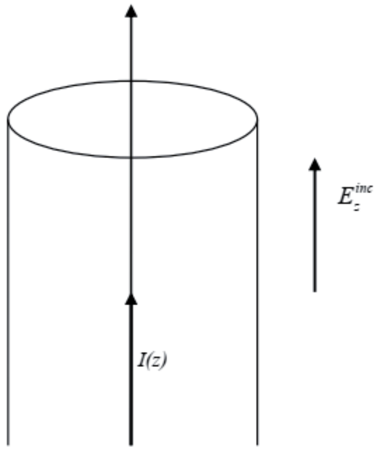


Fig. 6. Cylindrical body model

Axial current induced in the body is governed by the Pocklington integro-differential equation [2] given by

$$E_z^{inc} = -\frac{1}{4j\pi\omega\varepsilon_0}\int_{-L}^{L}\left[\frac{\partial^2}{\partial z^2}+k^2\right]g_E(z,z')I(z')dz' + Z_L(z)I(z) \qquad (14)$$

where E_z^{inc} denotes the external incident field being tangential to the finitely conducting cylinder, while $I(z)$ is the unknown current distribution along the cylinder, $Z_L(z)$ is the impedance per body length by which conducting properties of the body are taken into account and $g_E(z, z')$ is exact kernel of the integro-diffferential equation

$$g_E(z,z') = \frac{1}{2\pi}\int_0^{2\pi}\frac{e^{-jkR}}{R}d\phi \qquad (15)$$

Axial current can be expressed in terms of current density

$$I = \int_S \vec{J}\cdot d\vec{S} \qquad (16)$$

where S is the cylinder cross-section, while internal electric field is simply obtained from (12).

Furthermore, for the LF part of the electromagnetic spectrum the solution of equation (14) can be written in the form [2]

$$I_z(z) = j2\pi\frac{kL^2}{\psi Z_0}E_z^{inc}\left[1-\left(\frac{z}{L}\right)^2\right] \qquad (17)$$

while parameter ψ is [2]

$$\psi = 2\ln\frac{2L}{a} - 3 \qquad (18)$$

where L and a stands for the cylinder length and radius, respectively.

Provided the axial current distribution is computed from (17), it is possible to calculate the related electric field magnitude by combining (12) and (16)

$$E = \frac{I_z(z)}{a^2\pi\sigma} \qquad (19)$$

Note that the accumulative field over a frequency range of interest is obtained from (13).

In this paper cylinder radius and length, respectively, is assumed to be a=0.14m and L=1.75m [2].

B. DISK BODY MODEL

When the human body is exposed to LF magnetic field component perpendicular to the human body, circular currents are induced inside the torso. Provided that a uniform distribution of the magnetic field at a given frequency can be assumed over the human torso a homogeneous disk model of the trunk of radius and thickness a, and constant conductivity σ is used [2], as shown in Fig. 7.

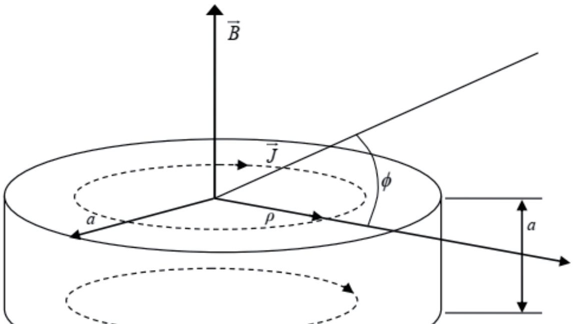


Fig. 7. Disk model of the human torso

Such a simple model is convenient as disk geometry correspond to the shape of circular current induced inside the body. This canonical geometry provides rather simple and quick assessment of the internal field starting from Maxwell equation

$$\oint_c \vec{E} d\vec{s} = -\int_S \frac{\partial \vec{B}}{\partial t} d\vec{S} \tag{20}$$

which represents integral form of Faraday law where $\vec{E}$ stands for the circular electric field, and $\vec{B}$ is magnetic induction perpendicular to the torso.

