GUIDANCE ON DETERMINING COMPLIANCE OF EXPOSURE TO PULSED AND COMPLEX NON-SINUSOIDAL WAVEFORMS BELOW 100 KHZ WITH ICNIRP GUIDELINES

The International Commission on Non-Ionizing Radiation Protection*

INTRODUCTION

THE INTERNATIONAL Commission on Non-Ionizing Radiation Protection (ICNIRP) has published guidelines for limiting exposure to electric, magnetic and electromagnetic fields (ICNIRP 1998a, b) and has provided frequency dependent basic restrictions and reference levels from which a hazard assessment for exposures to electric and magnetic fields can be made.

This document provides clarification for assessing compliance with the guidelines for pulsed and complex non-sinusoidal waveforms with frequency components predominantly up to 100 kHz. The approaches described may be helpful to product standards setting bodies concerned with metrology.

In the frequency range up to 100 kHz there are a number of sources of non-sinusoidal magnetic fields with the potential to exceed the reference levels for exposures specified in the ICNIRP guidelines. Common sources include electronic article surveillance gates, demagnetizers, electronic security systems, and metal detectors, and these generate predominantly magnetic fields. Therefore, this statement focuses mainly on magnetic fields; however, this can be readily extended to electric fields.

The ICNIRP guidelines specify "basic restrictions" and "reference levels." Basic restrictions on exposure to magnetic fields are based on established adverse health effects. For magnetic fields below 100 kHz the physical quantity used to specify the basic restrictions is current density (J) induced inside the body. Reference levels are values that are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Compliance with the reference levels is designed to ensure compliance with the relevant basic restriction. For exposures to magnetic fields below 100 kHz, the derived quantity magnetic flux density (*B*) is the parameter used for the reference levels. Reference levels expressed in terms of rate of magnetic flux density change dB/dt can also be derived from basic restrictions.

Although the reference levels for limiting exposure to time varying magnetic fields are expressed in terms of sinusoidal waveforms, the ICNIRP guidelines define a method to convert a simple rectangular waveform of current density to an equivalent sinusoidal waveform, Fig. 1. In order to test compliance with the basic restrictions, such pulses are set equivalent to a continuous sinusoidal field with a frequency of $1/(2\ t_p)$ where t_p is the duration of the pulse, Table 4, note 3, in the ICNIRP guidelines. However, most sources of pulsed electric and magnetic fields have more complicated waveforms (Chadwick 1998; Jokela 2000). Several general types of waveforms exist (Fig. 2) and ways for evaluating their compliance with guidelines must be considered separately.

One type of waveform is the narrow-band sinusoidal burst, Fig. 2a. This consists of a series of pulses, each containing at least five or more coherent cycles of sinusoidal oscillations with very little distortion (i.e., no higher order frequency harmonics). This waveform has a peak value that may greatly exceed the root-mean-square (rms) value depending on the duty cycle which is the ratio of the "on" time to the pulse repetition period. Typical examples of sources of sinusoidal-burst fields below 100 kHz are some anti-theft devices. The ICNIRP guidelines can be applied for exposures to phase-coherent sinusoidal bursts by simply restricting the peak amplitude below a value obtained by multiplying the rms reference value valid at the carrier frequency by $\sqrt{2}$.

The second type of waveform consists of multiple sinusoidal signals where the phases or frequencies of the harmonic components vary randomly as a function of time, Fig. 2b. A prominent peak may arise at a moment

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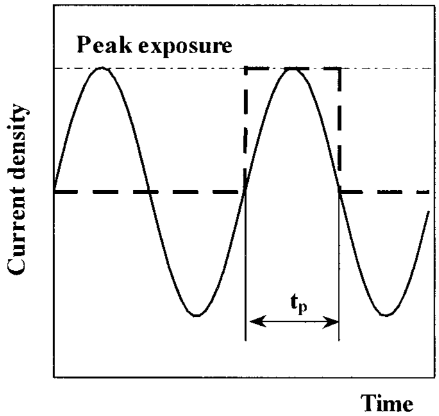

Fig. 1. Equivalent sinusoidal waveform for the determination of the peak restriction for a rectangular current density pulse.

