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Dedicated to the memory of Academician Andrei Ţugulea

ON THE ASSESSMENT OF HUMAN EXPOSURE TO LOW FREQUENCY MAGNETIC FIELD AT THE WORKPLACE

MIHAELA MOREGA[1], ILEANA MARIA BĂRAN[1], ALEXANDRU MIHAIL MOREGA[1,2], ALNAMIR KAZEM LEAIBI HUSSAIN[1]

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The community concerns on the possible harmful effects of electromagnetic fields and the pending safe labor conditions in the Member States were substantiated by the European legislative body through the Directive 2004/40/EC on the workers' exposure to hazards arising from physical agents (electromagnetic fields) and the related minimum safety and health requirements. After a decade of intensive consultation and debate on practical implementation issues with representatives of national authorities, labour organizations, scientists, stakeholders, *etc.* and following several postponed deadlines for its enforcement, the European Commission replaced this Directive with a revised version, the Directive 2013/35/EU, on 29 June 2013. The transposition deadline for the new document was set on 1 July 2016, raising administrative and technical challenges for employers and authorities responsible for occupational protection, for standardization and control. The scientific community is therefore expected to recommend implementation solutions, such as good manuals of practices and normative documents, required for the compliance with the provisions of the Directive, for specific working environments. The paper aims to illustrate practical issues on the analysis of low frequency magnetic fields in working environment, like: specific features related to field measurement methods, characteristics of currently available equipment, complementarities of measurement and computational approaches. Four illustrative assessment studies are finally presented and discussed.

1. INTRODUCTION

In a working environment, low frequency magnetic field (MF) is currently generated during the operation of power equipment at electric currents of high intensity, *e.g.*: electric power generators, transformers stations, aerial power lines (APL), various industrial applications, electric transportation networks etc. Low frequency range covers the domain up to 100 kHz, including a multitude of applications operating on the power line frequency (usually 50 or 60 Hz). Potential risk on human health due to associated biological effects are discussed by international official documents, like the guidelines on limiting the general public's and workers' (two distinct categories) exposure to electric, magnetic and electromagnetic fields (EF, MF, EMF) of low frequency, stated by the International Commission on Non-Ionizing Radiation Protection – ICNIRP. The subject is currently covered by the ICNIRP document of 2010 [1], in replacement of the low frequency section from the guidelines previously issued in 1998 [2].

In agreement with [1], the limits that are allowed for human exposure to MFs at the power frequency (50–60 Hz) for *occupational exposure* are 1 mT and for *general exposure* 0.2 mT (rms values); these limits are constant in the low frequency domain, for a large frequency range, as Fig. 1 shows (straight lines). The provisions of these guidelines, concerning the accepted exposure levels for low frequency magnetic field are compared in Fig. 1 with the levels recommended by the former version of the document (see horizontal lines at 1mT for occupational exposure and 0.2 mT for general public exposure, vs. respective descending curves). As one could observe, the MF levels stated by the 2010 version at the power frequency are twice higher than the corresponding values of the previously valid guidelines and they are generally higher than national limitations in different countries. It is however worth mentioning that ICNIRP limits for low frequency MFs are generally lower than respective limits stated by IEEE in 2002 [3] for similar exposure conditions.

The World Health Organization (WHO) launched in 1995 a surveillance and dissemination program on the possible risk for human health coming from exposure to electromagnetic fields. Since then, WHO maintains a special chapter on its website, dedicated to that specific topic (http://www.who.int/topics/electromagnetic_fields).

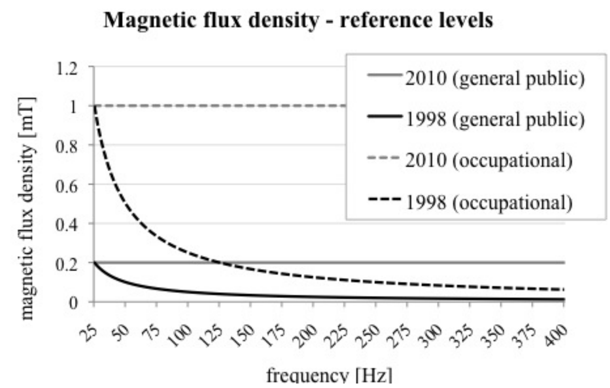


Fig. 1 – Reference levels (magnetic flux density in rms) for both general public and occupational exposure stated by ICNIRP guidelines (2010 vs. 1998 version).

Formal solutions were expected from the European Parliament too, for both the safety of human health and life quality; the EU is also concerned to guarantee at least a "minimum basis of protection and decent working conditions for all Community professionals, in the spirit of equity and free competition on the labor market", according to the Article 31(1) of the Charter of Fundamental Rights of the European Union, which stipulates that "every worker has the right to working conditions which respect his or her health, safety and dignity" and the principle of equal rights by providing "a minimum basis of protection for all Union workers, while

[1]University "POLITEHNICA" of Bucharest, Romania, amm@iem.pub.ro, alin.dobre@upb.ro, mihaela@iem.pub.ro
[2]Institute of Statistical Mathematics and Applied Mathematics "Gheorghe Mihoc – Caius Iacob", Bucharest, Romanian Academy

reducing possible distortions of competition" [4].

Potential health risk related to workers' exposure to EMFs represents a professional risk factor already considered by the European legislative bodies, the EU Parliament and the European Council. The Directive 2004/40/EC on occupational protection to electromagnetic environment was released by the Official Journal of EU, on 29 April 2004 [5]. Its content was, at that time, in good agreement with valid normative documents [2, 3, 6]. The so called "EMF Directive" is the first official EU document, setting on the employers the obligation of assessing the risks arising from electric, magnetic and electromagnetic working environments and, most important, taking adequate protective measures for the elimination of health risks, where necessary. A first attempt to set in force the provisions of the EMF Directive established, for the member states, a four years period to effectively address and solve this problem, by national specific regulations and good practices methods. During that time, discussions followed up in both scientific and stakeholder's communities, on practical implementation issues:

– the need of harmonization among national approaches to the problem, due to previous existence of specific national regulations, on the principle that national limitations must not regress as a result of the Directive implementation;
– the absence of administrative bodies responsible with assessment and control at national levels;
– the lack of assessment practices (good practices manuals, standards for measurement and/or computational assessments, *etc.*) at Community and/or international level;
– the lack of scientific consent on special exposure conditions (*e.g.,* superposition of multiple field sources, risks pending medical devices that are implanted movement related risks in static and quasi-static MFs, etc.);
– the evidence of sensitive working conditions; specific regulations are needed in such places because the associated levels of exposure are significantly exceed the general provisions of the EMF Directive.

