A QUICK AND EASY METHOD FOR CHECKING COMPLIANCE OF MULTI-FREQUENCY MAGNETIC FIELDS WITH ICNIRP'S GUIDELINES

George Filippopoulos and Efthymios Karabetsos*

Abstract—**In many practical cases human exposure to extremely low frequency magnetic fields with many spectral components (multi-frequency fields) has to be examined in order to check compliance with ICNIRP's guidelines. Showing compliance, according to existing methods, requires sophisticated instruments and measurement procedures to assess some complex exposure metrics. Furthermore, even where the field levels are very low, there is no method to show compliance using broadband instruments, which are the most common and simple ones. In this paper, a new method is described where the frequencies emitted by the source are known and only simple broadband instruments are required. First, the spectral distribution of the field that maximizes exposure metrics is found. Then, an effective reference level for the broadband value of the field is estimated for this distribution. If the measured broadband value of the magnetic field is lower than this reference level, then compliance with ICNIRP's guidelines is readily shown. A case study for a magnetic field consisting of 50 Hz and 60 Hz components is presented. The worst-case spectral distribution contained 64% 50 Hz and 76.8% 60 Hz components, and the corresponding effective broadband reference level is 64 μT for general public exposure. The method is generally conservative in cases of incoherent fields and very conservative in cases of coherent fields. To that end, it is practically a quick and easy test to check if further measurements are needed or not. Application of this method is expected to save time, money, and resources.**
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INTRODUCTION

In 1998, the International Commission on Non Ionizing Radiation Protection (ICNIRP) issued its guidelines (ICNIRP 1998) for the limitation of exposure to time varying electric and magnetic fields at frequencies up to 300 GHz. ICNIRP's guidelines are widely accepted as they were adopted by the European Union (EU 1999; EP/EU 2004) and many national agencies for both occupational and general public exposure. To that end, checking compliance of exposure levels with ICNIRP's guidelines serves both technical and legal perspectives.

In practical situations, however, where the electromagnetic environment is very complex, it is difficult to show compliance with ICNIRP's reference levels. For example, measurements for the determination of occupational exposure to extremely low frequency (ELF) magnetic fields concerning multiple frequencies require sophisticated instruments and methods (Bowman and Methner 2000; Chadwick 1998; IEC 1998; Jokela 2000, 2007). In this paper, a new, quick, and easy method is presented that allows an initial screening to distinguish between cases where compliance of multi-frequency magnetic fields with ICNIRP's guidelines may be readily shown and cases where more extended measurements are needed.

The most common, simple in operation, and inexpensive types of instruments for measuring low frequency magnetic fields are those indicating the broadband rms (root mean square) value of the field in μT or mG. However, readings from these instruments are readily comparable to the reference levels provided in ICNIRP's guidelines only for sinusoidal varying fields at a known frequency. In order to use the indication of these instruments, in case of multi-frequency fields, an effective broadband reference level is needed, that is, a broadband value of the field that can be used alternatively to exposure metrics to compare measurement results (Chadwick 1998; Cooper 2002). However, estimation of effective broadband reference levels requires knowledge of the field's spectral distribution. Obviously, this information cannot be acquired by broadband measurements alone.

To cope with this problem in this paper, the "strictest" reference level for the broadband value of a multi-frequency field is defined as the effective broadband reference level corresponding to the worst-case spectral distribution of the field. If measured broadband values

* Greek Atomic Energy Commission, Non Ionizing Radiation Office, P.O. Box 60092, 15310 Agia Paraskevi, Greece.
For correspondence contact G. Filippopoulos at the above address, or email at filippop@eeae.gr.
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are below the strictest reference level, then any spectral distribution of the field, and the actual one as well, will comply with ICNIRP's guidelines. If the strictest reference level is exceeded, then the actual spectral distribution of the field should be assessed in order to check compliance with ICNIRP's reference levels. The formulas for the calculation of the worst-case spectral distribution as well as the strictest broadband reference levels accompanied with instructions for using the method are given in the section "Proposed Method." Afterwards, a detailed case study is presented, concerning application of the method in the vicinity of a power frequency converter installation.

MATERIALS AND METHODS

ICNIRP's guidelines for multi-frequency fields

ICNIRP (1998) used the induced current density as a basic restriction to prevent electrostimulation effects from low frequency fields. It is generally difficult to measure the induced current density, so ICNIRP (1998) provided reference levels regarding the magnetic flux density as a more easily measured physical quantity. There are various models of the human body that can be used to derive the reference levels (Martens 2007). A simple physical model that describes the induction of current from a low frequency magnetic field, discussed by ICNIRP (1998), is that of a circular conductive loop. Using this model, the time function of the maximum induced current density, $J(t)$, in the body of an exposed individual may be evaluated by:

$$J(t) = -K_b \frac{dB(t)}{dt}, \quad (1)$$

where $B(t)$ is the time function of the magnetic field and $K_b = 0.064\ \Omega^{-1}$ (ICNIRP 2003).