when the amplitudes of each component are in phase, in which case the peak value is simply the arithmetic sum of component amplitudes. For this type of non-coherent waveform, the exposure assessment can be based on the summation formula given by the ICNIRP guidelines for multiple frequency fields which considers frequency components to 10 MHz with respect to possible stimulation related effects:

$$\sum_{j=1\mathrm{Hz}}^{65\mathrm{kHz}} \frac{B_j}{B_{L,j}} + \sum_{j>65\mathrm{kHz}}^{10\mathrm{MHz}} \frac{B_j}{b} \leq 1\,, \tag{1}$$

where

B_j = the magnetic flux density at frequency j;
$B_{L,j}$ = the magnetic flux density reference level; and
b = 30.7 μT (rms) for occupational exposure and 6.25 μT (rms) for general public exposure.

The third type of waveform is the non-sinusoidal, phase-coherent waveform. It consists of distorted sinusoidal cycles, Fig. 2c, or of a series of non-sinusoidal pulses. The spectrum displays significant harmonic frequency components over a broad frequency range, and the waveform may display prominent peaks where the peak value greatly exceeds the rms value.

The following guidance defines an approach that is based on the weighting of the exposure vs. frequency. The weighting function approximates the frequency dependence of the basic restrictions and reference levels (Jokela 2000).

RATIONALE AND GUIDANCE

For compliance assessment, the ICNIRP guidelines require application of the summation procedure for the various frequency components (eqn 1). This method will invariably result in conservative exposure assessments. This statement provides an alternative method for assessment based on weighted peak dB/dt that more closely recognizes the characteristics of the waveforms and nature of biological interactions. To determine the reference level, the complex frequency components of the time derivative of the magnetic flux density (dB/dt) are multiplied by a frequency-dependent and phase related complex weighting function. Above 820 Hz the magnitude of this weighting function is inversely proportional to the frequency while below 820 Hz it is constant.

One practical approach to implementing the weighting function would be to use an instrument with an appropriate low-pass filter that measures and processes dB/dt simultaneously for each of three orthogonal coils. Alternatively, compliance with the reference levels can be determined by computation, for example using Fourier analysis.

The magnetic flux density reference levels that are advised by ICNIRP can also be expressed as the time derivative of magnetic flux density dB/dt. Fig. 3 shows how the smooth curve which describes the response of the filter fairly approximates the reference levels for dB/dt. The peak reference levels were obtained by multiplying the rms values of the basic restrictions of the current density by $\sqrt{2}$. Then the current density (J) was related to the equivalent dB/dt by using the relationship

$$J = K_B \frac{dB}{dt}\,, \tag{2}$$

where the conversion factor $K_B = 0.064$ A m^{-2} s T^{-1} is in agreement with the model used by ICNIRP to derive the magnetic field reference levels from the basic restrictions. K_B is a constant proportional to the electrical conductivity of the tissue and the effective radius of the current loop (see eqn 4 in the ICNIRP guidelines). It has been assumed that the electrical conductivity is approximately constant over the frequency range in question. It should be noted that the reference levels for dB/dt are constant from very low frequencies up to a cut-off frequency f_c of 820 Hz for occupational exposure (Fig. 3). They equal 0.22 T s^{-1} and 0.044 T s^{-1} for the occupational and general public exposure, respectively. Above the cut-off frequency the reference level increases directly proportional to the frequency. The cut-off frequency specified for dB/dt is equal to the cut-off frequency for the reference levels of B (Table 6 in the ICNIRP 1998 guidelines).

For pulsed and broadband exposures compliance with reference levels can be verified by using the general multiple frequency rule

