Review Paper

THE WEIGHTED PEAK METHOD IN THE TIME DOMAIN COMPARED WITH ALTERNATIVE METHODS FOR ASSESSING LF ELECTRIC AND MAGNETIC FIELDS

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Abstract—**Directive 2013/35/EU of the European Parliament and Council recommends the weighted peak method for assessing non-thermal effects of low frequency (LF) electric and magnetic fields. This article shows that this method is very practical and user friendly and is absolutely reliable to lead to correct results when applied in the time domain. The method can be used without limitations for any field profile and emulates the underlying physical and biological effects significantly better than all other presently known methods. For this reason, this method is described and recommended in many technical standards for assessing the non-thermal effects of electromagnetic fields and is recognized by the international scientific community. The disadvantages of competing methods are demonstrated. Some technical aspects of real measurement systems are also examined.**

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INTRODUCTION

FREQUENCY-DEPENDENT reference levels $R(f)$ are used to specify the permitted exposure of persons to external electromagnetic fields. In Directive 2013/35/EU of the European Parliament and Council, these reference levels are called Action Levels. The reference levels specify the maximum permissible RMS (root of mean of squares) value for time stationary and sinusoidal-shaped field quantities at each frequency. They thus can only be directly applied to fields that comprise a single spectral component. Other shapes or pulsed fields, therefore, cannot be directly compared with the reference levels, so an unambiguous assessment method to handle any field characteristic is needed.

The weighted peak method (WPM) with filtering in the time domain is recommended in Directive 2013/35/EU as the reference assessment method for non-thermal effects in the frequency range from 1 Hz to 10 MHz. Other methods can also be used if they are scientifically proven and validated, provided that they lead to approximately equivalent and comparable results.

WPM is a special case of the shaped time domain method (STD). Measuring instruments with STD has been commercially available since the year 2000. WPM was described by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in a statement (ICNIRP 2003) and in the Guidelines of 2010 (ICNIRP 2010) and recommended as the reference method. WPM is also described in many technical standards on human safety in electromagnetic fields, such as IEC 62311 (IEC 2007) and IEC 61786-2 (IEC 2014), and it is recommended as the reference method and recognized by the international scientific community.

WEIGHTED PEAK METHOD

Brief description of WPM

For WPM, the field quantity $g(t)$ to be assessed is first passed through a weighting filter, which has a complex transfer function $W(f)$. The magnitude of this transfer function approximates the reciprocal of $\sqrt{2} \times R(f)$. A weighted time signal $s(t)$ is available at the output of the weighting filter.

The weighting filter convolves the field quantity $g(t)$ with an impulse response $w(t)$, where $w(t)$ is the inverse Fourier transform of $W(f)$:

$$w(t) \rightarrow W(f). \tag{1}$$

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There are two ways to calculate $s(t)$:

Directly, in the time domain:

$$s(t) = g(t) * w(t). \tag{2}$$

Indirectly, via the frequency domain:

$$G(f) \leftarrow g(t) \tag{3}$$

$$S(f) = G(f) \times W(f) \tag{4}$$

$$s(t) \rightarrow S(f) \;. \tag{5}$$

The first method performs the convolution (*) directly in the time domain. The second method initially determines the spectrum $G(f)$ of $g(t)$ by applying the Fourier transformation. Weighting then takes place in the frequency domain by multiplication with $W(f)$. Finally, $S(f)$ is transformed back into the time domain. This method is also known as fast convolution.

Both methods are identical if the same complex transfer function $W(f)$ is used. However, in known commercially available measuring equipment, WPM is performed directly in the time domain. The peculiarities that need to be taken into account when applying WPM in the frequency domain are therefore not discussed until later in this article.

The peak value of the weighted time signal $s(t)$ is determined in a second step. This peak value is a measure of the exposure and is designated as the exposure index EI (European Commission 2015):

$$EI = \max(|s(t)|). \tag{6}$$

Values of less than unity are permissible. Values greater than unity are initially no longer permissible without further in-depth investigation.

In practice, WPM is realized in the time domain as a real-time system; i.e., EI is calculated continuously from $g(t)$. The maximum hold function can be reset before the measurement to exclude older results. It is difficult to imagine an easier way of measuring the exposure index.

Of course, $g(t)$ can be recorded first and EI calculated later. This is, however, clearly more complicated and time consuming.

Definition of transfer function $W(f)$

The reference levels $R(f)$ are generally stated as magnitudes in the form of a table. The frequency range is divided into segments for which eqn (7) is valid:

$$R(f) = R_i \times \left(\frac{f}{f_i}\right)^{c_i} \;. \tag{7}$$

When displayed in log-log graphs, this gives piecewise linear reference-level curves. In the frequency range relevant to WPM, c_i has one of the values 0, −1, or −2. Thus, only straight lines with gradients of 0 dB per decade, −20 dB per decade or −40 dB per decade occur.

The reference levels for non-thermal effects always emulate at least the following two major effects:

1. Induction mechanism; and
2. Lapicque's law.

The electric field strength $e(t)$ within the body determines the stimulation effect. The induction mechanism described in eqn (8) shows that the internal electric field strength is proportional to the time derivative of the external electric field or magnetic field:

$$e(t) = k \times \frac{\mathrm{d}g(t)}{\mathrm{d}t} \;. \tag{8}$$

The parameter k in eqn (8) represents a coupling factor. Eqn (9) describes the induction mechanism in the frequency domain:

$$E(f) = \mathrm{j}\omega \times k \times G(f) \;. \tag{9}$$

The quantity ω is equal to $2\pi \times f$ and is used frequently in this article to improve legibility.

If rectangular direct current (DC) impulses are used as an internal electrical field strength stimulus, a stimulation effect does not occur until the amplitude of the internal field strength exceeds the threshold value e_T. This threshold value is around e_0 for impulses with a length $T_{impulse}$ significantly larger than the time constant τ_e. The time constant τ_e is a measure of the inertia of the cell types under investigation and is of the order of 100 μs. The threshold increases reciprocal to the impulse length for impulses significantly shorter than the time constant:

$$e_T = e_0 \times \left(1 + \frac{\tau_e}{T_{impulse}}\right). \tag{10}$$

Eqn (10) was devised by Weiss (1901) for stimulatory currents. Here, it has merely been reformulated for the internal field strength. Lapicque described the same circumstances more accurately in his work (Lapicque 1907) with eqn (11), which is also called Lapicque's law:

$$e_T = \frac{e_0}{1 - \mathrm{e}^{\frac{-T_{impulse}}{\tau_e}}} \;. \tag{11}$$

A first order low pass filter with time constant τ_e has a cut-off frequency f_e:

$$f_e = \frac{1}{2\pi \times \tau_e} \;. \tag{12}$$

Its transfer function $H(f)$ is described in eqn (13):

$$H(f) = \frac{1}{1 + \mathrm{j}\omega \times \tau_e} \ . \tag{13}$$

A low pass filter of this type reduces the peak value of rectangular DC impulses by a factor of e_0/e_T precisely, thus exactly emulating Lapicque's law.