When the exposure concerns a multi-frequency magnetic field, its time function $B(t)$ may be written as

$$B(t) = \sqrt{2}\sum_f B_f \cos(2\pi f t + \delta_f), \quad (2)$$

where B_f is the rms value and δ_f is the phase of the field's spectral component at frequency f, respectively, and the summing operation is over the field's frequencies. In case of a field with coherent spectral components, e.g., the Fourier analysis of a standard waveform, the values of δ_f will be fixed and independent of time. However, in case of incoherent spectral components, the values of δ_f will change with time and this change will be different for each one of them.

In accordance with ICNIRP (2003), compliance of a multi-frequency magnetic field with reference levels can be shown if the magnitude of the following time function $C(t)$ is lower than unity:

$$C(t) = \left| \sum_{f, f<f_c} -\frac{B_f}{L_f}\sin(2\pi f t + \delta_f) + \sum_{f, f>f_c} \frac{B_f}{L_f}\cos(2\pi f t + \delta_f) \right| \leq 1, \quad (3)$$

where L_f is ICNIRP's reference level for the magnetic flux density at frequency f and f_c (=820 Hz) is a cut off frequency below which $C(t)$ follows the instantaneous value of $dB(t)/dt$ and above which follows the instantaneous value of $B(t)$. This behavior is consistent with the dependence of electrostimulation thresholds on the peak value of induced currents at low frequencies and on its time integral at high frequencies (Jokela 2000; ICNIRP 2003). If the field's spectral components are coherent, then the peak value $\widehat{C}$ of $C(t)$ in eqn (3) is time independent and can be used as a metric in order to check compliance with ICNIRP's guidelines. However, for incoherent spectral components, the value of $\widehat{C}$ will change with time, depending on the phase angles δ_f of the field's spectral components. In this case another metric, D, is defined considering the phase angles δ_f that maximize the value of $\widehat{C}$:

$$D = \sum_f \frac{B_f}{L_f} \leq 1. \quad (4)$$

Metric D is useful for incoherent fields because it does not depend on the phase angles δ_f. However, for coherent fields it is conservative because it assumes worst-case values of phase angles δ_f. For incoherent fields there is a chance that this case will occur, even though the probability for it is very low, especially when there are many spectral components present (ICNIRP 2003; Jokela 2000). Metric D was included in ICNIRP guidelines (1998) for multi-frequency exposure, but it was amended in ICNIRP (2003) because it was conservative for coherent fields.

Metric D depends on the spectral distribution of the field. This distribution can be defined through the spectral fraction r_f of the spectral component at frequency f, B_f, to the broadband value of the field, B_{bb}. Hence,

$$r_f = \frac{B_f}{B_{bb}}, \quad (5)$$

where

$$B_{bb} = \left(\sum_f B_f^2\right)^{\frac{1}{2}}. \quad (6)$$

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Metric D can also be expressed through the field's spectral fractions r_f and its broadband value B_{bb} as

$$D = B_{bb} \sum_f \frac{r_f}{L_f}. \quad (7)$$

This way the effective broadband reference level L_{bb} can be calculated for the specific spectral distribution (Chadwick 1998; Cooper 2002) as

$$L_{bb} = \left(\sum_f \frac{r_f}{L_f} \right)^{-1}. \quad (8)$$

Comparing the field's broadband value B_{bb} with reference level L_{bb} is equivalent with checking if D is lower than unity. However, being a field level value, L_{bb} is more closely related to measurements than metrics as D, which are more abstract entities. The basic drawback of reference level L_{bb} is that it requires knowledge of the field's spectral distribution. If the field's spectral components B_f were known, then it would be easier to calculate metric D from eqn (4) than to find reference level L_{bb}.

In the following sections of this paper, the strictest effective reference level, SL_{bb}, for the broadband value of a multi-frequency field is derived after the worst-case spectral distribution of the field, that is, the spectral distribution that maximizes metric D or equivalently that minimizes the reference level L_{bb}. Table 1 shows an example of a 50 μT magnetic field comprising 50 Hz and 150 Hz spectral components for some cases of spectral distributions and relative phase angles of the spectral components. The first two lines concern single frequency fields at 50 Hz and 150 Hz and are there for reference purposes. The table includes calculations of three general public exposure metrics for each case. Metric $\widehat{C}$ is the peak value of $C(t)$ (eqn 3), and is different for every case because it depends on both the spectral distribution and the phase angles. For the set of phase angles $\delta_{50} = 0$ and $\delta_{150} = 0$, metric $\widehat{C}$ gets its minimum value or a value close to it. The set of phase angles $\delta_{50} = \pi/2$ and $\delta_{150} = \pi/2$ maximizes metric $\widehat{C}$, independently of the spectral distribution and metric $D = \widehat{C}$ for this set. Metric D depends only on spectral distribution. An effective broadband reference level L_{bb} can be calculated and the metric D can be considered as the ratio of the field's broadband value B_{bb} to the reference level L_{bb}. The spectral distribution at the last two lines of the table (cases g and h) is the one that maximizes metric D and is calculated according to the method presented in the following sessions. The strictest broadband reference level SL_{bb} (=31.6 μT for general public exposure) corresponding to this spectral distribution is the minimum of L_{bb} for a field comprising 50 Hz and 150 Hz components. The third metric, E, is calculated as the ratio of the field's broadband value B_{bb} to the strictest reference level SL_{bb}. Metric E is independent of the phase angles between the field's spectral components as well as the field's spectral distribution and depends only on the field's set of frequencies.

