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New Issues on Electromagnetic Biocompatibility

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Abstract. The paper presents some aspects on the concept of electromagnetic biocompatibility (EMBC), fully supported by epidemiological studies and in the same time by the latest document of the SCENIHR (an organism of the European Commission), regarding extremely low frequency magnetic fields.

Modern life is full of artificially generated electric and magnetic fields. We are always exposed to those electromagnetic fields composed of various frequency components. One of these sources is represented by the frequency of 50Hz, the electric power frequency of commercial power transmission and distribution and of household electric appliances. It can be mentioned also high frequencies near 1GHz for cellular phones, and other intermediate frequencies for various appliances.

The authors, adepts of the prudential avoidance policy, present several examples of possible harmful effects determined by extremely low frequency magnetic fields, dedicated to building services engineering in residences and in the industrial environment, along with several methods of mitigating them.

Key words

EMF (electromagnetic fields), ELF (extremely low frequency), EMC (electromagnetic compatibility), EMBC (electromagnetic biocompatibility), stray magnetic fields

1. Introduction

A major contemporary threat for health is represented by the so called man made “electrosmog”. This non-ionizing electromagnetic pollution of technological is particularly insidious, in that it escapes detection by the senses and in the same time its nature is such that there is literally “nowhere to hide” [1].

What distinguishes technologically produced electromagnetic fields from most natural ones is their much higher degree of coherence, i.e. their frequencies are well-defined and therefore, more easily discerned by living organisms, which opens the door to the frequency specific influences of various kind, against which existing Safety Guidelines (such as those issued by ICNIRP- International Commission for Non-Ionizing Radiation Protection) afford no protection.

In this case the organism will respond in a way akin to a radio, if the frequency of the external field matches or is close to that of its endogenous oscillatory electrical activity (e.g. like a tuned circuit). Some oscillatory endogenous activities of the human body (such those of the heart and brain or the circadian rhythm) are quite familiar. This could result in undesirably high resonant amplification, or in damaging interference, features of external fields other than its intensity.

Since electromagnetic fields are indispensable to technology, it is obvious that society is reluctant to abandon. The European Parliament studies recommend the extension of the familiar consideration of the electromagnetic compatibility (EMC), which represents the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment (called immunity) without introducing intolerable electromagnetic disturbance to anything in that environment (called emissions), to the living human organisms which should be considered as an electromagnetic instrument, par excellence.

The authors of this paper have made a first attempt in this respect, proposing some new features for the concept of electromagnetic biocompatibility (EMBC), derived from the wider concept of EMC and defined [2] as the ability of a functional device, equipment or system to allow the safe and healthy development of life in general and of the human beings in particular and have performed a short comparative study, drawing the separation lines and the common features between the two concepts of EMC and EMBC.

The present approach, focused especially on extremely low frequency (ELF) electromagnetic fields (up to 300Hz), is justified by the fact that until recently frequencies below the microwave band were assumed to be "biologically safe". But are they really, or they are a sort of uninvited guests for the utilities and the customers? The European Commission reiterated its opinion that they might by risky for health [3].

2. Possible Biological Effects of ELF Magnetic Fields

The latest released study entitled “Health Effects of Exposure to EMF” and adopted by the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) at the 28th plenary on 19 January 2009, concludes that extremely low frequency (ELF) magnetic fields are a possible carcinogen and might contribute to an increase in childhood leukemia and Alzheimer's disease.

This document differs greatly from the Directive 2004/40/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (EMFs), containing no mention about an association between EMFs (electromagnetic fields) and these diseases.

The problem is not a new one; there are already thirty years since Nancy Wertheimer and Ed Leeper (1979) published the first study suggesting an association between residential exposure to extremely low frequency magnetic fields (EMF) and childhood cancer [4].

Epidemiological studies of cancer have focused on two primary populations: children in residential settings and adults in occupational settings. The main cancers associated with EMF exposure are leukemia, nervous system tumors and, to a lesser extent, lymphoma among children and leukemia, nervous system tumors, and breast cancer among the adults.