Considerable debate, leading to successive extensions of the Directive's transposition deadline occurred mostly because some of the limitation levels and requirements regarding professional exposure to low frequency MFs were in conflict with the common conditions already encountered in certain medical applications (like magneto-resonance imaging) and industrial activities (like welding and some electrochemical processes) based on the use of high magnitude, very low frequency MFs. Under specialized scientific advice, it is expected to consider and treat such working places as exceptions from de Directive.

After a decade of intensive consultation and debate on practical implementation issues, with representatives of national authorities, labor organizations, scientists, stakeholders etc. and following several postponed deadlines for its enforcement, the European Commission replaced the Directive 2004/40/EC on 29 June 2013 with a revised version, the Directive 2013/35/EU [8]. The transposition deadline for the new document was set on 1 July 2016, raising administrative and technical challenges for employers and authorities responsible for occupational protection, for standardization and control. Consequently, the scientific community is more than ever concerned with *finding affordable and reliable methods for testing and monitoring the electromagnetic working environment* [7].

Following EU recommendations, Romania formally complies with ICNIRP guidelines by national normative documents [9] adopted during its pre-accession process and replaced by [10] following the transposition of the EMF Directive [8].

Under Directive 2013/35/EU, the exposure limits to very low frequency MFs are expressed in terms of the so-called *Action Levels* set for the magnetic flux density *ALs(B)*, *i.e.* the rms values of acceptable operational levels for harmonic MF (see Fig. 2 for the limitations). These levels differentiate with regard to biological effects and exposure conditions: *Low ALs(B)* represent the limits preventing sensory biological effects, while *High ALs(B)* are set for prevention of health effects (stimulation of the nervous system); this means that passing sensory effects (*e.g.* retinal phosphenes) or minor change in brain activity are possible between the two levels. *ALs(B)* for power frequency MFs are set between 1mT and 6mT (exposure of the trunk), as Fig. 2 exhibits; the upper limit is acceptable only under exceptional conditions, acknowledging the possible occurrence of transient biological effects (like minor stimulation of retina or brain and painful neuromuscular stimulation). One could observe that *Low ALs(B)* (continuous line in Fig. 2) correspond, for industrial frequencies, with the occupational reference levels of ICNIRP guidelines of 2010 [1] (dashed grey line of 1 mT in Fig. 1). *ALs for limbs* apply to localized exposure of limbs (critical organs and systems are not involved).

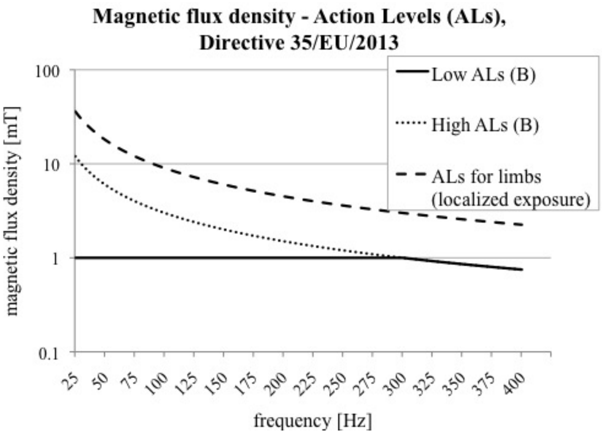


Fig. 2 – Action levels for magnetic flux density (rms) (occupational exposure Directive 2013/35/EU).

The Directive mentions also key aspects of the employer's responsibilities, in implementing the provisions, including: setting-up the objectives of the assessment and the schedule, a calendar of periodic assessments and updates, taking proper measures for complying with normative (like re-configuration of the workplace, shielding, reduction of current electromagnetic emissions *etc.*), inclusion of maintenance procedures in everyday activities (permanent or control monitoring of electromagnetic emissions, signaling or access prohibition of places where overexposure is present, provision of personal protective equipment for workers, instruction and information periodic sessions, safe preservation of all assessment records), following the assessment of local emissions around electromagnetic sources, the access zones should be mapped/advertized/organized for the prevention of hazardous exposure of personnel and visitors.

Implementation of the EMF Directive's provisions involves high responsibility and expenses from the employers and qualified assistance from electrical engineering professionals. As bioelectromagnetism and electromagnetic field technologies in medicine and biology evolve, based on dosimetry, efficient computational methods complemented by adequate measurement and testing protocols could represent valuable tools for biomedical investigations too. Giving assessment priority to sensitive places (electromagnetic interference, potential danger by explosion or fire, projectile risk from ferromagnetic objects etc.) is of high importance too. The general labour protection principle evoked here is based on *prevention and avoidance of risk.*

Technical standards for the regulation of measurement protocols and classification of exposure zones are expected to enter into force for the electromagnetic field of low frequency, as they are already elaborated for the high frequency range. The European Committee for Electrotechnical Standardization (CENELEC) and the International Electrotechnical Commission (IEC) assist the 106 Technical Committee in developing technical standards for measurement methodologies and technological restrictions concerning evaluation of the compliance of electrical and electronic equipment to international protection guidelines. The Romanian Standardization Association (ASRO), through its Technical Committee 279 *Human exposure to electromagnetic fields*, collaborates with TC106. Romania has already endorsed a comprehensive set of standardization documents in the area [11, 12].

International documents issued by professional authorities in the field show general theory and assessment methods for environmental low frequency MFs evaluation by measurement and computation, like the IEEE standard [13] and the series of non-binding guides published by the EC DG for Employment, Social Affairs & Inclusion in 2015, for clarification of practical aspects derived from the application of the EMF Directive [14].