Lapicque's law very closely describes the stimulation effect of rectangular monophasic DC impulses. Biphasic impulses, particularly if they are not repeated, are somewhat overestimated by Lapicque's law and hence also by a simple linear low pass filter. With the exception of this potential overestimation, it is possible to specify a very simple and exact model for the relationship between the external field quantity $g(t)$ and the stimulation effect.

The external field is differentiated and multiplied by a coupling factor k. The signal then passes through a first order low pass filter with time constant τ_e. The filtered signal is normalized to e_0. A stimulation effect occurs when the peak value of this normalized signal is greater than unity.

This simple model can thus be described by a weighting filter with transfer function $W(f)$ and a subsequent peak value detector, where:

$$W(f) = \frac{k}{e_0 \times \tau_e} \times \frac{\mathrm{j}\omega \times \tau_e}{1 + \mathrm{j}\omega \times \tau_e} \ . \tag{14}$$

So, $W(f)$ exactly describes a simple first order high-pass filter.

The magnitude of the associated reference level curve, given as the RMS value of a time stationary sinusoidal field quantity, is therefore:

$$|R'(f)| = \frac{e_0 \times \tau_e}{k \times \sqrt{2}} \times \frac{\sqrt{1 + (\omega \times \tau_e)^2}}{\omega \times \tau_e} \ . \tag{15}$$

The three parameters k, e_0, and τ_e are usually selected such that a stimulation effect can definitely be excluded. The magnitudes of the safety factors applied to the scientifically documented coupling factors, time constants, and stimulation thresholds greatly depend on the particular purpose of the reference curve. Thus, reference curves applicable to protect the general public will contain higher safety factors than those applicable to protect employees at their working places.

The reference levels for magnetic flux density, called High Action Levels (High ALs) and Action Levels for exposure of limbs in localized fields (Limbs ALs), in Directive 2013/35/EU actually do have the form described by eqn (15). The assumed time constant τ_e is 53.05 μs, as the cutoff frequency f_e of 3 kHz indicates. At higher frequencies, the reference level is at 100 μT or 300 μT, while at lower frequencies, it increases reciprocal to the frequency. If the value of 1.1 V m^{-1} from Table A2 of Directive 2013/35/EU is used as the stimulation threshold e_0, the coupling factors have the values 0.413 m and 0.138 m. The smaller coupling factor applies to the limbs. A value one-third that of the torso is apparently applied as the geometric dimensions of the limbs.

However, the expected smooth transition around 3 kHz is not reproduced by the piecewise linear reference levels quoted in Table B2 of Directive 2013/35/EU. Due to the tabular form, this transition is abrupt and not smooth as indicated by Lapicque's law.

Because the piecewise linear curves just describe the asymptotes of the magnitude response of the original first order filter, they can, of course, be replaced by the magnitude response of the original filter again. This is also possible when the original filter is unknown and only the piecewise linear reference levels are available. The reference level $R(f)$ at frequencies above 3 kHz should be used in eqns (16) and (17) as R_L in order to obtain an optimal approximation of $R(f)$ by $R'(f)$:

$$|R'(f)| = R_L \times \sqrt{\frac{1 + \left(\frac{f}{3\,\mathrm{kHz}}\right)^2}{\left(\frac{f}{3\,\mathrm{kHz}}\right)^2}} \cong R(f) \tag{16}$$

$$R'(f) = R_L \times \frac{1 + \mathrm{j}\frac{f}{3\,\mathrm{kHz}}}{\mathrm{j}\frac{f}{3\,\mathrm{kHz}}} \ . \tag{17}$$

The magnitude of $R'(f)$ is equal to $R(f)$ for very high and very low frequencies. Close to 3 kHz, the approximated reference level curve is smoother compared to the angular curve of $R(f)$ and is higher by 3.01 dB at 3 kHz.

The phase of $R'(f)$ is governed by the slope of the magnitude because this is a transfer function of a minimum phase system. The phase of $R'(f)$ is therefore −90° at low frequencies and 0° at high frequencies. The characteristic is also smooth around 3 kHz and has a value of −45° at 3 kHz.

The weighting filter $W(f)$ must have the inverse frequency response of $\sqrt{2} \cdot R'(f)$ and is therefore given by:

$$W(f) = \frac{1}{\sqrt{2} \times R'(f)} = \frac{1}{\sqrt{2} \times R_L} \times \frac{\mathrm{j}\frac{f}{3\,\mathrm{kHz}}}{1 + \mathrm{j}\frac{f}{3\,\mathrm{kHz}}} \ . \tag{18}$$

This again is precisely the transfer function of the familiar first order high pass filter of eqn (14), which emulates the induction mechanism and Lapicque's law.

The reference levels for magnetic flux density designated as Low Action Levels (Low ALs) in Directive 2013/35/EU basically correspond to the values for High ALs. However, they are 12 times lower in the frequency range from 8 Hz to 25 Hz. This is due to the fact that the central nervous system in the head reacts more sensitively to stimuli in this frequency range than in other frequency ranges. The following filter made up from a cascade of first order filters is a very good approximation for the reference levels of the Low ALs for magnetic flux density:

$$R'(f) = 100\ \mu T \times \frac{1 + j\frac{f}{3\,\mathrm{kHz}}}{j\frac{f}{3\,\mathrm{kHz}}} \times \frac{1}{12} \times \frac{1 + j\frac{f}{25\,\mathrm{Hz}}}{1 + j\frac{f}{300\,\mathrm{Hz}}} \times \frac{1 + j\frac{f}{8\,\mathrm{Hz}}}{j\frac{f}{8\,\mathrm{Hz}}}\ . \quad (19)$$