In some epidemiological studies, values of the magnetic flux densities as low as 0.2μT, are mentioned to correlate with significant increase in cancer incidence among populations living nearby power lines [5].

Limited evidence of carcinogenicity in humans was chiefly based on epidemiological studies showing a consistent association between magnetic fields above 0.3/0.4μT and the risk of childhood leukemia.

Nevertheless, a cause-effect relationship cannot be inferred. For such moderate epidemiologic associations, data from laboratory studies are usually critical to determine whether a causal link exists. Laboratory evidence should also be complemented by an understanding of the mechanisms via which exposures interact with biological tissues, which has not been identified for ELF exposure.

ICNIRP mentions a worse-case reference value of 100μT for the magnetic field (for 50 Hz) in general public exposure, which exceeds several hundred times the reference values mentioned by all the epidemiological studies and of 10kV/m for the electric field. At the first sight, the threshold of the magnetic field seems to be very low while that of the electrical field seems very high.

As mentioned in the introductory section, the existing Safety Guidelines are solely intensity based, so hereinafter we’ll perform an analysis of this point of view.

3. A Critical Analysis of the ICNIRP Reference Values for Extremely Low Frequency Electromagnetic Fields

ICNIRP Guidelines define two different types of limit values: basic restrictions and reference levels. Depending on frequency, the physical quantities used to specify the basic restrictions on exposure to EMF are current density, SAR, and power density. Protection against adverse health effects requires that these basic restrictions are not exceeded.

Since these quantities in the body are difficult to measure and consequently compliance with basic restrictions limits is difficult to verify, reference levels were introduced. They are defined as electromagnetic quantities in the free space in absence of the human body: electric and magnetic field strength, magnetic flux density and equivalent plane wave power density.

Reference levels of exposure are provided for comparison with measured values of physical quantities; compliance with all reference levels given in these guidelines will ensure compliance with basic restrictions.

If measured values are higher than reference levels, it does not necessarily follow that the basic restrictions have been exceeded, but a more detailed analysis is necessary to assess compliance with the basic restrictions.

Power density (Poynting vector) $\overline{S}$, i.e., the power per unit area normal to the direction of propagation, is related to the electric and magnetic fields by the expression:

$$\overline{S} = \overline{E} x \overline{H} \tag{1}$$

and the corresponding power becomes:

$$P_\Sigma = \int_{V_\Sigma} \mathrm{div}\left(\overline{E} x \overline{H}\right) dv = \int_\Sigma \left(\overline{E} x \overline{H}\right) \overline{ds} = \int_\Sigma \overline{S} \cdot \overline{ds} \tag{2}$$

For an electromagnetic wave:

$$S = EH = \sqrt{\frac{\varepsilon}{\mu}} E^2 = \frac{\varepsilon E^2}{\sqrt{\varepsilon\mu}} = v \cdot w' \tag{3}$$

where

w' - represents the energy density of the wave

v - represents the phase velocity (or phase speed) of the wave i.e. the rate at which the phase of the wave propagates in space; this is the speed at which the phase of any one frequency component of the wave travels.

In free space the relationship becomes:

$$S = \frac{E^2}{377} = 377H^2 \qquad (4)$$

where 377Ω is the impedance of the free space.

The ICNIRP guidelines stipulates that the situation in the near-field region is rather more complicated because the maxima and minima of E and H fields do not occur at the same points along the direction of propagation as they do in the far field (wrong: in near field there is no propagation in the proper sense of the term!).

As we have presented in [2], unfortunately, in EMC literature and EMC regulations both near-field coupling and far-field radiation are lumped under the term radiated emissions. Obviously, a net disjunction must be made between near-field coupling (which is an induced interference) and far- field radiation (which is a radiated interference) especially because near-field energy is a stored and not a radiated one.

Induced energy coupling has different characteristics compared with radiated energy, high-impedance circuits being very susceptible to interference from electric near fields, and low-impedance circuits very susceptible to interference from magnetic near fields. This is not a pure academic distinction, but a very important one when we deal with electromagnetic biocompatibility.