For time-harmonic dependence, taking into account a rotational symmetry of the disk, it follows

$$\int_0^{2\pi} E_\varphi \rho d\varphi = -j\omega B_z \int_0^\rho \int_0^{2\pi} \rho d\rho \, d\varphi \tag{21}$$

and the maximal value of the circular field at $\rho=a$ can be obtained from a simple relation

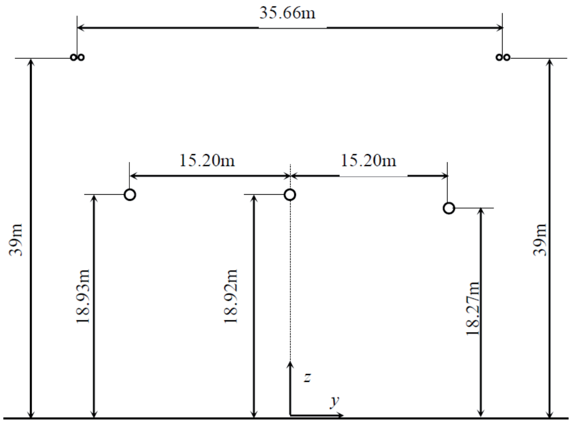
$$|E_\varphi| = \pi a f \cdot B_z \tag{22}$$

Thickness of the disk is not particularly specified in literature as the total current is not quantity pertaining to basic restriction. In this paper disk radius and thickness, respectively, is assumed to be a=0.14 m [8-9].

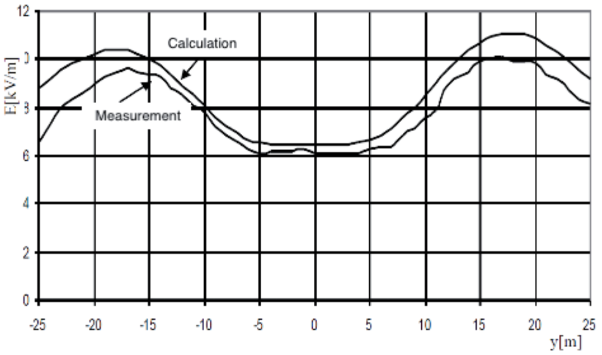
IV. Numerical Results

A. External Fields

First example deals with the electric field generated by 1050 kV power line composed from 3 aboveground conductors (Pittsfield, USA [10]). Figure 8.a shows the power line configuration, while our calculated results compared against measured results at height z=1m above ground are depicted in Fig.8b.



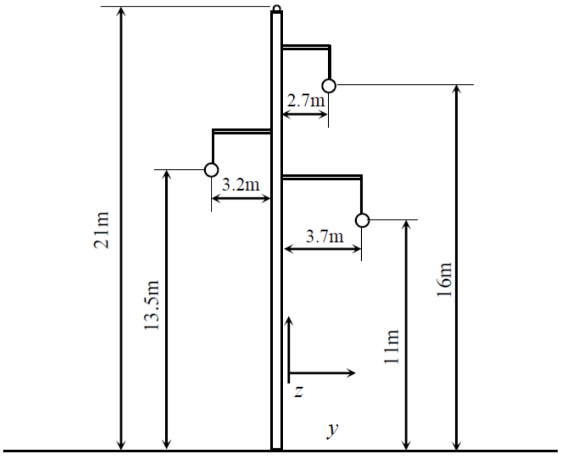
a) Geometry of 1050 kV power line



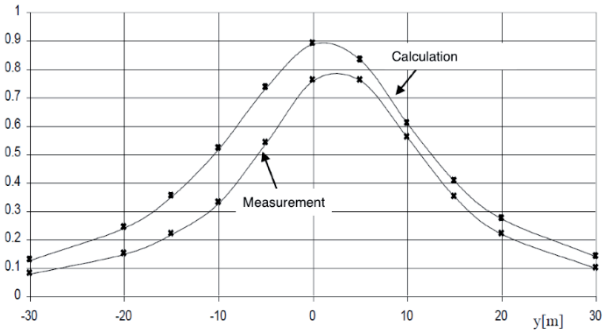
b) Calculated vs measured results at z=1 m above ground

Fig. 8. Electric field from 1050kV power line

Figure 9 deals with the magnetic flux density generated by 110 kV power line consisting of 3 aboveground conductors in triangular arrangement (industrial zone near city of Split [11]). Average value of the measured current is 90 A. Figure 9a shows the actual power line configuration while Figure 9b shows the calculated vs measured results at height z=1m above ground.



a) Geometry of 110 kV power line



b) Calculated vs measured results at z=1m above ground

Fig. 9. Magnetic field from 110 kV power line

The calculated and measured results agree satisfactorily and do not exceed the reference levels proposed in [1] and [5].