$$\sum_i (WF)_i A_i \leq 1\,, \tag{3}$$

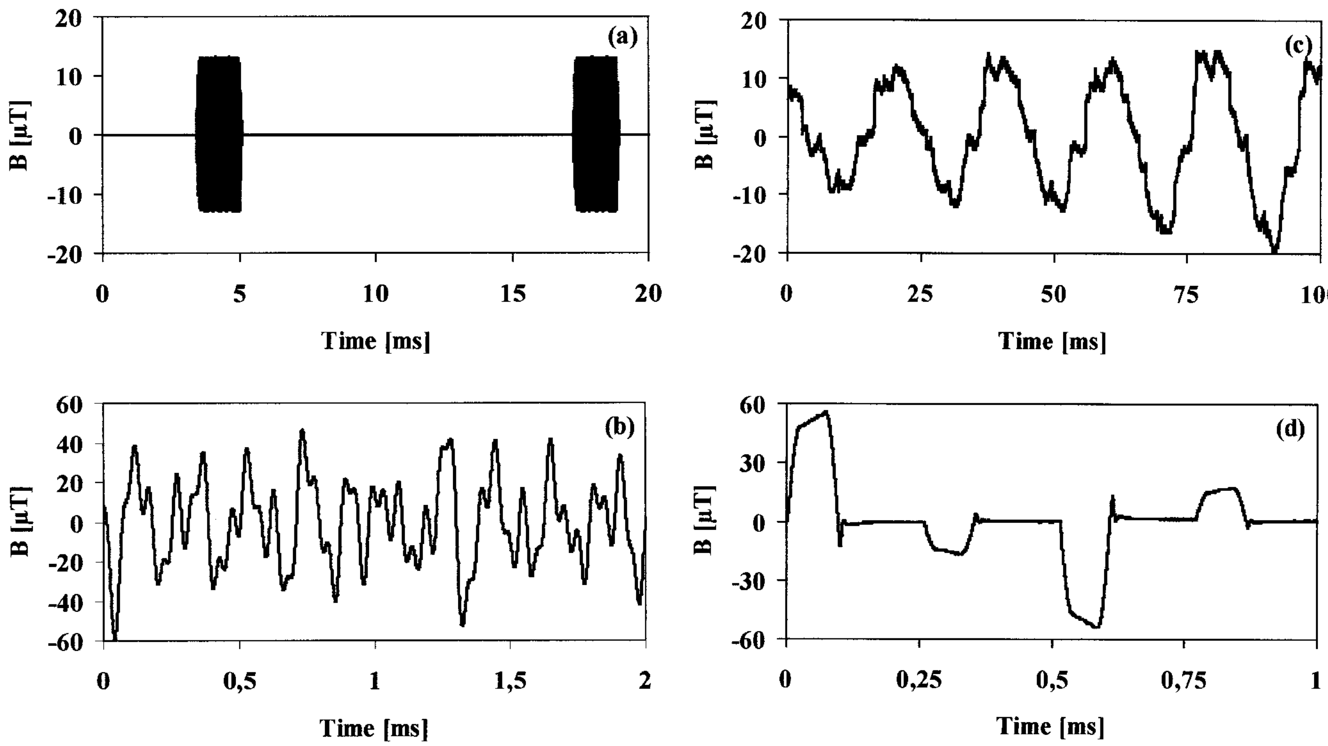

Fig. 2. Representative examples for broadband and pulsed magnetic fields. a) Burst of sinusoidal magnetic field oscillations measured inside an anti-theft gate; b) Simulated magnetic field consisting of seven non-coherent sinusoidal components; c) AC magnetic field measured in the vicinity of an industrial switched power source for high power electric motors; d) Magnetic field pulses measured inside a metal detector gate. Waveforms (a) and (c) were obtained from Jokela (2000).

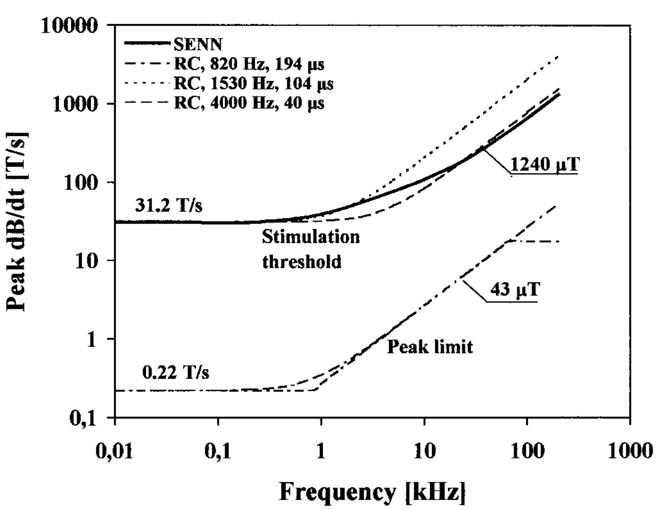

Fig. 3. Stimulation threshold and peak limit for a sinusoidal magnetic field as a function of frequency (Jokela 2000). The solid curve shows the stimulation threshold calculated with the SENN (spatially extended nonlinear nodal) model of Reilly (1998). The lower curve is the peak limit for occupational exposures.