The associated weighting filter has the following transfer function:

$$W(f) = \frac{1}{\sqrt{2} \times 100\ \mu T} \times \frac{j\frac{f}{3\,\mathrm{kHz}}}{1 + j\frac{f}{3\,\mathrm{kHz}}} \times 12 \times \frac{1 + j\frac{f}{300\,\mathrm{Hz}}}{1 + j\frac{f}{25\,\mathrm{Hz}}} \times \frac{j\frac{f}{8\,\mathrm{Hz}}}{1 + j\frac{f}{8\,\mathrm{Hz}}}\ . \quad (20)$$

Also this filter is easily realized. It consists of a cascade of two first-order high-pass filters and a simple "bass boost" circuit. If realized in analog form, it can be formed from a network consisting only of resistors and capacitors. Such filters are also called RC filters. If it is to be realized digitally, it is sensible to build it as a cascade of first order IIR filters. The filter coefficients can be derived from the cutoff frequencies of the analog filters with the aid of the bilinear transformation. The sampling frequency of the digital filter must be chosen much higher than 3 kHz, however, so that the analog high pass filter with 3 kHz cutoff frequency can be approximated without any significant deviations.

Fig. 1 shows the piecewise linear reference levels of Directive 2013/35/EU for magnetic flux density and the approximated reference levels achieved by means of first-order filter elements. The maximum deviations occur at the straight-line intercepts, and their values range from -2.93 dB to +3.43 dB. These deviations should not be considered as errors or deficiencies. Quite the contrary is the case, because the fundamental physical and biological effects are actually much more exactly emulated by first-order filter elements. The artifacts that occur when attempts are made to approximate the sharp edges of the piecewise linear reference curves as closely as possible with $R'(f)$ are described later in this paper.

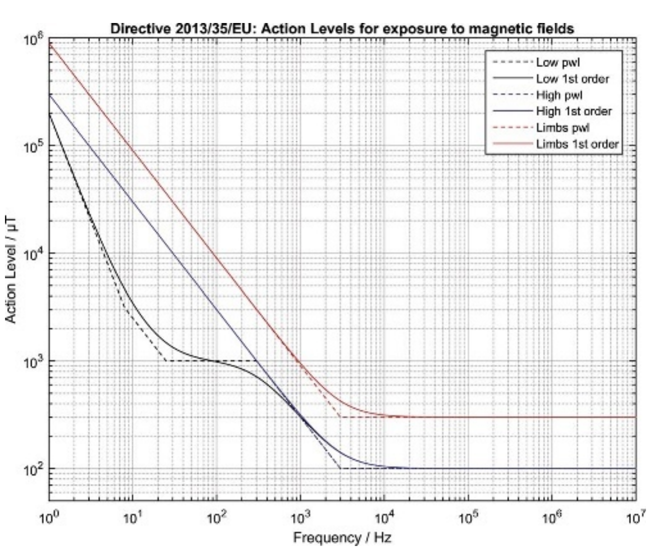

Fig. 1. Directive 2013/35/EU reference levels for the magnetic flux density. The acronym pwl stands for piecewise linear.

WPM using isotropic probes

So far, WPM has only been described for one field component. Initially, then, the method can only be used with a single axis field probe. This field probe must be carefully aligned for the maximum exposure index *EI* according to the polarization and angle of incidence of the field if an underestimation of the exposure situation is to be avoided. This alignment is time consuming and can be done accurately and clearly only if the exposure situation remains stable over a sufficiently long time period.

Isotropic field probes are used in practice to avoid the need for aligning the probe. Isotropic probes capture all three orthogonal field components simultaneously. Three time signals $g_x(t)$, $g_y(t)$, and $g_z(t)$ of the three orthogonal field components are thus initially available.

The isotropic variant of WPM is then calculated as follows:

$$s_x(t) = g_x(t) * w(t) \quad (21)$$

$$s_y(t) = g_y(t) * w(t) \quad (22)$$

$$s_z(t) = g_z(t) * w(t) \quad (23)$$

$$EI = \max\left(\sqrt{s_x^2(t) + s_y^2(t) + s_z^2(t)}\right). \quad (24)$$

In other words, the magnitude of $s(t)$ in the single axis version is replaced by the RSS value (root of the sum of squares) of the three weighted time signals, derived from the three time signals of the three orthogonal field components.

Alternatively, the exposure index could be determined separately for the three individual components and the RSS value from these three partial results considered as the overall result. This could, however, result in an overestimation if several field sources are present because the maximum values could occur at different points in time such that the RSS value of the maximum values may never actually be reached at any given time. This alternative should therefore be avoided and can only be used if a potential overestimation of the exposure index up to a factor of $\sqrt{3}$ is taken into account.

PITFALLS OF WPM IN THE FREQUENCY DOMAIN

Alternative transfer functions *W*(*f*) for WPM in the frequency domain

As already mentioned, WPM fundamentally delivers the same results in the time domain and the frequency domain as long as exactly the same complex transfer function $W(f)$ is used.

However, WPM is also used in the frequency domain with a $W(f)$ that closely approximates the sharp edges of the piecewise linear reference curves using very high order filters. Thus, the usual $W(f)$ that emulates the underlying physical and biological effects accurately, and can be realized using first order filter elements, is not always used.

If the magnitude of $W(f)$ exactly emulates the sharp edges of $R(f)$, there are three obvious variants to configure the phase of $W(f)$:

1. A minimum phase system is assumed. The phase can therefore be calculated from the magnitude: The phase response of a minimum phase system is known to be equal to the imaginary part of the Hilbert transform of the natural logarithm of the magnitude response;
2. The phase is selected as follows and depending on the slope: 0° for 0 dB decade^{-1}, 90° for 20 dB decade^{-1}, and 180° for 40 dB decade^{-1}. This phase characteristic is often recommended for the WPM in the frequency domain (ICNIRP 2003; ICNIRP 2010; European Commission 2015); and
3. The phase is 0° for all frequencies.