As can be easily verified from Table 1:

$$\widehat{C} \leq D \leq E. \quad (9)$$

This relation means that the proposed method in this paper is generally stricter than calculating metrics $\widehat{C}$ and D. If the strictest reference level is exceeded, then no firm conclusion about metrics $\widehat{C}$ or D can be drawn. However, in the common cases where this level is not exceeded, then both metrics $\widehat{C}$ and D are lower than unity and compliance with ICNIRP guidelines is readily shown.

Another observation from Table 1 is that the maximum exposure metric for a 50 μT field comprising 50 Hz and 150 Hz spectral components is 1.58, whereas it is 0.5 and 1.5 for a single 50 Hz and 150 Hz field, respectively. This means that the multi-frequency field can be more potent in eliciting electrostimulation effects than a single frequency field at any of the involved frequencies. This is contrary to the case of thermal effects, where the worst-case is to assume that a multi-frequency field is allocated

Table 1. Calculation of three general public exposure metrics for some example cases of a 50 μT field comprising 50 Hz and 150 Hz spectral components and having different spectral distributions and phase angles of spectral components.

						Exposure metric		
Case	B_{bb} (μT)	B_{50} (μT)	B_{150} (μT)	δ_{50} (rad)	δ_{150} (rad)	$\widehat{C}$	$D = \frac{B_{bb}}{L_{bb}}$	$E = \frac{B_{bb}}{SL_{bb}}$
a	50	50	0	any	—	0.50	0.50	0.50
b	50	0	50	—	any	1.50	1.50	1.50
c	50	49.8	5.0	0	0	0.45	0.65	1.58
d	50	49.8	5.0	$\pi/2$	$\pi/2$	0.65	0.65	1.58
e	50	40	30	0	0	1.09	1.30	1.58
f	50	40	30	$\pi/2$	$\pi/2$	1.30	1.30	1.58
g	50	15.8	47.4	0	0	1.45	1.58	1.58
h	50	15.8	47.4	$\pi/2$	$\pi/2$	1.58	1.58	1.58

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at the frequency with the lowest reference level. From a mathematical point of view, the difference is attributed to the fact that exposure metrics for thermal effects consider the weighted sum of the squares of the spectral components, whereas for electrostimulation effects consider a weighted linear sum of them. From a physical point of view, the difference is attributed to the fact that thermal effects are caused by absorption of power from the field, whereas electrostimulation effects are caused when the peak value of the induced currents for frequencies below a cut off frequency f_c or the peak value of the magnetic field above this frequency exceed certain thresholds. Thermal effects are independent of the waveform of the field, whereas electrostimulation effects are highly dependent on it. Under worst-case considerations of a multi-frequency field, the peak value of induced currents or of magnetic flux density is greater than an equal single frequency field at any of the involved frequencies. The more frequencies are involved in the field, the greater this peak value can be.

Measurement of multi-frequency fields

The most common types of instruments used for the measurement of extremely low frequency (ELF) electric and magnetic fields are broadband meters. These instruments show an indication for the rms value of the field in a broad spectral pass band (for example from 30 Hz to 2 kHz) (IEC 1998). Considering a magnetic field that comprises many spectral components, the broadband value indication B_{ind} of a measuring system is given by:

$$B_{ind} = \sqrt{\sum_f k_f B_f^2}, \tag{10}$$

where k_f is the instrument's response at the frequency f. The value of k_f may be considered as 0 for frequencies well outside of the instrument's pass band and 1 for frequencies well into it. For frequencies near the pass band limits, the value of k_f will be between 0 and 1. Specifically, the limits of the instrument's pass band are usually defined as the two frequencies where the instrument's response is 0.5 (−3 dB points). Measuring standards (IEC 1998) address the proper selection of instrument's pass band for the spectral content of the field being measured.

Though broadband instruments are simple in operation and relatively inexpensive, in the case of multi-frequency fields their indications cannot be readily comparable with ICNIRP's reference levels unless an effective broadband reference level such as L_{bb} or SL_{bb} is known. Knowledge of reference level L_{bb} is based on the levels of the field's spectral components, as seen in eqn (8). If this information was available, then metric D in eqn (4) could be found without any need for the broadband measurement in order to check compliance with ICNIRP guidelines. Furthermore, in most cases the spectral distribution of the field will change from point to point and the reference level L_{bb} would have to be recalculated. On the other hand, the strictest broadband reference level, SL_{bb}, proposed in the current paper, depends only on the frequencies involved in the field. Since those frequencies are characteristic of the field's source, the value of the strictest broadband reference level SL_{bb} remains unchangeable in its vicinity. A priori knowledge of the field's frequencies might be based on experience and the typical characteristics of the involved sources. Otherwise, a spectral analysis might be performed once, in order to determine them.