There are also many practical differences between how induced and radiated interference occurs.

Recall just how electromagnetic shields behave in different types of fields. In the near field, electric fields are reflected by a thin metallic shield quite well, whereas magnetic fields readily penetrate metallic shields unless the shield is several depth of penetration thick. The far-field behavior of shields is different from both magnetic and electric near-field behavior [4].

Whereas radiated waves always maintain the impedance of air and are therefore always electromagnetic, near-field waves are usually dominated by one component, electric or magnetic and they do not give rise to any new behavior, as far fields do.

The "ICNIRP (International Committee on Non-Ionizing Radiation Protection) Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields", 1998, find "intriguing" the cut off point of 0.2/0.3μT mentioned in the epidemiological studies as possible carcinogenic, compared to the cut offs of the electric fields [6]. We find it not at all intriguing, due to the relative low impedance of the human body (generally and even in the ICNIRP Guidelines a homogeneous conductivity of 0.2S/m is assumed).

Between 1 Hz and 10 MHz, basic restrictions are provided only on a current density limit of $2\text{mAm}m^{-2}$, to prevent effects on nervous system functions. This basic restriction results in a 50-Hz magnetic flux density of 100μT and an electric field strength of 10kVm^{-1} for exposure of the general public. For the specific case of occupational exposures the limits can be increased by a factor of 5in the case of the magnetic flux density and by a factor of 2 in the case of the electric field strength.

In our opinion, the ratio of 10^8 between the electric field strength and the magnetic flux density has a very simple energetic explanation, which does not take in account any coupling mechanisms in near fields or the highly inhomogeneous of the electromagnetic field structure claimed in the Guidelines.

If X_e and X_m are generalized forces and W_e and W_m the energy in electric and magnetic field respectively and x the lagrangian (generalized) coordinate:

$$X_e = \frac{dW_e}{dx};\ X_m = \frac{dW_m}{dx}. \qquad (5)$$

both forces will have the same effect if:

$$dW_e = dW_m \qquad (6)$$

and

$$\frac{B^2}{2\mu_0} = \frac{\varepsilon_0 E^2}{2} \qquad (7)$$

It results in:

$$\frac{E}{B} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = c \approx 3 \cdot 10^8 \qquad (8)$$

q.e.d.

Obviously at the 50Hz frequency there is no reference limit for the equivalent plane wave power density (plane waves can not occur at this frequency).

According to these considerations, if we adopt the prudential avoidance policy and trust in the epidemiological studies, i.e. in the cut off point of 0.2μT for the magnetic flux density, the corresponding electric field strength should be 20V, which is quite hilarious.

After all, an essential question rises: it is better to expect the results of medical studies which may extend even decades, and act afterwards, or to adopt from now on a policy of "prudential avoidance" trying to find and apply all the possible solutions for mitigating the influence of these electromagnetic fields? We believe the answer is more than obvious.

4. Measurements and Discussions

In order to design strategies of magnetic field reduction, a first step is to know how power frequency magnetic fields are produced.

Using the Biot-Savart formula, the superposition principle and integration, one can obtain the magnetic field from a more complex source. The analytic equations are well known from the literature and it is not our purpose to review them here.

Instead of it, we'll present two sets of measurements, the first, made in a residential environment and the second, in an industrial one. The measurements of the magnetic field were carried out for the RMS values and their components along three ortho-normalized reference axes (x, y, z) using the CA42 low frequency fieldmeter (Fig. 1.).