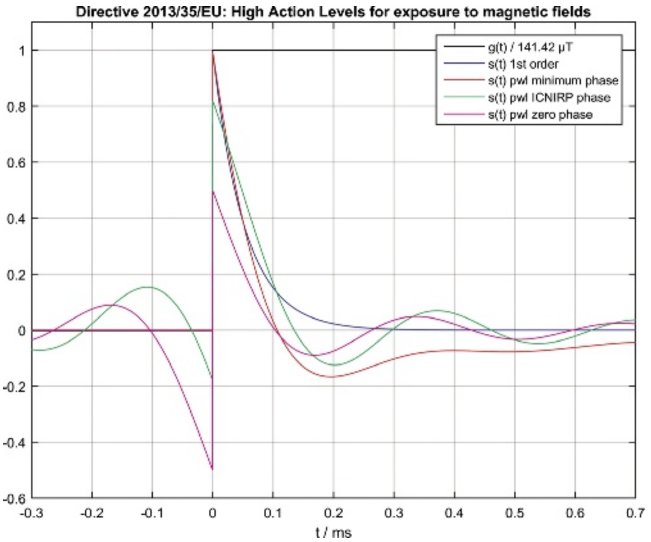

Fig. 2. Responses to a 141.42 μT step of a first order weighting filter and a piecewise linear (pwl) weighting filter with minimum, ICNIRP recommended and zero phase.

For a start, all three variants of the filter would have to be of infinitely high order and are therefore unrealizable as such. For this reason alone, the piecewise linear reference level curves cannot be a good description of any system occurring in the real world.

The transfer function of WPM in the frequency domain is realized by fast convolution. For this reason, very high order FIR filters can be realized at acceptable cost, so that filters with sharp edges can at least be very closely approximated.

The step responses of such weighting filters and the weighting filter made up from first order filter elements are shown in Fig. 2. A DC magnetic field of 141.42 μT is instantly applied at time zero and convolved with the impulse response of the weighting filter for High ALs.

The first order high-pass filter responds as expected, with $s(t)$ abruptly rising to the value of 1 and then decaying exponentially with a time constant of 53.05 μs.

The filter that emulates the piecewise linear reference level curve as closely as possible and shows minimum phase also has a causal step response. It is also still identical to the first order high pass filter at the start but shows strong oscillations and decays much more slowly. If another step occurred after the first one shown, these strong oscillations and the slower decay would lead to large over- or underestimations depending on the point in time and the sign of the second field step.

The filter with the phase response suggested by ICNIRP has a step response that is no longer causal. It actually already reacts before the stimulating step occurs. This is possible because for WPM in the frequency domain, the signal $g(t)$ is present and has already been stored before the fast convolution is performed. The simple reason for this is that the fast convolution cannot be calculated until $g(t)$ has already been stored. There is a noticeable sustained oscillation at a frequency of approximately 3 kHz, which slowly rises and falls in amplitude and which has maximum amplitude but negative sign at about the same time as the step occurs. The maximum value of $s(t)$ is only 0.82. The signal is therefore underestimated when compared to the first order high-pass filter realization. Here, too, any further changes in the field value would be strongly falsified by the sustained oscillation of the step response shown. This would result in additional large over- or underestimations depending on the point in time and sign of the field changes.

Looking now at the step response of the piecewise linear filter with constant zero phase, the situation is similar to the piecewise linear filter with phase as specified by ICNIRP. However, the artifacts here are even more pronounced, leading to an even larger underestimation by a factor of 0.5.

Emulation of the sharp edges of $R(f)$ should not therefore be pursued because artifacts occur that lead to erroneous estimation of the exposure index.

Piecewise linear reference level curves can certainly be simply stated in the form of a table, but they only roughly approximate the frequency responses of the underlying physical and biological effects. They cause artifacts that lead to incorrect assessment results. In contrast, filters that can be formed from a cascade of first order filter elements emulate the underlying effects much more realistically. For this reason, the $W(f)$ based on first order filter elements should always be used, even for WPM in the frequency domain.

Impact of the transformed time frame on WPM in the frequency domain

The fast convolution on which WPM in the frequency domain is based is performed in practice with the aid of discrete Fourier transformation (DFT) rather than Fourier transformation. The time signal $g(t)$ is not transformed over the maximum possible time span from minus to plus infinity; instead, a limited time frame of length T is transformed. The result of fast convolution using DFT is the same as if the selected frame of the time signal $g(t)$ were repeated with a period duration of T and a true convolution with $w(t)$ were to take place. The condition for this to be true and for DFT to be applicable to WPM is that the length T_w of the impulse response $w(t)$ is less than T; otherwise, $w(t)$ cannot be reproduced without errors.

If $W(f)$ can be described by first order filter elements, the filter with the lowest pole frequency largely determines the length of the impulse response. Thus, the relevant time constant for the High ALs and the Limbs ALs is 53.05 μs, and 19.89 ms for the Low ALs. The impulse response of the corresponding filter element has hardly any effect on the result of a convolution after a time duration that is approximately five times greater than the time constant. The effective length of the impulse response can thus be described very well by a T_w that is in the order of five times the time constant. If piecewise linear filters are used instead, the effective length of the impulse responses is significantly longer, and a value of 100 times the time constant must be reckoned with.

DFT is also based on a sampled time signal rather than a continuous time signal. The effects of sampling apply to all assessment methods though, because nowadays all measurement systems work with values sampled at discrete times. These effects are therefore discussed later after the various assessment methods have been presented.

The finite transformation length T of the DFT can lead to incorrect assessments in practice. Nevertheless, the following two exceptions are without problems:

1. The time signal $g(t)$ is itself periodic with a period duration T_g and T is an integer multiple of T_g; and
2. The time signal $g(t)$ is equal to 0 outside the period T. It is also equal to 0 inside the selected frame at the start and end for a total time period of T_o, and T_o is greater than or equal to T_w.

Situation (2) often occurs when assessing pulsed signals such as those encountered with welding equipment.

All other cases are potentially problematic. In these cases, it is usually possible to achieve correct results if $g(t)$ is multiplied by a window function $u(t)$ before DFT is performed. No appreciable errors occur if all three of the following conditions are concurrently met:

1. $u(t)$ meets the requirement for $g(t)$ given in situation (2) above;
2. $u(t)$ is equal to 1 generously around the areas of $g(t)$ that lead to the maximum EI; and
3. The transitions between 0 and 1 in $u(t)$ should but don't need to be smooth.

The problem here is that the areas of $g(t)$ that lead to the maximum EI are often not readily identifiable.

One way to overcome all the problems associated with the selection of a proper time frame and window function is to perform the WPM in the frequency domain with the aid of a real-time fast convolution technique. To do so, the transformation length T is selected to be equal or greater than $T_w + \Delta T$. After each time interval ΔT, a DFT, a weighting in the frequency domain, and an inverse DFT is performed, and only the last portion of $s(t)$ with a length ΔT is used as a result for each time interval. All the segments of $s(t)$ obtained this way are then concatenated to form the complete weighted time domain signal. This approach is not yet implemented in solutions that realize the WPM in the frequency domain, but it is the only known method that can guarantee to obtain exactly the same results as with the WPM in the time domain for any kind of signal.