2. MATERIALS AND METHODS – MAGNETIC FIELD MONITORING

MFs are generated in an industrial environment by different sources, usually configurations of current carrying cables. The fluctuation of electric power is highly dynamic and consequently, the characteristics of the currents (phase imbalance and harmonic content) are in continuous change. Several technical aspects were discussed previously by Goiceanu *et al*. [15] in the context generated by the implementation of normative European documents.

2.1. MAGNETIC FIELD ANALYSIS CONSIDERING THE FIELD SOURCE TYPE

Single-phase lines generate linearly polarized MF, meaning that the field vector (**H** or **B**) maintains its direction in one plane; its tip is describing a line. Multiple-phase lines create an elliptically polarized MF, which is a vector that changes its magnitude and direction over a cycle, so that its tip is describing an ellipse, as in Fig. 3.

Time variation of the elliptical vector. Let us consider the three-dimensional representation of a harmonic time-varying MF vector, **B**(t) or **H**(t), in a fixed point in space (the observation point), using a Cartesian reference frame:

$$\mathbf{B}(t) = B_x(t)\cos(\omega t + \alpha_x)\mathbf{u}_x + B_y(t)\cos(\omega t + \alpha_y)\mathbf{u}_y + \\ + B_z(t)\cos(\omega t + \alpha_z)\mathbf{u}_z \tag{1}$$

Introducing in (Eq. 1) the phasor representation of the harmonic time-varying scalar and vector quantities, we have:

$$\mathbf{B}(t) = \mathrm{Re}\left\{\left(\underline{B}_x \mathbf{u}_x + \underline{B}_y \mathbf{u}_y + \underline{B}_z \mathbf{u}_z\right)\mathrm{e}^{\mathrm{j}\omega t}\right\} = \mathrm{Re}\left\{\underline{\mathbf{B}}\,\mathrm{e}^{\mathrm{j}\omega t}\right\}, \\ \text{where} \quad \underline{B}_k = B_k\,\mathrm{e}^{\mathrm{j}\alpha_k},\ k = x, y, z. \tag{2}$$

Phasors $\underline{B}_k$ (k = x, y, z) are complex time invariant scalar quantities depending only on the geometry of the MF sources and the space-coordinates of the observation point. The complex quantity $\underline{\mathbf{B}}$ is the phasor vector representation of **B**(t), which can be divided into its real and imaginary parts:

$$\underline{\mathrm{B}} = \underline{B}_x \mathrm{u}_x + \underline{B}_y \mathrm{u}_y + \underline{B}_z \mathrm{u}_z = \\ = \sum_{k=x,y,z} B_k \cos\alpha_k\ \mathrm{u}_k + j \sum_{k=x,y,z} B_k \sin\alpha_k\ \mathrm{u}_k = \mathrm{B}_1 + j\mathrm{B}_2,$$

$$\text{where } \mathrm{B}_1 = B_1(x,y,z)\mathrm{u}_1 \text{ and } \mathrm{B}_2 = B_2(x,y,z)\mathrm{u}_2. \tag{3}$$

Both vectors, $\mathbf{B_1}$ and $\mathbf{B_2}$ are time-invariant vectors defined in the 3D – real space; they have fixed orientation ($\mathbf{u_1}$ respectively $\mathbf{u_2}$) and fixed magnitude (B_1 respectively B_2). Substitution of (Eq. 3) in (Eq. 2) produces

$$\mathbf{B}(t) = \mathbf{B}_1 \cos(\omega t) + \mathbf{B}_2 \cos\left(\omega t + \frac{\pi}{2}\right). \tag{4}$$

Consequently, the MF vector is the result of the superposition of two linear polarization states, not necessarily perpendicular, oscillating with a phase lag of $\pi/2$, which makes them to be also in quadrature [16]. The result is an ellipse contained in the plane defined by the directions $\mathbf{u_1}$ and $\mathbf{u_2}$ making an angle θ. The vector $\mathbf{B}(t)$ (*i.e.* the instantaneous value of the MF vector) moves on the ellipse from $\mathbf{B}_2$ to $\mathbf{B}_1$. The instantaneous values vary between two limits: a minimum value $B_{\min}$ (*i.e.*, the ellipse semi-minor axis) and a maximum value $B_{\max}$ (*i.e.*, the ellipse semi-major axis), as shown by Fig. 3.

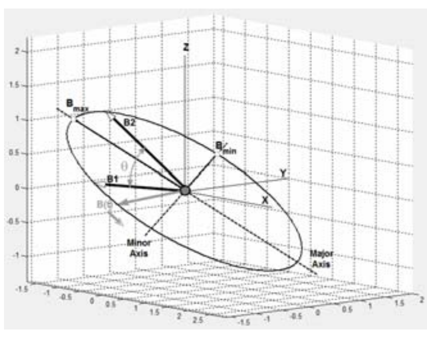


Fig. 3 – Elliptically polarized **B** vector.

For arbitrary combinations of values B_x, B_y, B_z, α_x, α_y and α_z, the degree of polarization defined as the ellipse axial ratio $AR = B_{\max} / B_{\min}$ can take any value from 1 (circularly polarized MF) to infinity (linearly polarized MF). The rms value of the time varying MF can be obtained from its components $B_{rms} = \sqrt{B_1^2 + B_2^2}$.

Multiple frequency fields. The harmonic content of the source current is another important factor affecting the accuracy of the MF measurements; power electronics used in electric drives and several unconventional electro-technologies are among the main causes of distortion for the electric current waveforms. Total harmonic distortion (THD) factor is commonly used as the measure of the influence (distortion) harmonic components have on a complex (non harmonic) waveform; it shows the balance between the weight of harmonics and the weight of the fundamental in the waveform. For example, if the harmonic content of a current waveform is identified by: I_1 – the rms of the fundamental and I_2, I_3, I_4, ... the rms values of the harmonic components,

$$\text{THD} = \sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots} / I_1 .$$

The environmental MF, like its source current, might be represented by a series of its harmonic components, each of them characterized by an elliptically polarized vector as discussed before. Generally, polarization ellipses of harmonic components fall in different planes; they have different semi-major and semi-minor axes, and they reach their extremum at different moments, because each harmonic field component has a phase lag dependent on its frequency. Therefore if the MF is generated by currents with high harmonic content then the MF resultant vector describes over time a complicated spatial pattern, as a result of the individual polarization of each MF harmonic component. An accurate representation of the MF requires, *for each frequency component*, the *identification of the polarization ellipse.* The *multiple-frequency fields* are considerably difficult to estimate or measure properly, with minimal error; they usually are assessed in particular contexts, with particular methodologies.