where A_i is the amplitude of the ith frequency component for B or dB/dt and $(WF)_i$ is the weighting function where the magnitude is equal with the inverse of the peak reference level at ith frequency. The application of this rule always results in a conservative assessment of exposure.

In the case of broadband fields consisting of higher frequencies harmonic components, the limitation based on eqn (3) is too restrictive because, in general, the amplitudes are not in the same phase. To take the phases into account the eqn (3) can be replaced by

$$\left|\sum_i (WF)_i A_i \cos(2\pi f_i t + \theta_i + \varphi_i)\right| \leq 1 , \qquad (4)$$

where θ_i is the phase of the ith component of either B or dB/dt at any time t, and the phases of the weighting function should satisfy the conditions

$$\begin{aligned} \varphi(f) &= 0 \qquad f < f_c \\ \varphi(f) &= -\frac{\pi}{2} \quad f > f_c \end{aligned} \qquad (5)$$

for dB/dt, and

$$\begin{aligned} \varphi(f) &= \frac{\pi}{2} \qquad f < f_c \\ \varphi(f) &= 0 \qquad f > f_c \end{aligned} \qquad (6)$$

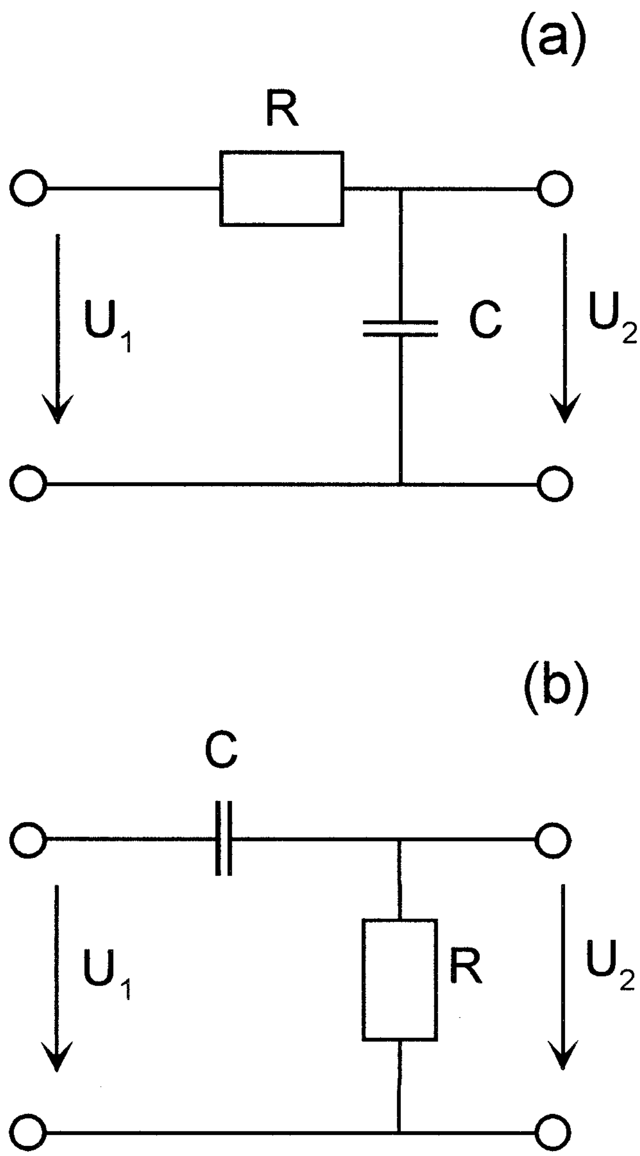

Fig. 4. Simple RC circuits for the weighting of dB/dt (a) and *B* (b).

for *B*. These conditions ensure that at low frequencies the waveform of the induced current density follows the instantaneous value of dB/dt (unweighted) while at high frequencies it follows the instantaneous value of *B* (time integral of dB/dt).