The "3 % rule" applied to WPM in the frequency domain

Some users also apply a so-called 3% rule for $G(f)$ or $S(f)$ with WPM in the frequency domain. This rule came up to counteract overestimations that could occur when the original summation formula of the ICNIRP Guidelines was used for multiple-frequency fields. In this formula, the amplitudes of all spectral lines are divided by $\sqrt{2} \times R(f)$ at the associated frequencies, after which these weighted amplitudes are added together. If the result is less than unity, the exposure may be considered to be permissible. Because the phase of the spectral components is not taken into account in this simple approach and the worst case (with a phase of 0 for all components) is assumed, this often leads to a clear overestimation of exposure but never to an underestimation. The 3% rule states that components having an amplitude less than 3% of the amplitude of the strongest component may be ignored in the assessment. If the 3% rule is applied to the weighted components or, even worse, to the original spectral components, there will be a tendency toward lower results, with extreme underestimations not only possible but even likely. Despite this, a significant overestimation cannot be excluded either. Thus the 3% rule, when applied to the simple summation formula, does not solve the problem of the likely overestimation but introduces a new problem of a likely and potentially huge underestimation.

Application of the 3 % rule to $S(f)$ or, even worse, to $G(f)$ of WPM is not indicated for two more reasons:

1. The phase is taken into account in WPM, so an overestimation cannot occur; and
2. Application of the 3% rule to WPM does not necessarily lead to a tendency towards a lower estimation as originally desired for pragmatic reasons. The sign of the incorrect estimation that occurs actually depends here strongly on the phase values of the neglected spectral components.

Application of the 3% rule to WPM in the frequency domain leads to potentially huge and unnecessary assessment errors in both directions and must be strictly avoided.

Summary of WPM in the frequency domain

WPM in the frequency domain produces the same correct results as WPM in the time domain if the following three conditions are met concurrently:

1. The same $W(f)$ is used;
2. An adequate time frame with a suitable window function is used; and
3. The 3% rule is not applied.

Unfortunately, these three conditions are not always met in practice. In particular, meeting the second condition requires a sound understanding of system theory. This specialized knowledge is not possessed by all users, however. A real-time fast convolution based implementation that would fulfill the second condition by design is not available on the market yet.

ALTERNATIVE ASSESSMENT METHODS

Weighted RMS method

The weighted RMS method (WRM) is very similar to WPM. It also can be performed in the time domain or indirectly via the frequency domain, although Parseval's theorem means that transformation back into the time domain is unnecessary here. The RMS value of $s(t)$ is used as the exposure index EI instead of the peak value. The RMS integration time is usually 1 s. The WRM was introduced for the assessment of domestic equipment for practical reasons in IEC 62233 (IEC 2005). It delivers an underestimation of the exposure compared with WPM. However, there is no justification for this underestimation based on physical or biological grounds.

BGV B11 method

An evaluation method that operates like WPM in the time domain is described in BGV B11 (Berufsgenossenschaft der Feinmechanik and Elektrotechnik 2001). A revised form of this method is now described in the non-binding guide to good practice for implementing Directive 2013/35/EU (European Commission 2015). This method, compared with BGV B11, has been adapted to the Action Levels of Directive 2015/35/EU, and the factor V_{max} now has the value 2.6 instead of 8. This revised method of the German Social Accident Insurance (DGUV) is referred to as BGM in this article.

BGM is described for exactly four different shaped curve segments:

1. One complete cycle of a sinusoidal signal;
2. One complete cycle of a triangular signal;
3. Field change of the form $1-e^{\frac{-t}{\tau}}$; and
4. DC pulse with linear rise and linear fall.

If $g(t)$ actually consists only of segments that correspond exactly to these four curve forms, BGM can be used. In all other cases, BGM is not defined and can therefore cannot be used without unavoidably vulnerable assumptions and interpretations made by the user. Nevertheless, the BGV B11 method has been applied to different signals too. In an information brochure (Berufsgenossenschaft der Feinmechanik and Elektrotechnik 2006), the German Social Accident Insurance encouraged users to do so, but it did not give any advice as to how to generalize this method for arbitrary signals. However, the application of the method to three examples of more realistic signals has been demonstrated there.

Because BGM is based on only one time signal, it cannot always be applied using isotropic probes. If only one linearly polarized field source is present, there is only one principal component $g(t)$ contained in $g_x(t)$, $g_y(t)$, and $g_z(t)$. This principal component can be extracted with the aid of eigendecomposition of the covariance matrix of the three probe signals. The eigenvector with the highest eigenvalue indicates the direction of an optimally aligned single axis probe. So, the principal component can be expressed as a suitable linear combination of the three probe signals. Where there are several field sources with different polarizations, however, all three eigenvalues will have significant values, and the reduction to only one component can thus lead to a significant underestimation. Thus, BGM can only be used in such cases if a significant underestimation is taken into account.

BGM with V_{max} equal to unity

Within its range of definition, BGM delivers results similar to WPM in the time domain, presupposing that the V_{max} parameter in BGM is set equal to unity. This is demonstrated here for all four BGM curve forms and using the example of the High ALs reference level curve. BGM converts the piecewise linear reference levels for magnetic flux density into similarly piecewise linear reference levels for the time derivative of the magnetic flux density. For this reason, the known differences between the angular and smooth transitions in the reference level curves in the vicinity of 3 kHz can be expected to have an effect. To eliminate this effect initially, the frequency f_p of the field quantity change is investigated in two regions:

1. f_p is much smaller than 3 kHz (low frequencies); and
2. f_p is much greater than 3 kHz (high frequencies).

In the following, the results of WPM in the time domain are assumed to be the correct assessment results:

1. BGM gives correct results for sinusoidal signal segments;
2. BGM gives an overestimation by a factor π/2 for triangular signal segments at low frequencies. The assessment is correct at high frequencies;
3. BGM gives a correct assessment for signal segments with a field change of the form $1-e^{\frac{-t}{\tau}}$; and
4. BGM gives an overestimation by a factor of π/2 at low frequencies for DC pulses with linear rise and linear fall. The assessment is correct at high frequencies.