Space variation of MFs. If generated by multiple sources, MF could present large variations from one location to another, both in terms of magnitude and orientation. During a session of measurements designed to map the MF (which usually lasts from a few minutes up to half a day), the fluctuation of the electrical current, due to load variations can bias the MF mapping. Isolate, instantaneous measurements are, therefore, poor indicators of field characteristics over the whole occupational site. Space variations of the MF parameters are better captured by several simultaneous measurements that are synchronized, taken at different positions, which span over the entire region under surveillance. Space distributed and synchronized measurements can offer the realistic map of variation, in contrast to the spot measurements of the field, which complies with the strategy currently recommended by standards.

Temporal variation refers to the changes of the MF parameters listed above, over long periods (hours, days) at a specific location, due to power fluctuations of the field sources. The sets of parameters acquired at a particular location are stored in a database; they are later accessed as individual time-series and statistical analysis is performed. Compact measurements of time variation are usually called *exposure metrics*. Various exposure metrics are proposed in the literature. Their selection is made upon evaluation of their ability to outline relevant physical aspects of the MFs; the one currently applied in different European countries in low frequency professional surveys is the time weighted average (TWA) [17]. It could be applied for the magnetic flux density, with the common formula $B_{TWA} = \frac{1}{T_{av}} \int_0^{T_{av}} B_{res} \mathrm{d}t$, using a simple time averaging of the recorded values of B_{res} (the resultant MF), over the interval T_{av}. All magnetic field monitors provide this exposure metric and it represents the basis of the main measurement assessment performed for epidemiologic studies. Without having concluding information on all aspects regarding interaction mechanisms of MFs and human body, TWA has been adopted as an adequate metric basis, by analogy with other environmental agents.

Exposure assessment standards describing specific measurement techniques for checking compliance of various MF environments with ICNIRP guidelines of 2010 [1] and EU Directive of 2013 [8], provisions recommend the Weighted Peak Method (WPM) with weighted filtering in the time domain, as a reference method for complex (non-harmonic) fields, within the low and intermediate frequency range (up to 10 MHz). WPM is most suitable for assessments that target non-thermal biological effects of electric and magnetic fields and it is implemented in the operation software with measurement equipment that became available in the past two decades; WPM is largely discussed and critically compared with alternative assessment techniques in [18].

Several other exposure metrics, not so widely used as the TWA, but with a good potential related to the biological significance of MFs interaction with human tissue had also been identified [19, 20], like: duration of exposure at a given intensity, frequency content (single frequency or harmonic components, transients, intermittency), simultaneous exposure to static MF (including geomagnetic) and low frequency components etc. Also it should be considered that stored information during a long-term survey could produce, if necessary, other exposure metrics.

2.2. METHODS AND INSTRUMENTS FOR MAGNETIC FIELD MEASUREMENT

Current concern for the quantification of MFs in the power frequency systems favors the design and fabrication of various instruments, adequate for easy and precise measurement of certain field characteristics. Guidelines and standards are already developed for establishing proper scientific measurement methods useful in environmental MF exposimetry [17, 21]. A large variety of commercial MF-meters is also available, while newest generations comply with standardized procedures, detailed in international normative documents [3, 13, 22, 23].

A measuring device for the environmental magnetic field (MF-meter) shows the magnitude of the MF field vector (**H** or **B**) or one of its directional components; it consists of two parts: the probe (sensor and transducer device) and the analyzer (measuring instrument). The probe incorporates a MF transducer; for static and extremely low frequency MFs, Hall transducers are preferred, while induction coils are used at low frequencies. The MF probe is commonly built on a tri-axial structure (three identical transducers in orthogonal positions, to capture the three space components of the MF vector. The detector is set either for the *directional operation mode* (acquisition of one vector component, determined by its orientation), or for the *isotropic operation mode* (acquisition of three space components and the calculation of the vector norm, where the vector orientation is unknown). Exposure assessment measurements are mostly performed as isotropic. Upon the type and complexity of the detector, the MF-meter devices can be grouped into some large classes:

Survey meter – it represents a battery-operated lightweight meter, for surveys and safety tests, in different locations; it usually performs real-time measurements of the MF parameters (rms values) in an easy to apply manner.

Broadband/ selective measuring device – recommended for achieving direct, informative measurements in various practical situations; its main function is the analysis of the MF with low harmonic content, specifically with a single frequency spectral component. The acquired quantity (e.g., field strength) is normally displayed as a rms value; for assessment procedures, it might be directly compared with the reference level. For the accurate analysis of multiple-frequency fields, the actual exposure level cannot be rendered correctly even using a narrow band filter to select the frequency of the measured signal (under the assumption of knowing this frequency). It is important to mention that selective measurements must always be graded; they are thus unable to reflect the instantaneous situation at a given moment and they are used for sequential signals recording.

Evaluation in frequency domain – Spectrum Analyzer (FFT analyzer). The analysis of a multiple-frequency field should start with a spectral analysis, for the assessment of the harmonic component. The waveform of the recorded signal is stored temporarily and its spectral analysis is performed with the numerical method FFT (fast Fourier transform). With an adequate recording resolution, the spectrum analyzer measures multiple-frequency fields in a direct way, as well as it does with harmonic (single-frequency) fields. Either the rms or the peak value of each harmonic component is available and the comercial analysers are commonly equiped with adequate software for the computation of the THD.