Next set of Figs deals with the simultaneous human exposure to multiple frequency fields.

A view to a part of 110 kV overhead bus is shown in Fig. 10. Note that electric and magnetic field spectra are measured below this bus segment.

Fig. 10. A view to a part of 110 kV bus

Figure 11 and 12 show the spectrum of electric and magnetic field, respectively.

Observing the comparison of calculated versus measured results for the electric and magnetic fields some discrepancies can be noticed. This is mainly due to the free space approximation being used in calculation thus neglecting the reflection/absorption phenomena. The calculation of the reflected fields using the reflection coefficient approximation is likely to be carried out in a future work. Nevertheless, the simplified approach implemented in this paper provides a rapid estimation of the phenomena with useful results in an engineering sense.

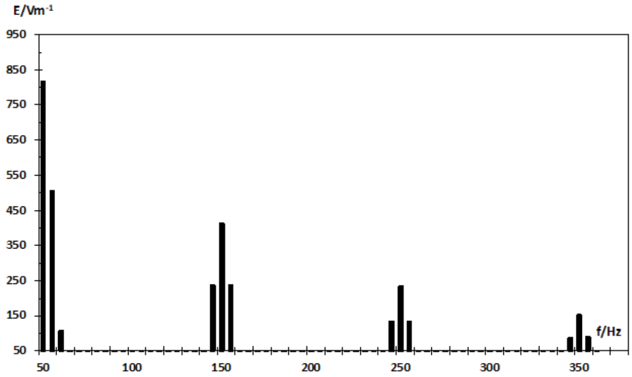


Fig. 11. Electric field spectrum

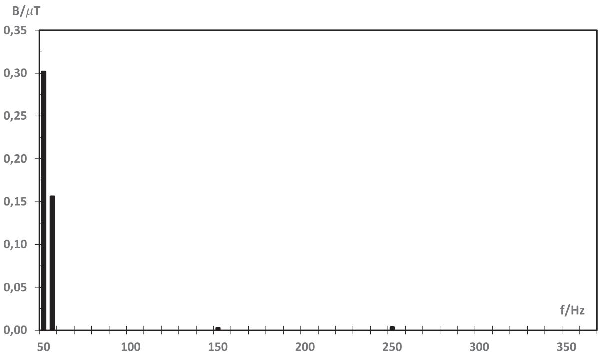


Fig. 12. Magnetic field spectrum

Furthermore, the results are postprocessed according to formulas (1) and (2). It is found that the measured electric and magnetic field values satisfy the limits expressed by conditions requested in (1) and (2).

For example, for measured magnetic induction values: B=0.303 μT at f=50 Hz and B=0.156 μT at f=55 Hz, taking into account condition (2) for magnetic field harmonics one obtains:

$$\frac{0302}{40}+\frac{0.156}{40}=0.01145\leq 1$$

Based on data provided by the equipment manufacturer, B-type measurement uncertainty is calculated for the fundamental harmonic. The obtained value taking into account confidence interval of 99.7 % (k=3) is 42.9 V/m and 0.02 μT for electric field and magnetic flux density, respectively. Note that the reference level for general population according to [5] B_{lim}=40μT.

Considering the aforementioned value for the magnetic field density and corresponding measurement uncertainty, experimental result is significantly lower than reference level. Similar reasoning may be applied in case of the electric field.

B. INTERNAL FIELDS

Internal fields are determined using canonical models of the human body (cylindrical and disk model) taking into account all field harmonics having significant values.

For example, for measured value of electric field: E=815 V/m at f=50 Hz, the maximal value of the electric induced in the cylindrical body model, as a basic restriction quantity is E^{ind}=0.426 mV/m. Note that basic restriction according to [1] is E_{lim}=0.1 V/m which is couple of order of magnitude higher value.