The overestimation at low frequencies for triangular segments or pulses with linear rise and linear fall is due to the fact that the BGM reference levels for the average slope of the signal are unnecessarily only 2/π times the reference levels for the maximum slope of the signal. This is only justifiable above 3 kHz because it is only in this frequency range that the averaging effect described by Lapicque's law occurs. An averaging time in the range of 50 μs is irrelevant for very slow field quantity changes. So at low frequencies, it is sufficient and necessary to limit the maximum value of the slope only. These relationships are already described correctly in the literature (Rueckerl and Eichhorn 2011).

At medium frequencies (i.e., where f_p is of the order of 3 kHz), BGM leads to further overestimations because it does not use the smooth transitions in the reference level curves of WPM in the time domain. The maximum overestimation for sinusoidal signals is by a factor of $\sqrt{2}$ and occurs precisely at a frequency of 3 kHz. The maximum value of the overestimation could be calculated numerically for the other three curve shapes. Suffice it to say at this point that it may be considered to be definitely not negligible.

With V_{max} equal to 1, BGM represents an alternative to WPM in the time domain for its four selected curve shapes. This alternative can lead to an overestimation by a factor of π/2 though. It is intricately worded and can only be used by experts who have studied it in detail. It cannot be applied outside its limited scope of definition anyway without unavoidably vulnerable assumptions and interpretations made by the users.

BGM with V_{max} greater than unity

Originally the BGM was published without the parameter V_{max} (Boerner et al. 2011) with the same effect as V_{max} equal to unity, as V would then also always equal unity and thus have no effect. For no apparent reason, a V_{max} equal to 2.6 was again introduced in the non-binding guide to good practice for implementing Directive 2013/35/EU (European Commission 2015). The effect of this parameter, therefore, also needs to be discussed.

Parameter V_{max} in BGM has the same effect as increasing the reference levels by a factor of V_{max}. To start with, this corresponds to an underestimation by the reciprocal of V_{max}.

However, this is only true if there are significant pauses between the signal segments where field quantity changes are present. Let T_i be the duration of the field quantity changes plus the duration of the subsequent pause. In cases where T_i is greater than 1 s, T_i is set equal to 1 s. Let τ_D be the total duration of the field changes. Now, for BGM:

$$V = \min\left(\sqrt{\frac{T_i}{\tau_D}}, V_{max}\right). \tag{25}$$

This means that the reference levels actually are only increased by the factor V. This factor lies between unity and V_{max} and depends on the crest factor of the signal.

How this works can be seen clearly from the example of a pulsed and sinusoidal signal: If T_i is equal to τ_D, there are no pauses. Thus, V is unity, and the sinusoidal signal must meet the normal reference levels. If τ_D is now kept constant and T_i is increased, V increases in inverse proportion to the falling RMS value of the pulsed signal. The permissible amplitude of the sinusoidal signal is now higher by the factor V, but the permissible RMS value of the pulsed signal remains the same as that of the non-pulsed signal. This is allowed until V equals V_{max}.

The intricate and exemplified wording of BGM can now be translated very roughly as:

$$EI_{BGM} = \max\left(EI_{WRM}, \frac{EI_{WPM}}{V_{max}}\right). \tag{26}$$

In eqn (26), EI_{BGM} is the exposure index of BGM, EI_{WRM} is the exposure index of WRM with an integration time of 1 s, and EI_{WPM} is the exposure index of WPM.

Because BGM is worded very intricately and only covers specific examples, eqn (26) is naturally not an exact description of BGM. It also does not emulate the unnecessary overestimations at low frequencies and linear field changes or the negative effects of the unrealistic piecewise linear reference curves. Nevertheless, it does make the effect of V_{max} quite clear and shows what BGM does in principle, as well as how BGM could be expanded to cover any field characteristic mathematically exactly and unambiguously. The STD method available in commercial measuring devices since the year 2000 can be configured so that it exactly calculates eqn (26).

Nevertheless, there is no comprehensible physical or biological reason for the systematic underestimation of the weighted peak value by V_{max}. The same is true for the use of the weighted RMS value with an integration time of 1 s.

Schmid and Hirtl applied the BGM to some analytical signals and came to similar results (Schmid and Hirtl 2016).

BGM Rationale

Others have tried to give a rationale for the BGV B11 method (Heinrich 2007), but the argumentation there is not comprehensible. Lapicque's law is mentioned and used in the arguments there, but the fact that its time constant is about 50 μs and its cutoff frequency is about 3 kHz is not recognized.

Correct conclusions made for high frequencies and short times are wrongfully applied to low frequencies and long times. These misconceptions lead to the unnecessary overestimation of BGM at low frequencies and linear field changes that have already been discussed.

The factor V is derived from the fact that signals with pauses have higher stimulation thresholds than signals without pauses. This is correct in principle, but it is already predicted by Lapicque's law in many cases. Although the factor V would reduce a potential overestimation in the remaining cases, it means that an underestimation has to be taken into account in those cases that are already covered by Lapicque's law adequately. It is overlooked that the averaging effect of Lapicque's law is irrelevant at low frequencies and long times. That this averaging effect is sufficiently taken into account in the progression of reference levels above 3 kHz and for short times is also completely overlooked.

Limiting V to V_{max} is justified by an alleged but otherwise unexplained safety risk with very short pulses. Lapicque's law states, however, that the stimulation threshold of very short pulses increases reciprocal to the pulse duration. So, there is no upper limit for very short pulses, and if there were, a correct assessment would have to be more stringent than WPM, not less so.

The relevance of forming the RMS value is nonsensically derived from the fact that the reference levels are mostly given as the RMS values of time-stationary sinusoidal field characteristics. However, no conclusions relevant to this discussion can be drawn from this fact.

The integration time of 1 s for the ostensibly relevant RMS value formation is claimed to be based on fiber-dependent physiological data in the range from 100 ms to a few seconds. The known time constants relevant to electrostimulation effects in living humans are, however, several orders of magnitude smaller than this, namely in the order of 100 μs, and they indicate a linear rather than a quadratic averaging effect. So, it is Lapicque's law again, which in this case is applied completely out of its scope for this discussion.

Method of Rueckerl and Eichhorn

Rueckerl and Eichhorn compared WPM with BGV B11 and proposed an alternative to the BGV B11 method (Rueckerl and Eichhorn 2011; Rueckerl 2016).