This procedure may be approximated by filtering the dB/dt signal with a low-pass filter, which processes the measured dB/dt signal. For slowly-varying fields with the rise or decay time $t_r >> 1/(2\pi f_c)$, the dB/dt are not changed. For magnetic field transients, with the rise or decay time $t_r \ll 1/(2\pi f_c)$, the filter behaves as an integrator that converts the dB/dt signal to a signal that is directly proportional to the magnitude of time-varying magnetic flux density (*B*). It should be noted that this procedure is valid for a certain frequency range. When applied to check the compliance with reference levels of the ICNIRP guidelines, this range is from 8 Hz to 100 kHz for the general public and from 8 Hz to 65 kHz for occupational exposure.

The low pass filter can be approximated with a simple resistor (R) and capacitor (C) circuit (Fig. 4a) where the time constant RC = 194 μs. In this case its response follows the smooth curve shown in Fig. 3. For a narrow-band exposure near the cut-off frequency, the RC weighting allows a slightly higher exposure by up to 3 dB more than indicated by the guidelines. From the standpoint of health and safety this approach is appropriate since the guidelines themselves are conservatively derived. An equivalent approach is to filter the B-field instead of dB/dt and to replace the low-pass filter with the high-pass filter shown in Fig. 4b. The proposed low-pass filter response is based on the electrophysiological model of a myelinated nerve cell (Reilly 1989, 1998). Below the stimulation threshold the model consists of a RC ladder network where the pulse response of the induced transmembrane voltage approximately follows the time course of the capacitor voltage in Fig. 4a (Jokela 1997). This is the reason why the phase of the weighting function should approximate the phase dependency of the simple RC circuit.

When the induced transmembrane voltage approaches the stimulation level the membrane becomes non-linear, but the stimulation threshold calculations indicate that the threshold function (solid curve in Fig. 3) can still be approximated with simple RC type functions (dash curve) although the effective time constant and cut-off frequency are not fully compatible for different waveforms (Jokela 2000). This is revealed by the shift of the dotted curve towards lower frequencies. The dotted curve depicts the threshold for single monophasic pulses converted to the frequency scale. At high frequencies the stimulation threshold for a monophasic pulse is higher by

Table 1. Guidance values for non-sinusoidal fields expressed as a weighted peak value and corresponding cut-off frequencies.

	J (mA/m^2)	f_c (Hz)	*E* (V/m)	f_c (Hz)	*B* (μT)	f_c (Hz)
General public	$\sqrt{2} \times 2$	1,000	$\sqrt{2} \times 87$	3,000	$\sqrt{2} \times 6.25$	800
Occupational	$\sqrt{2} \times 10$	1,000	$\sqrt{2} \times 610$	820	$\sqrt{2} \times 30.7$	820

a factor of 2.6 than the threshold for a long burst of high-frequency sinusoidal oscillations.

Comparison of the peak limit curve with the stimulation threshold curve indicates that at low frequencies there is a reduction factor of approximately 5, which is due to the lower cut-off frequency of the peak limit (820 Hz) compared with the cut-off frequency for the stimulation threshold (4,000 Hz). This takes into account the relatively well established sub-threshold electric field effects on nerve cells, such as magnetophosphenes and other synaptic effects (ICNIRP 1998a, b).

Although the peak restriction method presented above was discussed in terms of dB/dt, it is directly applicable to the basic restriction for the induced current density J and electric field strength E. The guidance values and cut-off frequencies f_c related to J, E, and B for both members of the public and those occupationally exposed are listed in Table 1. Additionally, the method can easily be extended to the exposure to electric fields because the coupling equation that relates the external electric field to induced J is similar than that from magnetic flux density B to J. For example, for occupational exposure replace the $\sqrt{2} \times 30.7\ \mu T$ (43 μT) peak level by $\sqrt{2} \times 610\ V\ m^{-1}$ and use the low-pass filter with the cut-off frequency of 820 Hz.

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