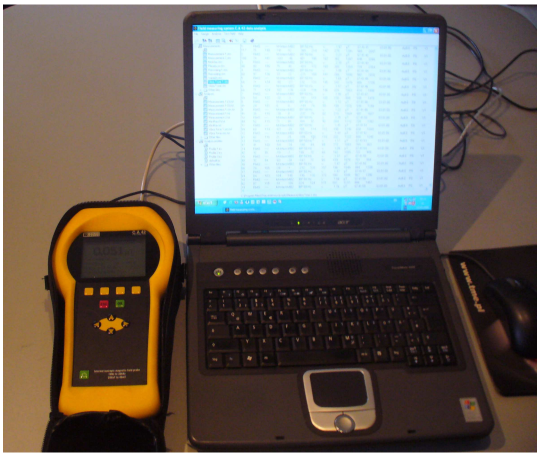

Fig. 1. The CA42 low frequency spectrometer

If k is the frequency, the RMS values on each reference axes of a signal having N frequency components are respectively:

$$V_{eff}(x)=\sqrt{\frac{1}{N}\sum_{k=1}^{N}x(k)^2}\quad \text{etc.} \tag{9}$$

and the global RMS value of the resultant is:

$$V_{eff}(x,y,z)=\sqrt{V_{eff}(x)^2+V_{eff}(y)^2+V_{eff}(z)^2} \tag{10}$$

In the near field, magnetic fields readily penetrate metallic shields unless the shield is several depth of penetration thick.

For near-field electric sources, reflection loss is predominant at the lower frequencies, while absorption loss is predominant at the higher frequencies. Absorption loss tends to be the dominant shielding mechanism for near-field, magnetic sources at all frequencies. However, both reflection and absorption loss are quite small for near-field, magnetic sources at low frequencies.

When a harmonically varying magnetic field $B(x,\omega t)$ penetrates a medium with conductivity σ, and permeability μ, the magnetic flux change produces an electromotive force (EMF), which induces eddy currents circulating in the conductor and opposing the incident field. As a result of this, the net magnetic field is altered [7].

This is a situation that can be solved exactly using Maxwell's equations for the quasi-static regime. In fact, the problem is fully 1-dimensional, even though three dimensions are involved (i.e. the fields B and H have only one component along the vertical direction y, the eddy currents and the associated electric field propagate along z, yet these four quantities vary only in the direction x).

Considering the configuration of a magnetic field inside a semi-infinite medium: $\frac{\partial}{\partial y}=0$ and $\frac{\partial}{\partial z}=0$, consequently the set of Maxwell equations simplify. Thus Faraday's law that governs eddy currents becomes:

$$\frac{1}{\sigma}\frac{\partial \underline{J}}{\partial x}=j\omega\underline{B} \tag{11}$$

In the same time, these currents generate a magnetic field, described by Ampere's law:

$$\frac{\partial \underline{H}}{\partial x}=\underline{J} \tag{12}$$

These two equations and the constitutive relation

$$\underline{B}=\mu\underline{H} \tag{13}$$

give a second order differential equation:

$$\frac{\partial^2 \underline{B}}{\partial x^2}-j\omega\mu\sigma\underline{B}=0 \tag{14}$$

with the general solution:

$$\underline{B}=C_1\exp\left(\sqrt{j\omega\mu\sigma}x\right)+C_2\exp\left(-\sqrt{j\omega\mu\sigma}x\right) \tag{15}$$

Applying the boundary condition and defining the field at the surface of the interface as $B(x\to\infty)=0$ and $B(x=0)=B_0$ and introducing the penetration depth

$$\delta=\sqrt{\frac{2}{\omega\mu\sigma}} \tag{16}$$

the solution becomes:

$$\underline{B}=B_0\exp\left[-(1+j)\frac{x}{\delta}\right] \tag{17}$$

Thus the magnetic field is both damped and phase shifted with distance inside the conductor.

A similar behavior is obtained for the current density J. Eq. (10) together with Eq. (16) gives

$$\underline{J}=-B_0\frac{(1+j)}{\mu\delta}e^{-(1+j)\frac{x}{\delta}} \tag{18}$$

and defining the current density at the surface

$$\underline{J}_0=-B_0\frac{(1+j)}{\mu\delta} \tag{19}$$

it results

$$\underline{J}=\underline{J}_0\cdot e^{-(1+j)\frac{x}{\delta}} \tag{20}$$

In the EMC literature, other models for thin layers have been developed [11], but it is still common to consider infinite dimensions in the direction perpendicular to the plate, which enables to study the model analytically.