The only problem associated with the use of the strictest broadband reference level SL_{bb} is that in some cases, especially where there are many spectral components present, the value of SL_{bb} may occur too low so that measured values might easily exceed it. If the measured value is greater than strictest broadband reference level SL_{bb}, less strict measurement methods are to be used in order to check compliance with ICNIRP guidelines. The value of the strictest broadband reference level SL_{bb} can be calculated before a measurement survey, allowing the identification of locations where other measurement methods are needed. In the following paragraphs existing methods of measuring multi-frequency fields are described. Generally, the basic drawbacks of these methods are that they require expensive instrumentation and skilled personnel to perform them, they can be time consuming, and compliance results may not be readily available during measurements.

Multi-frequency magnetic fields can be measured utilizing instruments with narrow pass band filters in order to measure the spectral components at specific frequencies alone and calculate metric D in eqn (4) (narrowband measurements). This procedure requires a priori knowledge of the frequencies involved in the field, or the use of a spectrum analyzer to determine them, similarly to the proposed method in this paper. However, instruments with narrow pass filter options are generally more expensive than instruments without them and narrowband measurements are more time consuming than broadband ones. Furthermore, it is difficult to calculate the value of metric D on the spot, in order to check compliance with exposure guidelines.

In Bowman and Methner (2000), a sophisticated measuring instrument was used to capture the whole waveform of the 3D magnetic field vector at a point in space that allowed detailed analyses of the magnetic field characteristics. In this way, the time function $C(t)$, in eqn (3), can be found and compliance with ICNIRP guidelines is checked. However, instruments with wave capturing capabilities are even more complicated and more

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expensive than instruments with narrow pass filters. Furthermore, these instruments cannot give an instant result about compliance status during measurements.

In Jokela (2000) a resistance-capacitance (RC) filter response is proposed as a complex weighting function for the measured multi-frequency magnetic field. Jokela's proposal, which was adopted by ICNIRP (2003), allows the direct estimation of metric $\widehat{C}$. Instruments with such filter options will be most valuable in cases of coherent multi-frequency fields as these are usually the fields with rich harmonic content (Jokela 2007). However, instruments applying Jokela's filters might not indicate the worst-case value of fields with incoherent spectral components, as are the fields produced by two independent sources, unless they are left for a relative long time in the field.

Measuring instrumentation

The magnetic field measurements that will be presented later on in this paper were performed with an EFA-300 electric and magnetic field analyzer produced by NARDA Safety Test Solutions (NARDA STS, Sandwiesenstrasse 7, 72793 Pfullingen, Germany). This is a measurement system capable of broadband measurements in the frequency range from 5 Hz to 32 kHz and narrowband measurements, and is capable of harmonic and FFT (fast Fourier transform) analysis of the measured signal for multi-frequency fields. Furthermore, this instrument can calculate and indicate metric $\widehat{C}$ for multi-frequency fields according to ICNIRP's guidelines for both occupational and general public exposure. The instrument was used in conjunction with a NARDA STS high accuracy external probe, with 10-cm diameter, for magnetic field measurements.

Though the reported measurements were performed with this highly sophisticated instrument, the idea of this paper is to present a new method allowing an initial screening of multi-frequency fields with much simpler instruments only capable for broadband measurements. If instruments with narrowband filter, wave capture, or RC filter options are available, the proposed method can still be used as a simple and time-saving process.

PROPOSED METHOD

The proposed method for checking compliance of multi-frequency magnetic fields with ICNIRP guidelines consists of two steps. The first step is to find the spectral distribution that maximizes the field's potential to elicit electrostimulation effects. That is, the spectral distribution that maximizes metric D in eqn (7) or equivalently that minimizes the effective broadband reference level L_{bb} in eqn (8). Metric D was chosen instead of $\widehat{C}$, considering cases of incoherent fields or as a conservative approach for cases of coherent fields. The second step is to find the strictest broadband reference level, i.e., the effective broadband reference level for the worst-case spectral distribution calculated in the first step. The strictest broadband reference level is the value used to compare broadband measurement results.

In order to distinguish the fractions r_f that define the worst-case spectral distribution, they are written as sr_f. In the Appendix, the values of fractions sr_f and the strictest broadband reference level SL_{bb} are calculated as:

$$sr_f = \frac{SL_{bb}}{L_f} \tag{11}$$

$$SL_{bb} = \left(\sum_f \frac{1}{L_f^2} \right)^{-\frac{1}{2}}. \tag{12}$$

SL_{bb} is the minimum value of the effective broadband reference levels for any spectral distribution of the field for the given set of frequencies.

In order to apply the proposed method, personnel performing measurements should follow the next steps:

1. Determine the frequencies, f, involved in the field;
2. For each involved frequency, find ICNIRP's reference level, L_f;
3. Find the strictest broadband reference level, SL_{bb}, after equation (12);
4. Perform simple broadband measurements in the area of interest;
5. If the measured values are below the strictest broadband reference level, then compliance with ICNIRP's guidelines is shown and no further actions are required; and
6. If there are locations where measured broadband values exceed the strictest broadband reference level, then advanced measurement methods are required in these locations in order to check compliance with ICNIRP's guidelines.