Evaluation in time domain – Waveform recorder. These instruments are much more complex than MF-meters; they are broadband devices, the frequency range may cover dc to 3000 Hz, depending on the probes. Both waveform recorders with directional or isotropic operation modes are available. A waveform recorder collects large volumes of data, which can easily exceed several megabytes of information per day. Therefore, waveform recorders are designed with a computer connection and adequate software for the storage and analysis of large volumes of data. On the market are available only a few models; most of them are portable, but they vary in size and complexity.

An ideal assessment of MF levels for a given workplace should provide the accurate evaluation of MF parameters as much as their spacial and temporal variation. This goal could be accomplished by simultaneous data acquisition in different locations; the surveilled area needs to be covered by a *network of magnetic field sensors*. The mapping and monitoring solution applies for fast occasional inspection of the working space, but it helps also to the optimization of environmental conditions. Exposure assessments by such setups could serve other purposes too: epidemiology studies, investigation of various sources of electromagnetic emissions, compliance with protection guidelines and technical product standards, etc.

3. RESULTS AND DISCUSSION

The compliance assessment with the Directive 2013/35/EU of a workplace could be carried on either by direct, experimental measurement, or by numerical simulation; the two approaches could also successfully complement each other. The assessment procedure is supposed to be performed periodically, considering technical aspects: exposure characteristics (type, duration), magnetic field parameters (amplitude and frequency), stipulation of measured against calculated quantities and evaluation methods, multiple field sources possible superposition (in space, in time, multiple frequencies), as Börner *et al*. have shown in their comprehensive report [21].

A comparison of resources and efforts accompanied by comments and useful insights on the applicability of the methods is further ported to practical applications; four examples were selected to exemplify the main characteristics of respective MF sources and practical methods of evaluation, as described above.

3.1. HIGH VOLTAGE OVERHEAD LINE

The functioning of an overhead line was monitored for two weeks, using a fully class A compliant power quality analyzer. The line is single circuit, operates at 110 kV rated voltage and feeds an industrial platform.

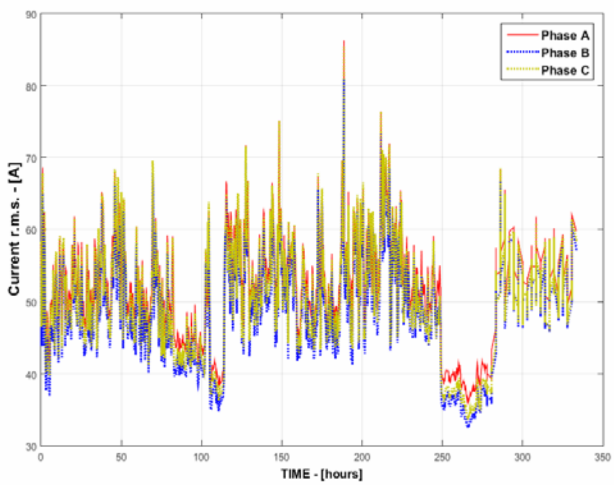
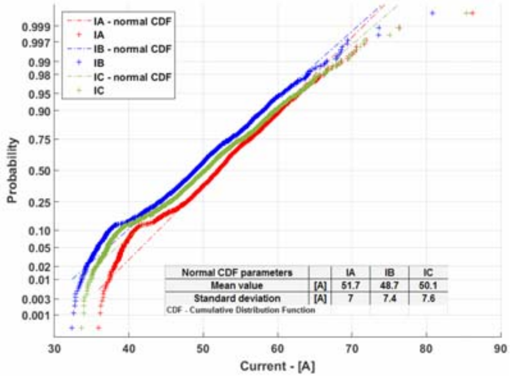
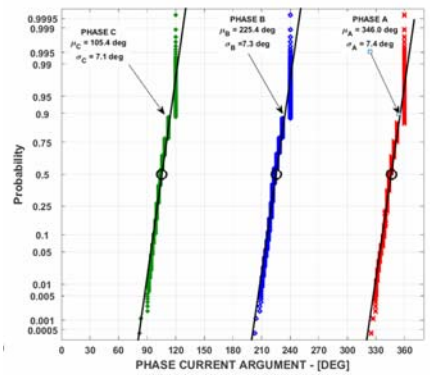


Fig. 4 – Phase currents of an overhead 110 kV transmission line; time series of recorded values during two weeks [7].

The analyzer was set to measure voltages and currents with an aggregation interval of 15 min., and to record, on all three phases simultaneously, different parameters, such as the power factor and the Total Harmonic Distortion Factor (THD) for current and for voltage. The recorded values of the phase currents are represented in Fig. 4 as time series.



a) The magnitude



b) The phase

Fig. 5 – Empirical and theoretical cumulative distribution functions (CDF) of complex (phasor) currents.

Two intervals of lower values are visible and correspond to the decreasing of the power consumption in weekends, while several peaks allow for the identification of short overload intervals.

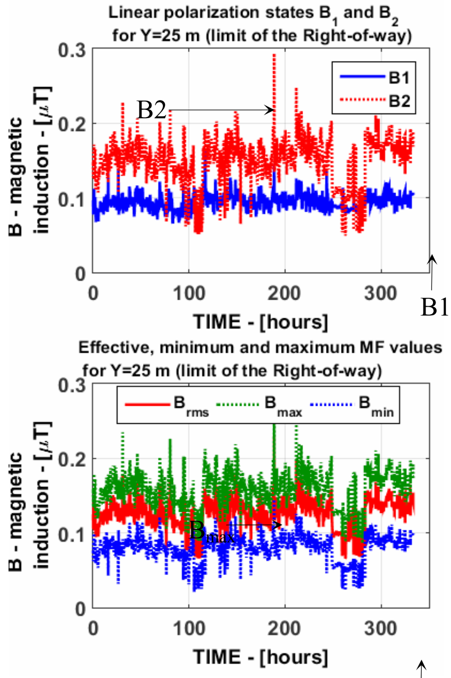
A short statistical characterization of both current's magnitude and phase are given in Fig. 5, where the corresponding empirical and theoretical cumulative distribution functions (CDFs) (not normalized on the x-axis) can be seen, together with the maximum likelihood estimators for the mean and variance of the fitting models –the dots represent the empirical CDFs while the lines are the theoretical CDFs (fitting models); the means and standard deviation values are marked on each plot (μ – mean value, σ – standard deviation). This particular example exhibits the usual main characteristics of power flow in a high voltage network: CDFs of phase currents magnitude represented in Fig. 5a are normal and indicate an important variability of the actual current's values during the observation interval (the standard deviations and the coefficients of variation can be read in the legend of the figure); the absolute current deviation [24] which can be regarded as an unbalance indicator, is fluctuating randomly following the actual power demand on each phase of the network; the average values and the standard deviations of the absolute current deviation (δ_{fi}) are given in Table 1; values recorded for both voltage and current THDs are very low on each phase, therefore they can be neglected, which leads to harmonic phase currents.