Furthermore, for measured values of magnetic induction: B=0.303 μT at f=50 Hz and B=0.156 μT at f=55 Hz, the internal electric field, as a basic restriction quantity, is calculated by means of (19), and applying the condition (13) it follows:

$$3.14\times 0.14\times\left(\frac{50\times 0302}{0.1}+\frac{55\times 0.156}{0.1}\right)=1.041\times 10^{-4}\leq 1$$

Again, for the basic restriction E_{lim}=0.1 V/m, it is obvious that condition (13) is satisfied.

V. Legal Issues

A. Historical Overview of Organizations Dealing with Protection of Human Beings from Exposure to Low – Frequency Electric and Magnetic Fields

Along with the development of the technology, there has been ~~is~~ an increasing public concern regarding the exposure of human beings to non-ionizing radiation and possible adverse health effects. International Radiation Protection Association (IRPA) published guidelines on protection of humans from electromagnetic radiation decades ago. Guidelines based on scientific knowledge regarding the short-term exposure of humans to non-ionizing radiation, while warning in cases where risks and biological effects of long-term exposure are recognized, other measures should be taken to avoid or reduce risks [12].

In 1992, ICNIRP was established as an independent body, separated from IRPA, with a sole scientific mission to work on protection from non-ionizing radiation, continuously collaborating with international research organizations, as well as universities and other academic institutions. ICNIRP has been producing several publications such as guidelines, statements, reviews, proceedings, and notes. These publications should be regarded as strictly non-binding scientific opinions formulated into documents and by no means opinions that any country is obliged to implement into a national legislation [13]. It is worth noting that ICNIRP has established four standard committees covering: epidemiology, medicine and biology, physics and engineering, and biological aspects of radiation. ICNIRP's international membership includes individual experts covering areas such as medicine, biology, epidemiology, physics, and engineering.

B. A Review of Guidelines for Limiting Exposure to Low Frequency Electric and Magnetic Fields

It is important to emphasize that EU member states apply international guidelines and recommendations arising from research findings, aiming to protect humans from possible adverse effects of non-ionizing radiation.

This paper focuses on the ICNIRP 2010 guidelines pertaining to ~~for~~ limiting exposure to LF electric and magnetic fields [1].

The procedure for establishing these guidelines involves several steps: identification of scientific data on effects of exposure to the fields at the relevant frequency range (laboratory and epidemiological studies); detection of considered effects with respect to possible health risk based on a proper scientific explanation; setting the minimum levels of exposure to the subject frequency range that cause harmful effects; consideration of the scientific basis related to establishing the causal relationship between the subject frequency range and diseases in humans; gathering data arising from direct interaction of fields with the human body and indirect interactions arising from contact currents.

The main objective intended to be achieved is to establish guidelines for limiting exposures to electric and magnetic fields, thus providing the protection against known harmful health effects. These guidelines are based on the evidences of thermal, neuropsychological, and reproductive effects of electric and magnetic fields on health. One of the purposes of issuing such guidelines is to provide protection to both occupational and general populations and are based on the ICNIRP 1998 guidelines [7]. The guidelines concern limiting exposure to non-ionizing radiation in order to protect against known adverse health effect on human beings.

The guidelines are based on currently available scientific knowledge and data, regardless of short-term or long-term exposures, age, or health status, and the biophysical mechanism.

Since the guidelines are not legally binding documents and, as emphasized by ICNIRP, they are based on scientific research, each country decides on the adoption of the guidelines into its legislation, considering other factors as well. Therefore, the guidelines are not implemented in the same way throughout the countries. For example, Japan and Germany have adopted the 2010 guidelines [14] which are also incorporated into their national legislation, while among other countries, Singapore, Brazil, South Africa, Croatia, and Greece fully or partially apply the 1998 guidelines [15].

In addition to the mentioned differences in defining the basic restrictions in the ICNIRP guidelines from 1998 and 2010, there are also some differences in reference levels. Table 1 shows a comparison of reference values for occupational and general population~~s~~, respectively, according to the ICNIRP 1998 and ICNIRP 2010 guidelines.