The worst-case spectral distribution, estimated after eqn (11), is not required in order to use the method. However, as a good measurement practice, it is advised that the worst-case spectral distribution should be estimated and presented in the results together with the strictest broadband reference level for reference purposes.

A CASE STUDY

The authors had to deal with the problem of measuring an incoherent multi-frequency magnetic

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field when they were called upon to examine the levels of the magnetic field in the vicinity of an electromechanical electric power converter installed in a shipyard supplying electric power to the ships anchored in its dock. This device converted the 50 Hz electric voltage supplied by the grid to the 60 Hz required by the ships. It comprised two electrical rotating machines with a common rotation axis where the one operated as a motor producing mechanical energy and the other one as a generator producing electric power. Though the common axis of the two machines means that the mechanical angle between their rotors is fixed, the electrical phase between their currents is affected by so many parameters that the magnetic field produced by this device is an incoherent mixture of 50 Hz and 60 Hz components.

Typically, the authors would perform narrowband measurements at 50 Hz and 60 Hz in order to determine the field's spectral distribution. However, the area we were called upon to examine was an office store right above the converter installation, and the broadband measurements of the magnetic field in this area showed values well below ICNIRP reference levels for both 50 Hz and 60 Hz frequencies and general public exposure. It was obvious during the measurements that with these levels of broadband magnetic field there was no need to examine its spectral distribution to 50 Hz and 60 Hz; no matter what this distribution would be, the magnetic field levels were well below ICNIRP's reference levels for general public exposure. What was not known at this time was what level of broadband magnetic field we could certify to support this hypothesis and avoid the time-consuming narrowband measurements. For example, if the measured magnetic field levels were at 30 μT, it would not be possible at that point to decide whether ICNIRP's reference levels for general public exposure could be exceeded or not through broadband measurements alone.

In order to analyze the results of the broadband measurements without any knowledge of the field's spectral distribution, we determined the worst-case spectral distribution to 50 Hz and 60 Hz, that is, the spectral distribution that maximizes metric D in eqn (4). The worst-case spectral distribution is defined through the strictest fractions sr_f in eqn (11). It is noteworthy that in eqn (11) the strictest fraction sr_f is inversely proportional to the reference level at frequency f. An interesting combination is when the reference levels are inversely proportional to the frequency f (as happens in ICNIRP's reference levels for general public exposure in the frequency range from 8 Hz to 800 Hz). In this case, the strictest fraction sr_f is written as:

$$sr_f = \frac{f}{RSS(f)}, \tag{13}$$

where

$$RSS(f) = \left(\sum_f f^2 \right)^{\frac{1}{2}}, \tag{14}$$

and RSS stands for root of the sum of the squares.

For example, in the examined case of a field comprising 50 Hz and 60 Hz components, the strictest fractions sr_f are:

$$\begin{aligned} sr_{50} &= \frac{50}{\sqrt{50^2 + 60^2}} = 64.0\% \\ sr_{60} &= \frac{60}{\sqrt{50^2 + 60^2}} = 76.8\%. \end{aligned} \tag{15}$$

Assuming the worst-case spectral distribution, a broadband value of 30 μT is analyzed to 19.2 μT at 50 Hz and 23 μT at 60 Hz. ICNIRP's reference levels for general public exposure are L_{50} = 100 μT and L_{60} = 83.33 μT, so the sum of quotations D in eqn (4) is calculated for this worst-case consideration as (19.2% + 27.6%) = 46.8%. This value for D may be interpreted as being (at least) 2.1 times lower than ICNIRP's guidelines for general public exposure.

A remaining question is still, at what broadband value of a field consisting of 50 Hz and 60 Hz components can it be concluded that, independently of the spectral distribution, the field values comply with ICNIRP guidelines for general public exposure? Using eqn (12), the strictest broadband reference level is calculated as:

$$SL_{bb} = \left(\frac{1}{100^2} + \frac{1}{83.33^2} \right)^{-\frac{1}{2}} \mu\text{T} = 64\ \mu\text{T}. \tag{16}$$

If a broadband value for a magnetic field consisting of 50 Hz and 60 Hz components is below 64 μT, then it will definitely comply with ICNIRP guidelines for general public exposure; otherwise, other measurement methods are needed in order to assess compliance.