In deriving the exposure index, they use a model that only takes the induction mechanism and Lapicque's law into account. As already shown here, this model is completely and precisely described by the three parameters k, τ_e, and e_0. It has also been shown here that WPM precisely emulates this model if the transfer function of the first order high-pass filter for the High ALs or Limbs ALs of Directive 2013/35/EU is used as the weighting filter.

From the above model, Rueckerl and Eichhorn correctly conclude that only the peak value of the induced electric field strength is relevant for long pulse durations $T_{impulse} \gg \tau_e$ or low frequencies $f \ll f_e$. Any additional limitation of the average value of the induced field strength, as required by the BGV B11 method and in BGM, is recognized as unnecessary and questionable.

This insight means that the time derivative of the external field quantity must be restricted according to eqn (27) to ensure that a stimulation effect is avoided:

$$\left|\frac{\mathrm{d}g(t)}{\mathrm{d}t}\right| < \frac{e_0}{k} = \omega \times \sqrt{2} \times R(f). \tag{27}$$

For short impulse durations $T_{impulse} \ll \tau_e$ or high frequencies $f \gg f_e$, Rueckerl and Eichhorn (2011) correctly infer that only the field quantity swing Δg achieved during the change in the external field quantity is relevant. The permissible field quantity swing, however, is derived incorrectly from the reference levels, as it is assumed there that the permissible field quantity swing corresponds to twice the peak value or the peak-to-peak value of a time stationary sinusoidal field quantity with an amplitude that is just permissible. However, it is actually the case that the rule for the field quantity swing only applies to field characteristics free of DC components and then only for field quantity swings within the same sign. The reason for these constraints is because the induction mechanism and the inertia of the nerve cells together form a first order high pass filter. A constant component is always suppressed by this high-pass filter. Only the signal after the high-pass filter is relevant to stimulation, and its magnitude must be compared with the stimulation threshold e_0. It is therefore clear that the field quantity swing relevant to stimulation is the peak value and not the peak-to-peak value of the field characteristic. Equation (28) must therefore be satisfied to avoid a stimulation effect:

$$|\Delta g| = \max(|g(t)|) < \frac{e_0 \times \tau_e}{k} = \sqrt{2} \times R_L \ . \tag{28}$$

Equations (27) and (28) are only exactly applicable to very short and very long impulses or to very low and very high frequencies. However, the stimulation effect of the model is exactly described for all impulse lengths and frequencies by the magnitude of the internal electrical field strength taken after Lapicque's low-pass filter and normalized to the stimulation threshold. This normalized stimulation signal is exactly the magnitude of $s(t)$ in WPM.

The following field profile, among others, is used for an example calculation by Rueckerl: The external magnetic field $g(t)$ is normally zero. It rises linearly to a value of 1 mT over a period of 20 μs. It remains at this level for 180 μs and then drops linearly to 0 within 20 μs.

As Fig. 3 shows, *EI* for the example calculation is 5.89 for WPM if the first order high pass filter model is used.

However, *EI* for WPM is 6.32 if the piecewise linear $W(f)$ with the phase profile recommended by ICNIRP is used in the frequency domain, as Rueckerl did.

Once again, it is clear here that the result of WPM in the frequency domain is usually strongly distorted by the artifacts associated with the piecewise linear $W(f)$. It is also necessary to use a sufficiently long transformation frame. A time frame of 5 ms was transformed for Fig. 3 to keep the additional errors that could occur due to cyclic convolution negligibly low.

As already described, $W(f)$ for WPM should always be defined by a cascade of first-order filter elements. The artifacts that clearly occur in the red curve depicted in Fig. 3 can only be certainly avoided if this is the case. The best thing is to use WPM exclusively in the time domain, as additional potential errors due to cyclical convolution cannot occur. All currently known commercial measuring devices that use WPM only operate in the time domain using first order filter elements and reliably deliver the correct results.

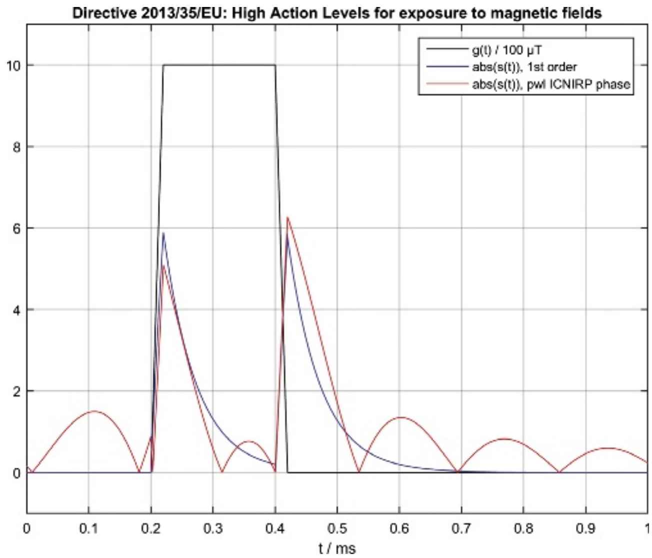

Fig. 3. The magnitude of $s(t)$ on excitation with an impulse with amplitude 1 mT. The rising and falling edges are linear and are 20 μs long. $W(f)$ of WPM is defined by the first order high pass filters for the High ALs of Directive 2013/35/EU (blue) or the piecewise linear approximation with phase as recommended by ICNIRP (red).

A value of 3.5 is specified as the correct *EI* for this example by Rueckerl. This is because the permissible field quantity swing has been set too high by a factor of 2. If this coarse error is corrected, *EI* becomes 7.07. This is also exactly the value that would be given by WPM if the rise and fall times of the signal edges were very much smaller than the τ_e of 53.05 μs. However, rise and fall times of 20 μs are used for the signal edges in the example calculation. The method of Rueckerl and Eichhorn only represents a very rough approximation in this transitional area. Here too, though, WPM exactly emulates the induction mechanism and Lapicque's law.

Exactly the same model as for WPM is thus used by Rueckerl and Eichhorn. Nevertheless, only very short and very long impulses can be evaluated exactly. The permissible field quantity swing they specify for very short impulses is too high by a factor of 2, however.