TABLE I

Comparison of reference Levels for the Occupational (General) Population at 50Hz

	Electric field (kV/m)	Magnetic field (A/m)	Magnetic induction (μT)
ICNIRP (1998)	10 (5)	400 (80)	500 (100)
ICNIRP (2010)	10 (5)	800 (160)	1000 (200)

It is evident from Table 1 that the reference levels for electric field exposure for the occupational and general population, respectively at a frequency of 50 Hz have not changed, while the reference levels for exposure of the occupational and general populations to magnetic field, i.e., magnetic induction, have doubled.

C. Precautionary >Measures/Preventive Measures

It is necessary to emphasize that member states of the European Union (EU) face challenges in determining the level of exposure protection due to potential scientifically unconfirmed adverse health effects resulting from exposure to fields generated by forthcoming technology systems. Also, this is due to the fact that scientific research, intrusions into human rights, industry interests, and environmental preservation should be taken into account. An overview of exposure limits for the general population of EU member states is depicted in Fig. 13.

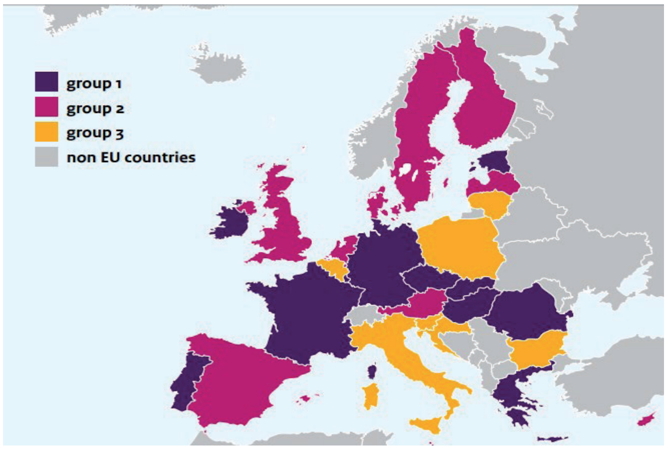


Fig. 13. Overview of exposure limits for the general population to low-frequency fields in the EU [16]: Group 1 (purple): legal limitations derived from EU recommendation- preventive policy in some countries; Group 2 (pink): no legal limitations or less strict limitations than the EU recommendation-preventive policy in some countries; Group 3 (yellow): higher limitations than the EU recommendation.

EU member states from Group 1 have adopted the ICNIRP guidelines and have implemented them into their national legislation, which means they adhere to the exposure limits determined by basic restrictions (depending on frequency, the physical quantities on which basic restrictions are based include: magnetic flux density (B), current density (J), specific absorption rate (SAR), power density (S), and internal (induced) electric field (V/m)). Some of the member states from Group 1 are: Czech Republic, France, Greece, Hungary.

EU member states from Group 2 have prescribed limitations lower than those specified by the ICNIRP guidelines and have implemented certain policies for the protection from electric and magnetic fields. Some of the member states from Group 2 are: United Kingdom (which has since ceased to be an EU member), Spain [17].

EU member states from Group 3 have established higher exposure limits than those recommended in the ICNIRP guidelines, taking into account the precautionary principle. These higher reference levels are often applied as actual exposure limits that must not be exceeded. Some of the member states from Group 3 are: Croatia, Italy, Slovenia.

In order to account for precautionary/preventive measures, the governments of member states recommend and adopt policies and principles to limit exposure to electric and magnetic fields, including:

- By applying the precautionary principle to protect people from potential harm due to exposure to electric and magnetic fields, construction of new kindergartens and schools are only allowed if they are located outside zones where the exposure to magnetic fields averaged over one year exceeds 0.4μT (e.g. Croatia, Belgium);
- By applying the principle of limiting exposure to non-ionizing radiation establishing an upper limit for permissible human exposure to non-ionizing radiation and reducing the level of non-ionizing radiation as low as technically, economically and reasonably feasible, following the ALARA principle (As Low As Reasonably Achievable). Germany, for example, applies this principle in the vicinity of schools, kindergartens, and children's playgrounds.
- By limiting the exposure of the general population to magnetic fields, for instance, through the construction of power lines in locations distant from kindergartens, schools, and residential areas (France, Luxembourg);
- By introducing a legal obligation to measure electromagnetic fields near power lines in urban areas, with a note that citizens can request the measurement results (France);
- By introducing an obligation, during the construction of electromagnetic networks, for an environmental impact assessment study to be aligned with a maximum magnetic flux density of 1μT (Austria);
- By raising awareness through educating the general population and publishing advice, for example, on how to reduce exposure to electromagnetic fields from mobile phones by limiting talk time, using headphones (Austria, Belgium, Cyprus, Netherlands, etc.)