Fig. 1 is a graphical verification of the above. A field comprising 50 Hz and 60 Hz spectral components, B_{50} and B_{60}, respectively, is assumed. In the upper part of the figure the spectral fractions at 50 Hz and 60 Hz, r_{50} and r_{60}, respectively, are plotted as functions of the spectral component ratio B_{60}/B_{50}. These fractions can

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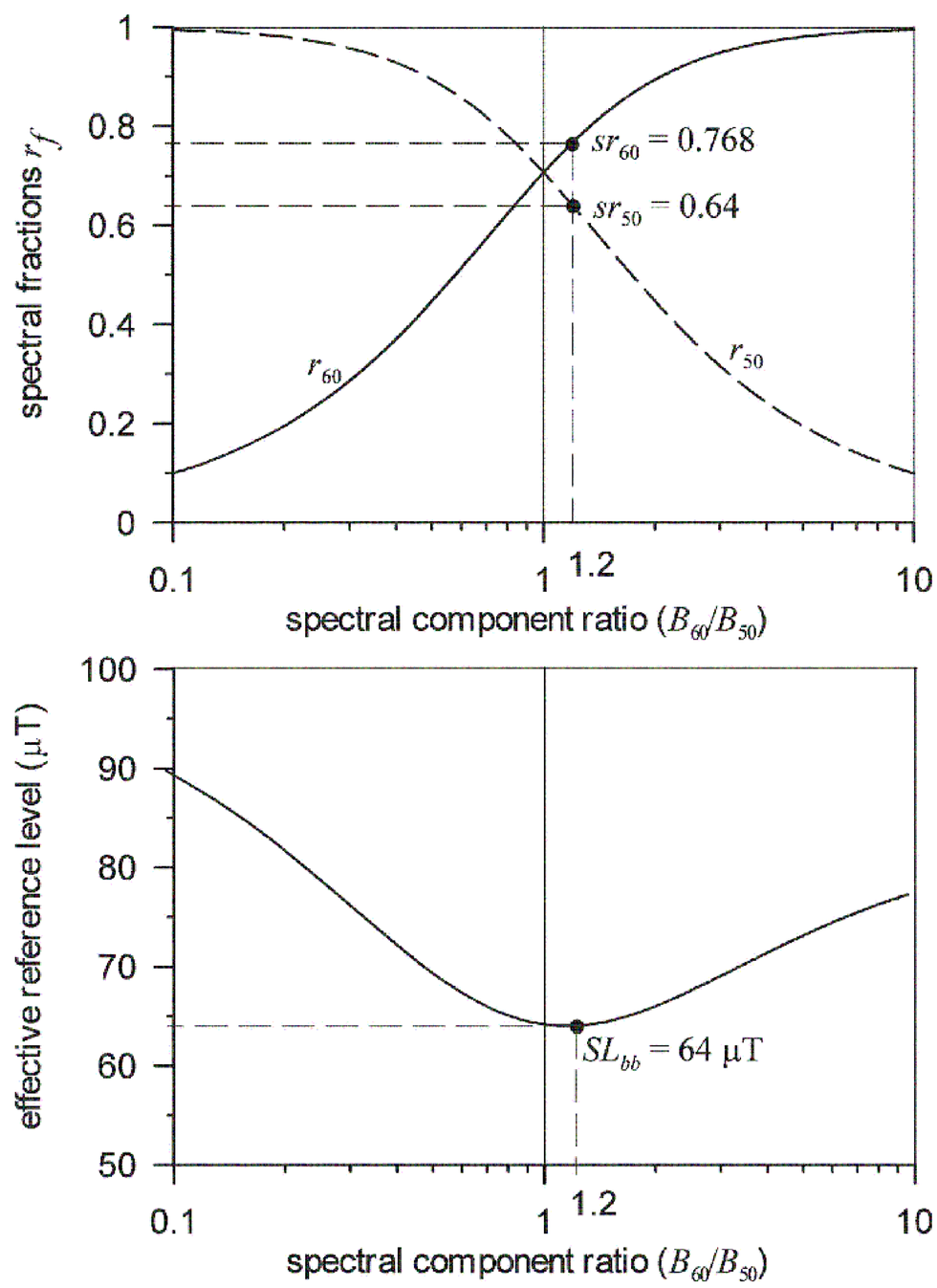

Fig. 1. A graphical verification of the worst-case spectral distribution and the strictest broadband reference level of a field comprising 50 Hz and 60 Hz spectral components, B_{50} and B_{60}, respectively. In the upper part of the figure and in the lower part of it the fractions $r_{50} = B_{50}/B_{bb}$ and $r_{60} = B_{60}/B_{bb}$ and the effective broadband reference level, respectively, are plotted as functions of the spectral component ratio B_{60}/B_{50}. The effective broadband reference level is minimized (= SL_{bb}) and the strictest fractions (= sr_{50} and sr_{60}) occur for $B_{60}/B_{50} = 1.2$.

been calculated from the following equations derived from eqn (5) and eqn (6) as:

$$r_{50} = \left(1 + \frac{B_{60}^2}{B_{50}^2}\right)^{-\frac{1}{2}}$$
$$r_{60} = \left(1 + \frac{B_{50}^2}{B_{60}^2}\right)^{-\frac{1}{2}}. \quad (17)$$

If the spectral component ratio B_{60}/B_{50} is low, then the 50 Hz component of the field is dominant; if it is high, then the 60 Hz component is dominant, and the spectral fractions take the corresponding values. In the lower part of the figure, the effective broadband reference level, calculated after eqn (8) for general public exposure, is plotted as a function of the spectral component ratio B_{60}/B_{50}. It is verified that for the spectral component ratio $B_{60}/B_{50} = 1.2$, the value of this reference level is minimized to the strictest broadband reference level of 64 μT. The strictest fractions $sr_{50} = 0.64$ and $sr_{60} = 0.768$ occur for $B_{60}/B_{50} = 1.2$.