The authors have measured the stray magnetic field generated by a gas heating central (24kW heating power, steel enclosure, 1.5mm thick, 1.8 mm penetration depth for μ_r =200) placed in a block of flats right near the kitchen table.

During the heating process of the water in the 60 liter boiler, the ELF magnetic field values raised up to 19μT. The decay of the RMS magnetic flux density versus distance (in m) is presented in Fig. 2; the calculated values are represented on the lower curve and the measured ones on the upper curve.

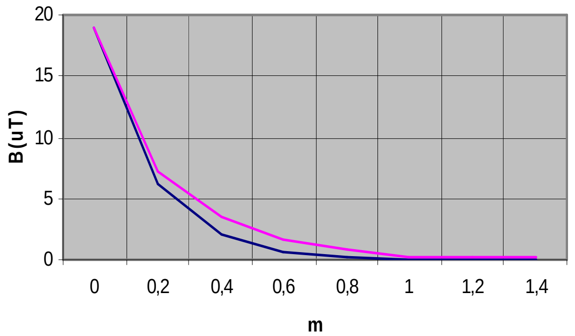

Fig. 2. Magnetic flux density versus distance in the case of the heating central

Obviously, in that case, the location of the heating central was a wrong one.

The final distribution stage of the electrical energy flow, before reaching the customer (in particular secondary substations), is often a source of similar field values in areas of concern, because when the voltage diminishes (via transformer operation), the current increases. In the industrial environment it is usual to situate secondary substations transformers inside buildings, in metal enclosures and placed on the ground.

The analyzed substation contains a three-phase transformer (20/0.4 kV, 400kVA). It also contains medium and low voltage switchboards that have covers made of plane steel and they both enclose bus bars. However, due to the reduction in voltage, the currents increase with the same factor at the secondary side of the transformers. Therefore cables and bus bars at the low voltage part of the substation constitute major sources of magnetic fields.

The magnetic field from transformers is rather complex and has various origins, such as the leakage field from the coils and ferromagnetic laminations, or the connections at the low/high voltage parts. To model the complete field emission from a transformer is rather a difficult task.

We have carried out a set of measurements in a substation situated inside a factory. In the neighboring room there was a working space.

We have performed a series of 30 measurements in the substation's room, in the bus bars' region (Fig. 3. a, b).

The currents on the three output lines are: $I_1 = 550(A)$; $I_2 = 700(A)$; $I_3 = 550(A)$.

On the other side of the 30(cm) depth concrete wall, measurements are presented in Fig. 4. a, b.

So, the shielding efficiency of the concrete wall is:

$$SE(dB) = 20 \cdot \lg\left(\frac{B_0(x,y,z)}{B_{shielded}(x,y,z)}\right) = 17.55 \qquad (12)$$

Even on the opposite wall of the room (at 4m distance) the levels of the magnetic flux density exceed 20 times the prudential avoidance limits (Fig.5. a, b.)

Range / µT	Number
102,000 .. 105,000	0
105,000 .. 108,000	1
108,000 .. 111,000	2
111,000 .. 114,000	5
114,000 .. 117,000	17
117,000 .. 120,000	5
>= 120,000	0

Fig. 3. a. Measurement results in the bus bars region

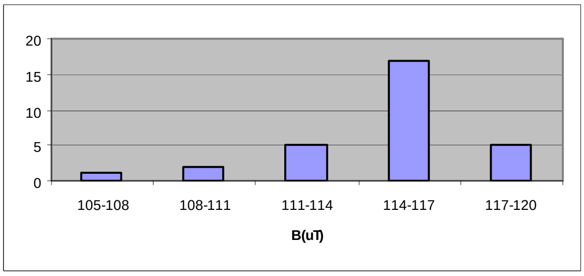

Fig. 3. b. Measurement results in the bus bars region

Range / µT	Number
13,600 .. 14,000	0
14,000 .. 14,400	0
14,400 .. 14,800	3
14,800 .. 15,200	16
15,200 .. 15,600	15
15,600 .. 16,000	6
>= 16,000	0