Table 1

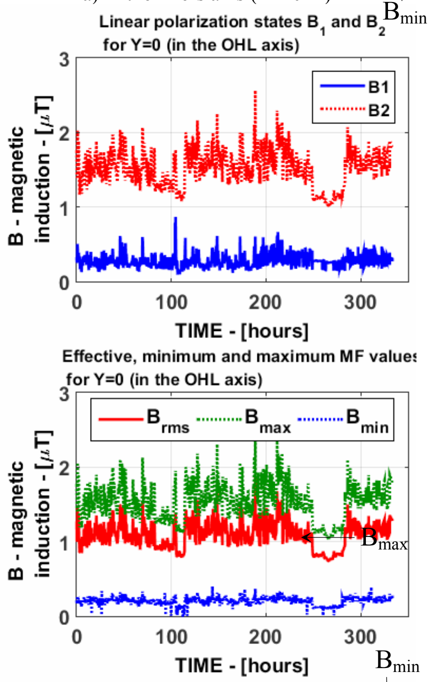
Statistic parameters showing the unbalance of currents

Absolute current deviation, δ_{fi}	PHASE A	PHASE B	PHASE C
Mean value of δ_{fi} [%]	3.21	3.04	0.17
Standard deviation of δ_{fi} [%]	1.46	0.95	1.04

$\delta_{fi} = |I_i - I_{av}| / I_{av}$ where I_i with $i = A, B$ and C – rms value of the phase current $I_{av} = (I_A + I_B + I_C)/3$ – average absolute current.



a) in the line's axis ($Y = 0$ m)



b) at the limit of its right-of-way ($Y = 25$ m)

Fig. 6 – MF features plotted as time series in two different observation points placed at height $Z = 1.8$ m.

Following the characteristics of the currents commented above, the MF has no harmonic content as its sources (the phase currents) are (nearly) harmonic.

Consequently, the MF can be considered as a time-varying elliptical vector with two linearly polarized states (B_1 and B_2) and the resultant characteristics defined in section 2.1 of the paper – B_{min}, B_{max}, B_{rms}. Knowing the high voltage line configuration, the MF was computed as the sum of the elementary contributions of each phase conductor, applying the analytical method recommended by CIGRE [25] for assessing MF, based on Biot–Savart formula. Due to the accepted assumption regarding the plane-parallel field pattern, the MF has only two space components. The polarized states, and consequently all the associated features, are changing every 15 min. due to the fluctuations of line current phasor magnitude and argument (Fig. 5).

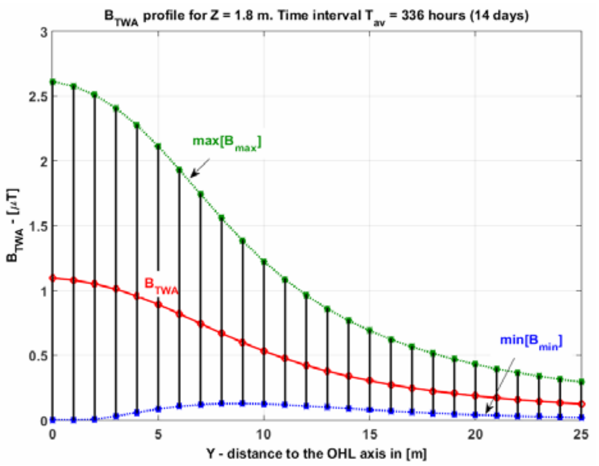


Fig. 7 – Lateral profile of the TWA and of the high and low MF variation limits.

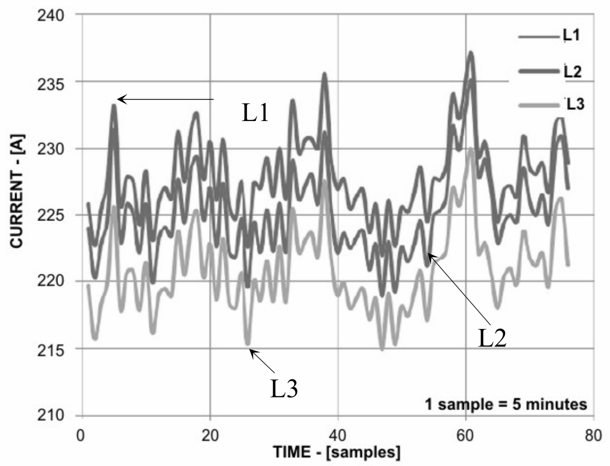
The MF features represented in Fig. 6 can be used to assess the field variability in space and in time. The time weighted average (TWA), as presented in section 2.1 of the paper, was computed for the magnetic flux density at different distances from the line's axis. The resulting B_{TWA} lateral profile was plotted in Fig. 7, together with the lateral profiles traced for the minimum and maximum values of the MF identified over the entire time interval.