Table 2 shows the worst-case spectral distributions and the derived strictest broadband reference levels for the magnetic field in environments where there are two frequencies present. The mentioned frequencies are commonly used in the industry (16 and ⅔ Hz is used in electric train systems in Europe, 400 Hz is used in airplane and marine installations, and 50 Hz and 60 Hz are used worldwide for main electric power systems), so this table will be useful for the evaluation of magnetic fields in the vicinity of frequency converter installations.

DISCUSSION

The proposed method allows an easy assessment of compliance with ICNIRP's guidelines in an environment where the magnetic field has more than one spectral component. This is achieved by the introduction of the strictest reference levels for the broadband value of the magnetic field. These reference levels are the strictest in the sense that they assume the worst-case spectral distribution of the field's components. When a measured value of a broadband magnetic field is lower than this strictest reference value, then compliance with ICNIRP's guidelines is demonstrated. If, however, the measured broadband value is greater than the strictest reference level, then other measurement methods have to be used in order to assess the real spectral distribution of the field and compare with the corresponding reference values for the involved frequencies.

The proposed method requires a priori knowledge of the field's frequencies in order to calculate the broadband reference level. This is not an exclusive requirement, however, as narrowband measurements also require this knowledge. In many practical situations the field's frequencies will be known through experience, or else measurements with a spectral analyzer might be performed in advance in order to find out the field's frequencies. It is noted that the set of a field's frequencies is generally a non-changing characteristic of its source, whereas the fractions of the spectral components are generally changing from point to point.

The proposed method does not seem to be suitable for direct application in cases of fields with many spectral components, as for example in the vicinity of rectifier installations, where the field has rich harmonic content. The reason is that the strictest spectral reference level becomes too low when there are many frequencies present, occurring after a highly unrealistic worst-case spectral distribution. In the case of fields with rich harmonic content, it is better to assess realistic spectral distributions based on worst-case operational scenarios

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Table 2. Worst-case spectral distribution and strictest reference level for the broadband value of the magnetic field in the vicinity of installations emitting two frequencies f_1 and f_2.

Involved frequencies		Worst-case spectral distribution[a]		Strictest broadband reference level (μT)	
f_1 (Hz)	f_2 (Hz)	sr_1 (%)	sr_2 (%)	Occupational exposure	General public exposure
16 and 2/3	50	31.6	94.9	474	94.9
50	60	64.0	76.8	320	64.0
50	400	12.4	99.2	62.0	12.4
60	400	14.8	98.9	61.8	12.4

[a] The spectral distribution is described through the fractions sr_1 and sr_2 of the spectral component at frequency f_1 and f_2, respectively, to the broadband value of the field.

of the examined equipment and then calculate an effective reference level for this spectral distribution. Alternatively, instruments employing Jokela's filters (Jokela 2000) might be used in these cases.

In most cases the application of the method proposed in the current paper will save time, money, and resources as the measured values are usually much lower than ICNIRP's reference levels, and broadband measurements are generally faster and simpler and require less sophisticated equipment than other measuring methods. Safety surveillance personnel might readily apply the method in occupational settings as an initial screening test to determine whether measured values adhere to ICNIRP's reference levels or if further measurements are needed. In other cases, however, the proposed method might yield the need to use other measurement methods too often and so it may be more efficient to conduct these measurements from the beginning. Those performing measurements must always take into account the psychological impact on personnel or occupants being informed that the measured values exceed a "limit" value. To that end, it should always be pointed out that comparing measured values with the strictest broadband reference level is just a simple and strict test to see if more measurements are needed.

The proposed method might be modified to cover cases where the instrument's output is not the broadband value of the field, i.e., $k_f \neq 1$ in eqn (10). For example, many instruments use coils as sensor elements of the magnetic field. These elements will respond with a voltage proportional to dB/dt. To compensate for this effect, instruments usually have an integrator circuit between the coil and the rms detector (IEC 1998; Jokela 2007). If we assume an instrument without this integrator stage, its indication B_{ind} for a multi-frequency field will be:

$$B_{ind} = \sqrt{\sum_f \frac{f^2}{f_o^2} B_f^2} \tag{18}$$

where f_o is the instrument's calibration frequency, i.e., the instrument's indication is equal to the rms value of the magnetic field for this frequency. Working similar to the proposed method in this paper, a strict reference level SL_{ind} for the indication of this instrument is calculated as

$$SL_{ind} = f_o^{-1}\left(\sum_f \frac{1}{f^2 L_f^2}\right)^{-\frac{1}{2}}. \tag{19}$$

For cases where all the involved frequencies are below 820 Hz, reference levels L_f are inversely proportional to frequency and the strict reference level SL_{ind} becomes

$$SL_{ind} = \frac{L_o}{\sqrt{n}}. \tag{20}$$

where L_o is the reference level at frequency f_o and n is the number of involved frequencies. The strictest reference level SL_{ind} in this case depends only on the number of frequencies involved in the field.