Fig. 4. a. Measurement results on the other side of the concrete wall

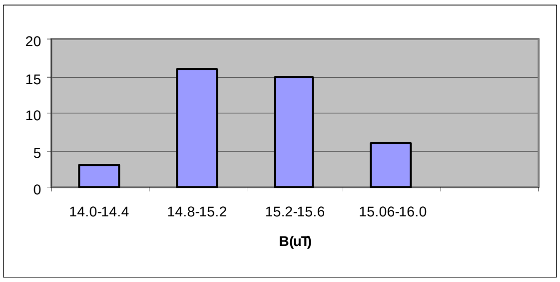

Fig. 4. b. Measurement results on the other side of the concrete wall

We have performed magnetic flux density measurements in the neighbor room meter by meter. Following the Eq. 16 and considering the median (which in probability theory and statistics, is described as the number separating the higher half of a statistical population from the lower half), we have obtained the graph depicted in Fig.6.

The calculated values are represented on the lower curve and the measured ones on the upper curve.

Range / µT	Number
0,900 .. 0,930	0
0,930 .. 0,960	1
0,960 .. 0,990	3
0,990 .. 1,020	14
1,020 .. 1,050	16
1,050 .. 1,080	5
1,080 .. 1,110	1
>=1,110	0

Fig. 5. a. Measurement results on the opposite wall (4m distance)

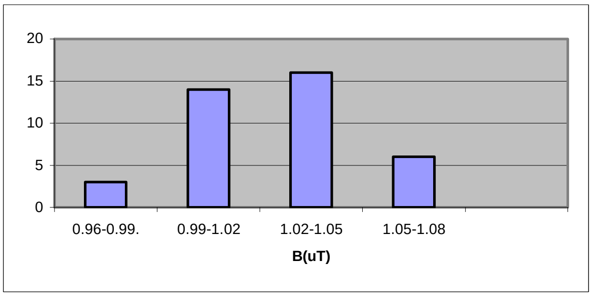

Fig. 5. b. Measurement results on the opposite wall (4m distance)

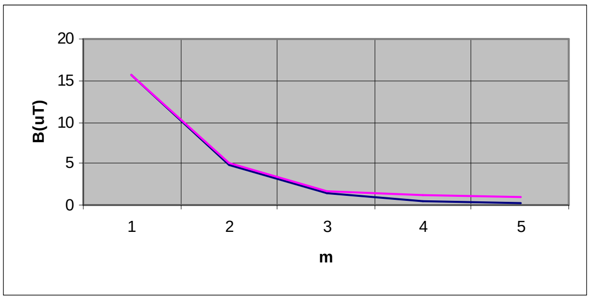

Fig. 6. Magnetic flux density versus distance in the working place neighbor to the secondary bus bars of the transformer substation

From the point of view of the epidemiological studies, the values of the magnetic flux density reported on the other side of the substation's room could affect humans on long-term exposure.

So, in accordance with the prudential policy, a passive or active compensation of the magnetic field is needed.

4. Conclusions

The paper's main purpose is to ring a warning bell.

Nowadays, when environmental problems became more and more acute, electromagnetic threat can no more be neglected.

The new electromagnetic compatibility regulations deal mainly with interference and the prevention of it through the design of electric systems.

But electromagnetic pollution is a serious problem for the human being himself and in the latest years, its prevention became a serious concern both for the technical and medical world.

We really do believe that it is important to draw an ambitious global plan for the implementation of the electromagnetic biocompatibility, which in our opinion was quite neglected so far.

Electromagnetic biocompatibility must represent an important point, both for the regulatory and control organizations and technical specialists, the latest being held to find proper ways for the cancellation or at least for the mitigation of the environmental electrosmog.

After all we must understand that electromagnetic pollution represents a severe environmental issue, a disharmony on the earth, and it is our duty to fight against it.

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