3.2. LOW VOLTAGE SWITCHBOARD

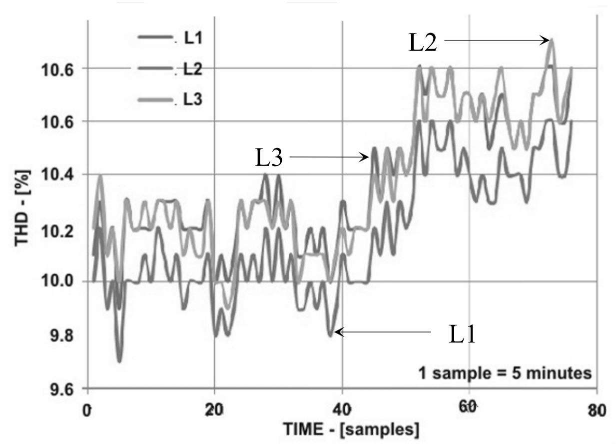
An example of low voltage source of magnetic field is further analyzed, considering the main switchboard at the supply of an industrial consumer. This electric source presents similar characteristics with the previous example – the fluctuation and unbalance of line currents, with impact on the generated MFs. The nonlinear character of the load adds significant harmonic content to the frequency spectra of the currents.

Distortion is quantified by the total harmonic distortion Factor, defined in section 2.1 of the paper and computed on each line with the amplitudes of the spectral components of currents. Phase currents and THD indices show fast and random variations, as Fig. 8 clearly reflects.

Phase currents unbalance, load variability and harmonic content of the current, all three features of the low voltage source act as important factors that determine the generated MF. A quantitative assessment of the characteristic indices shows their strong dependency on the network. Our examples confirm the fact that distribution networks present much more disturbances than transmission lines. Thus, the MF particularities of either a workplace, in an industrial environment, or nearby electric power ancillaries (e.g., overhead lines, substations, electric appliances), are oftentimes more complex than in the case of a general public environment. The analysis and assessment of such MF distributions require specific instrumentation and exposure assessment protocols; spatial, as much as time variations of the field, need to be considered for the identification of the worst-case exposure scenario.



a.



b.

Fig. 8 — Low voltage main switchboard currents (true rms) recorded for an interval of 6 hours (a) and computed THDs (b).

3.3. MAGNETIC FIELD DISTRIBUTION IN AN INTENSIVE HEALTH CARE UNIT

Another case study analyzed here refers to a medical interventional and monitoring space, an intensive therapy unit (ITU), where medical personnel is present for full working time, while the general public (*i.e.* patients in critical conditions) is present for limited intervals, *e.g.* for post-surgery monitoring or intensive therapy. From the human exposure perspective it is a complex situation, open to discussion, while considering both professional and general public exposures.

A MF assessment was performed in an ITU of an emergency hospital, which comprises, as Fig. 9 shows: nine single-bed cubicles (R2 – R10), a centralized monitoring service space (NS), two utility rooms and a large hall (R1) which facilitates fast interventions (like circulation of wheelchairs, or transport of personnel and equipment at patients bed). Local MF sources in the ITU include all electric and electronic equipment: ventilation devices, vital indices monitors (electrocardiographic, respiration, pulse-oximetry), emergency intervention devices, laboratory facility, refrigerators, communication devices, air cleaning and conditioning systems, water purification and heating facilities and of course, electric mains.

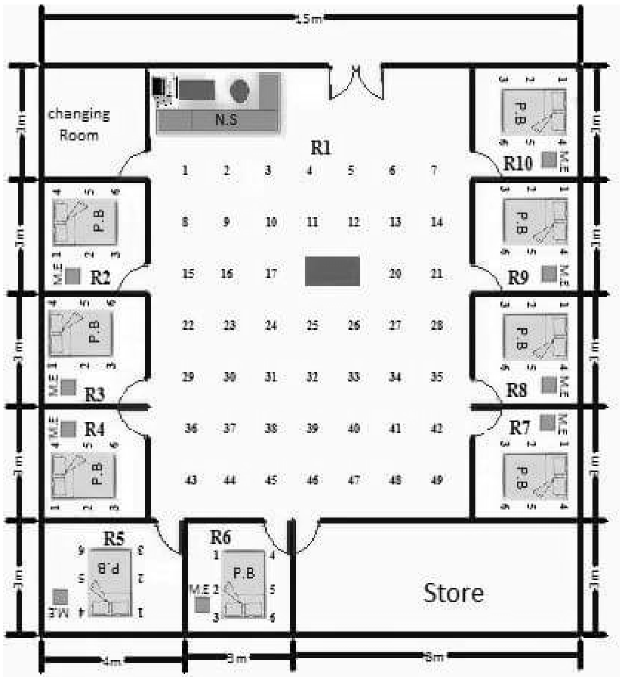


Fig. 9 – Blueprint of the ITU under assessment; numbers indicate locations where the measurements were performed.

Magnetic field measurements were performed inside each functional room, in the locations identified by numbers on the blueprint in Fig. 9, at a height of 1.20 m above the floor; the ITU was operational at full load. The magnetic flux density (rms value) was determined by a common MF-meter (Extech family), each measurement lasting around 30 seconds. The testing protocol was performed for the measurement of the low frequency magnetic flux density, according to the standard IEC of 2013 [22].

Table 2 presents the minimum and maximum values measured in each compartment and the percentage difference of the maximum values, relative to the ICNIRP *reference level of 0.2 mT for the general public* (Fig. 1); several values exceeding the guideline provision are observed. The positive percentages, highlighted in bold, represent overexposure for the general public, including the patients. If the measured maximum values are compared with ICNIRP *reference level for occupational exposure* (1 mT shown in Fig. 1), no overtaking is recorded.