The proposed method can also be modified for measurements of electric field strength or contact currents and comparison with the corresponding reference levels.

CONCLUSION

Assessing compliance of multi-frequency fields with ICNIRP's reference levels is generally a complicated and time-consuming process requiring sophisticated equipment and skilled personnel. The common, simple, and relatively inexpensive instruments indicating the broadband value of the field in μT or mG cannot be used for checking compliance with ICNIRP's guidelines, unless the spectral distribution of the field is known. In this paper, a new, quick, and easy method was proposed for utilizing the indications of simple broadband instruments alone for this purpose.

The proposed method is based on the consideration of the worst-case spectral distribution and a derived

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strictest broadband reference level for the set of the field's frequencies. The measurements can then be compared to this reference level. If the broadband measurements of the field are lower than the strictest broadband reference level, then compliance with ICNIRP's guidelines is demonstrated; if not, then other measurement methods might be needed to assess compliance.

The frequencies comprising the field have to be known in order to apply the proposed method. The set of field frequencies might be a priori known through experience and the typical characteristics of its sources, or else it might be estimated on the spot with the use of a spectrum analyzer. It is noted that the set of emitted frequencies is generally a non-changing characteristic of the source, whereas the levels of the field's spectral distribution might change in the space surrounding the source.

The proposed method is intended to be a quick and easy way of checking compliance with ICNIRP's guidelines that may be readily used by safety surveillance personnel as an initial screening test to check if the guidelines are been adhered to, or if more detailed measurements are needed. Since in most practical cases the measured values are well below ICNIRP's values, the application of the method is expected to save time, money and resources.

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APPENDIX

In this appendix the worst-case spectral distribution and the strictest broadband reference level of a multi-frequency field are found.

The worst-case spectral distribution maximizes metric D in eqn (7). Combining eqn (5) with eqn (4), the following constraint for the fractions r_f is derived:

$$\sum_f r_f^2 = 1. \tag{A1}$$

The problem is treated by considering that the fraction of the field at an arbitrary frequency ν is not an independent variable, but it depends on the fractions at the rest frequencies through the following relation derived from eqn (A1):

$$r_\nu = \sqrt{1 - \sum_{f, f \neq \nu} r_f^2}. \tag{A2}$$

Replacing this relation in eqn (7), it becomes:

$$D = B_{bb} \left(\frac{\sqrt{1 - \sum_{f, f \neq \nu} r_f^2}}{I_\nu} + \sum_{f, f \neq \nu} \frac{r_f}{L_f} \right). \tag{A3}$$

A necessary condition so that the sum of quotations D in the former relation is maximized is that all its partial derivatives in relation to the independent variables r_f are equal to zero. So for the worst-case spectral distribution $r_f = sr_f$ and

$$\left. \frac{\partial D}{\partial r_f} \right|_{r_f = sr_f} = B_{bb} \left(\frac{-sr_f}{L_\nu \sqrt{1 - \sum_{f, f \neq \nu} sr_f^2}} + \frac{1}{L_f} \right)$$

$$= B_{bb} \left(\frac{-sr_f}{L_\nu sr_\nu} + \frac{1}{L_f} \right) = 0. \tag{A4}$$

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This relation is equal to zero only if

$$sr_f = \frac{L_\nu \, sr_\nu}{L_f}. \tag{A5}$$

Using this relation in eqn (A1) (after the replacement $r_f = sr_f$) and solving for sr_ν, it results:

$$sr_\nu = L_\nu^{-1}\left(\sum_f \frac{1}{L_f^2}\right)^{-\frac{1}{2}}. \tag{A6}$$

Since the frequency ν of the dependable variable is arbitrary, the former relation can be used to determine the values of the fractions sr_f for all the involved frequencies. This relation can be written as

$$sr_f = \frac{A}{L_f}, \tag{A7}$$

where

$$A = \left(\sum_f \frac{1}{L_f^2}\right)^{-\frac{1}{2}}. \tag{A8}$$

The strictest broadband reference level SL_{bb} is derived, assuming the worst-case spectral distribution ($r_f = sr_f$) in eqn (8):

$$SL_{bb} = \left(\sum_f \frac{sr_f}{L_f}\right)^{-1}. \tag{A9}$$

Replacing the values of sr_f from eqn (A7) in (A9), the following result is obtained:

$$SL_{bb} = A^{-1}\left(\sum_f \frac{1}{L_f^2}\right)^{-1}. \tag{A10}$$

Replacing the value of A from eqn (A8) into (A10), the formula for SL_{bb} is obtained giving directly its value through ICNIRP's reference levels at the field's frequencies:

$$SL_{bb} = A = \left(\sum_f \frac{1}{L_f^2}\right)^{-\frac{1}{2}}. \tag{A11}$$

■ ■

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