World Health Organization (WHO) considers the precautionary principle as the foundation of a risk assessment when determining protective measures against non-ionizing radiation. These measures should be proportional to the chosen level of protection and non-discriminatory in application; aligned with state-of-the-art of research findings in the area; and designed to enable a comprehensive risk assessment [18].

D. Final Considerations on the Legal Aspects of Protection against Exposure to Low-Frequency Electric and Magnetic Fields

The presence of electromagnetic fields in the environment and their potentially harmful impact on health of humans arouses persistent scientific, technical, and often public interest. In urban environments, it is common for numerous power engineering facilities (transformer substations, power lines) to be located in close proximity to family homes, residential areas, or workplaces.

Consequently, EU member states use various mechanisms to protect people from potential harmful effects of exposure to LF fields.

The member states are generally in charge for the implementation of the EU law. By legal acts, guidelines, and scientific opinions within the EU, it is recommended that member states, when enacting regulations, adhere to recommended exposure limits or, if deemed necessary, may prescribe higher limits. Since the Republic of Croatia is a member of the EU, the EU law has become part of its legal framework upon accession [19].

The Republic of Croatia, by enacting legal acts in the aforementioned area, participates in shaping the common EU policies. The increasing exposure of humans to non-ionizing radiation poses challenges for the Republic of Croatia, including: the proliferation of non-ionizing radiation sources in the human environment encountered by both the occupational and general population. The continuous progressive development of new technologies, which requires the use of new devices and higher frequencies; adaptation and amendment of legislation due to technological advancements by adopting new regulations or implementing various opinions of international organizations, EU directives into the legislation of the Republic of Croatia.

In the Republic of Croatia, the Law on Protection from Non-Ionizing Radiation is currently in force [17]. The principle of precaution, recommended to Member States by European Union legal acts, has been incorporated into the aforementioned law of the Republic of Croatia. Currently, in the Republic of Croatia, the Regulation on Protection from Electromagnetic Fields is also in force [5] The Republic of Croatia, as a Member State, has determined through the Regulation, by applying the precautionary principle that the limit values of reference quantities are reduced in relation to their corresponding basic restrictions. The relevance and significance of the mentioned Law and Regulation are indicated primarily by the interest of various groups in the topic, including industry, public authorities, citizen associations, and individual citizens. However, considering a rapid development of technologies, updates and changes to existing regulations are necessary.

Note that scientific opinions presented in ICNIRP by no means bind member states to apply them as they are not legal norms contained in the EU Treaties or derived from them. Nevertheless, besides member states, other non-EU countries have decided to apply these guidelines and have incorporated them into their legislation, thereby enabling all citizens of those countries to exercise the rights arising from legal acts. By enacting the Law on protection against non-ionizing radiation as well as the Regulation on protection against electromagnetic fields [17], the Republic of Croatia has opted for further lowering the values of the recommended ICNIRP limits and, consequently, for a responsible approach to preventing potential negative effects of non-ionizing radiation.

V. CONCLUSION

The paper deals with several aspects of human exposure to LF electric and magnetic fields dealing with incident and internal dosimetry procedures and related legal issues pertaining to radiation protection. Exposure to lf fields at single and multiple frequencies are of interest. Typical 110 kV transmission substation as well as 110 kV overhead power line (fir tree mast), is considered as the most common LF source. Note that the measured fields pertain to the worst case scenario, i.e. to the fields below tubular busbar within the substation. Furthermore, the measured results are postprocessed and, finally, internal fields are determined by using the canonical body models (disk model and cylindrical model). The obtained results are compared against reference levels proposed by Croatian regulations for the protection from electromagnetic fields (National Gazette No 146/2014, 31/2019) and ICNIRP (International Commission on Nonionizing Radiation protection) Guidelines 2010.

Future work is likely to deal with several aspects of human exposure to high frequency (HF) fields.

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