Table 2

Distribution of *B*-values inside the ITU of a hospital; minimum and maximum values recorded inside each investigated space, at 1.2 m above the floor

ROOM	No. of locations in the room	Minimum value of B [mT] (rms value)	Maximum value of B [mT] (rms value)	Percentage difference relative to 0.2 mT [%]
R1	49	0.062	0.399	**99.5**
R2	6	0.143	0.401	**100.5**
R3	6	0.090	0.404	**102**
R4	6	0.060	0.185	-7.5
R5	6	0.033	0.151	-24.5
R6	6	0.105	0.260	**30**
R7	6	0.057	0.144	-28
R8	6	0.067	0.122	-39
R9	6	0.095	0.444	**122**
R10	6	0.081	0.242	**21**

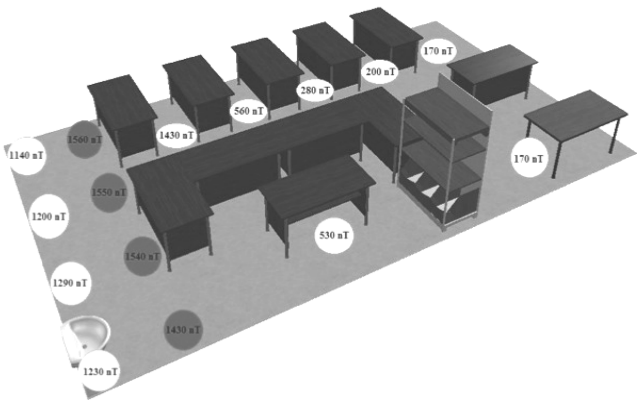
3.4. MAGNETIC FIELD SOURCE IN CLOSE PROXIMITY OF A LABORATORY ROOM

The case presented further refers to a space used as a research and educational laboratory in electrical engineering. The room is currently set up as a computer cluster (LAN consisting of 14 PCs). Right under its floor, in the technical basement, one of the major electricity mains of the building operates. There are no suspicions that exposure to MF might be dangerous for students and staff in this laboratory; in fact, the measured MF levels here are far lower than reference values acceptable for the general public exposure, not mentioning the action levels of the Directive 2013/35/EU. The investigation is further presented just to illustrate the applied methodology.

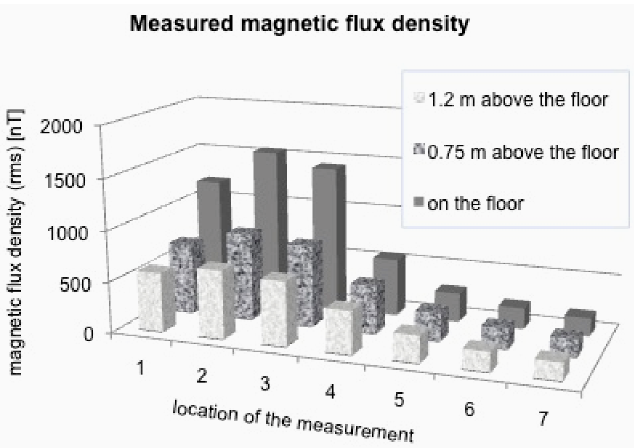
The testing protocol was performed for the measurement of the magnetic flux density of low frequency, according to the standard IEC of 2013 [22]. The Narda field-meter EFA-300 was used, with its magnetic field isotropic probe, in the frequency range 5 Hz to 32 kHz; the band pass filter was set for 15 Hz to 2 kHz. The test consists of successive magnetic flux density measurements at different locations inside the room and different levels [7]. Figure 10a shows the distribution of measured values on the floor; dark coloured spots (on the left) mark the highest measured magnitudes, around 1 500 nT.

Figure 10b presents a synthetic diagram of the magnetic flux density measurements along an observation line, through the room (from left to right, along the aisle between tables, at the spots shown in Fig. 10a), at three heights: on the floor (highest values coloured in dark grey) and at two different levels above the floor (0.75 m and 1.2 m). A few other spot measurements were also performed. The results offer the possibility of calculating, by interpolation, the magnetic flux density in the entire room. The distribution suggests the existence of a major MF source, along the left side of the room. For this particular case, a model of the whole arrangement might be constructed and coupled with a flexible, yet controlled, layout of the source. This tool allows for the best fitted identification of particular exposure conditions and could be useful for prediction of results in other scenario.

A brief overview of the results shows off an almost uniform MF background in the room ~170 nT; the value is reached at the right margin of the room (opposite to the MF source) where it is constant on the height too (see Fig. 10b for the *B*-values on the last row – location no. 7).



a) measured *B* values on specific locations on the surface of the floor (values are in nT)



b) distribution of *B* values along the aisle between tables, from left to right, at three levels (1.2 m above the floor – light marbeled, 0.75 m above the floor – dark marbeled, on the floor – dark grey)

Fig. 10 – Magnetic field density (rms values) distribution in the room.

This case study opens the possibility for some comments:

Since an isotropic operational mode is applied for the measurements, no information on the magnetic field density orientation is obtained.

The measurements are performed at a certain distance from the field source (local electric mains in the building) and possible current unbalance of the three-phase line is not evidenced by the MF distribution.

The electric network load might present fluctuations during the measurement session, which could modify the MF distribution.

A computational model may provide for more detailed information on the MF distribution and its time evolution. Once properly formulated and validated, a numerical model should be able to generate such MF maps for many operating conditions, as illustrated by [26, 27]. The analysis of many other source configurations is easy doable by simulation and the assessments of the magnetic environment could be performed at any time and in any location of the modelled space.

The design and validation of computational models are generally considerably more difficult to obtain and are more expensive than direct measurements; IT resources and qualified operators are needed, specific data is required (*e.g.*, EMF source, material properties, particularities of the geometry, *etc.*), and a large budget of time should be allocated for the pre-operational stages. The models are also highly personalized and the observations, conclusions and results are hardly transferrable to other situations.

4. CONCLUSIONS

The aim of elaborating guides of good practices for the application of the Directive 2013/35/EU at a wide variety of conditions continues to be an issue of strict actuality and it demands the active participation of the electrical engineering community. Several procedures for the assessment of low frequency magnetic environment were discussed and presented with examples, starting from practical considerations and normative limitations. Some common measurement protocols, complying with technical standards are introduced for environmental estimates of low frequency magnetic field. In the same time, illustrative measurement outputs in common working environments are analyzed in a critical manner, coherent with the Directive provisions.

Numerical simulation could be an efficient alternative to measurements, but design (description and validation) of numerical models represents a demanding enterprise. On the other hand, the measurement of quantities relevant as "exposure limit values" is not accessible *in vivo*, but computing them, in connection with relevant "action levels" measurements seems a reasonable enterprise. However one could consider that numerical simulation remains an accurate and powerful research tool and it should be of common sense to see it a complementary solution to the measurements performed for conformity assessment of workplaces with the Directive 2013/35/EU.

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