TECHNICAL ASPECTS OF MEASUREMENT SYSTEMS FOR NON-THERMAL EFFECTS

Band-limiting low-pass filter and sampling rate

The reference levels for non-thermal effects are specified for frequencies up to 10 MHz in the ICNIRP Guidelines of 2010 and in Directive 2015/35/EU. To start with, $g(t)$ must be captured so that the unavoidable band limiting low-pass filter used in the measurement system does not show any significant attenuation for frequencies up to 10 MHz yet. All currently available measurement systems sample either $g(t)$ or $s(t)$. The sampling rate used in such a measurement system must be at least twice the cutoff frequency of the band-limiting low-pass filter to avoid artifacts due to undersampling.

Many measurement devices for non-thermal effects only have a bandwidth of 100 kHz or 400 kHz and usually use a sampling rate around 2.56 times higher than the bandwidth. This does not lead to an incorrect assessment for most practically relevant field sources because $g(t)$ often contains hardly any energy above a few tens of kHz.

If the spectrum of the field source to be assessed is unknown, however, the peak value in the frequency band starting from the low frequency measurement instruments cutoff frequency up to 10 MHz should be measured with a high frequency measurement instrument and an *EI* calculated for this frequency range. If this *EI* is distinctly less that the *EI* of the low frequency instrument, it is sufficient to use the *EI* of the low frequency instrument. If this is not the case, adding the two *EI* values will give a worst-case estimation of the exposure.

It is, however, dangerous and unreasonable to reduce the cutoff frequency of the band-limiting low-pass filter or the sampling rate unnecessarily. Reducing the bandwidth or the sampling rate too much will naturally lead to considerable measurement errors, which must be strictly avoided.

Band-limiting high-pass filter and assessment of DC components

The reference levels for non-thermal effects are specified for frequencies from 1 Hz upward in the ICNIRP Guidelines of 2010 and in Directive 2015/35/EU. Exposure limits that must be adhered to unconditionally are given for the DC component of the magnetic flux density. Only conditionally effective Action Levels are specified for the AC components. To some degree, the effect of the DC components is based on completely different physical or biological effects than for the AC components.

It is therefore neither necessary nor sensible to evaluate both effects with a single method or to somehow add their effects together. In particular, there is no point in trying to extend WPM so that it also evaluates the DC components. Quite the opposite is the case. An additional band-limiting filter should prevent any DC components from influencing the *EI* of WPM. The cutoff frequency of this high-pass filter should be 1 Hz because the reference levels for the AC components are still defined at this point and not for lower frequencies.

The DC component must be assessed separately. It is important that the measuring system used should have a band-limiting low-pass filter with a cutoff frequency of 1 Hz as well to prevent any AC components from influencing the *EI* of the DC component.

In practice, it has been shown that field generators that are designed to generate very high direct currents also generate significant AC components. It is usually even the case that the *EI* of the AC components is clearly higher than that of the DC components. The *EI* of the DC components thus usually has no effect at all on the overall assessment result.

Intrinsic noise and dynamic range

All measurement systems have intrinsic noise. This means that a value EI_{noise} greater than 0 is displayed even when there is no external field present. This value is about three times higher for WPM than for WRM.

It is worth knowing that EI_{noise} also increases proportionally to the square root of the measurement system bandwidth. Thus, a measurement system with a bandwidth of 10 MHz displays an intrinsic noise level that is a factor of 5 times higher than one with a bandwidth of 400 kHz. This would at least be true if the amplifiers and AD converters are equivalent and the field probes used are equally sensitive. In practice, though, the sensitivity of a magnetic field probe also drops reciprocal to the square root of its bandwidth, which means that the intrinsic noise could be as much as 25 times higher in practice.

All modern measurement systems sample and digitize either $g(t)$ or $s(t)$ using an AD converter. Since an AD converter can only capture a finite signal amplitude without strong distortion, there will always be a value $EI_{\max}$ up to which measurements can be made reliably. The ratio of $EI_{\max}$ to EI_{noise} is called the dynamic range of the measurement system.

Because the reference levels are very strongly dependent on frequency, the dynamic range of measurement systems [that digitize $s(t)$ instead of $g(t)$] is significantly larger. This is true if the quality of the AD converter is the same. The disadvantage of digitizing the weighted signal is that the weighting filter then must be realized as an analog filter and can't be a programmable digital filter. Measurement systems that use an analog filter for the fundamental weighting high pass filter and digital filters for the remaining filter elements represent a good compromise. This combines both the advantages without having to accept any significant disadvantages. The first measurement system available with STD had precisely this structure. Measurement systems for non-thermal effects that already digitize $g(t)$ unfortunately show a much lower dynamic range.

The maximum relative measurement deviations of *EI* due to EI_{noise} for WPM are in the range:

$$-\frac{EI_{\mathrm{noise}}}{EI} \leq \frac{\mathrm{d}EI}{EI} \leq +\frac{EI_{\mathrm{noise}}}{EI}. \tag{29}$$

However, the standard deviation of the measurement uncertainty due to EI_{noise} is only about a third of EI_{noise}.

The relative systematic measurement deviation of *EI* due to EI_{noise} for WRM is:

$$\frac{\mathrm{d}EI}{EI} = \sqrt{1 + \left(\frac{EI_{\mathrm{noise}}}{EI}\right)^2} - 1. \tag{30}$$

The measurement deviations due to intrinsic noise are therefore much more pronounced in WPM than in WRM, and unfortunately they are not systematic, and their sign also cannot be predicted.

WPM is thus relatively sensitive to the intrinsic noise of the measuring system. However, the ensuing measurement deviations in some high quality commercially available measurement systems are so small that they can be neglected in practice.

CONCLUSION

WPM is the only known method that is suitable for assessing non-thermal effects of LF electric and magnetic fields in the sense of Directive 2015/35/EU for any field pattern. It emulates the underlying physical and biological effects significantly better than all other presently known methods. In particular, WPM in the time domain can be used without a second thought. High quality commercial measuring equipment with implemented WPM has already been available since the year 2000. This makes the application of WPM absolutely reliable, simple, and timesaving.

The alternative assessment methods WRM, BGM, and the method of Rueckerl and Eichhorn can lead to significant assessment errors and should not be used.

Some problems in the technical realization and the usage of measurement systems have been discussed. The solutions used in state-of-the-art equipment have been demonstrated.

FREQUENTLY USED ABBREVIATIONS

- WPM: Weighted peak method;
- WRM: Weighted RMS method;
- STD: Shaped time domain method. It is a generalized time domain assessment method comprising WPM, WRM and any weighted combinations of both; and
- BGM: Method of BGV B11 but adapted to the reference levels of Directive 2013/35/EU and with reduced V_{max}.

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