QUICK AND EFFICIENT METHOD FOR LOW-FREQUENCY EMF EVALUATION OF ELECTRIC POWER SYSTEMS CONSIDERING MULTIPLE SOURCES WITH DIFFERENT FREQUENCIES AND HARMONICS

Ernst SCHMAUTZER
TU Graz / IFEA – Austria
schmautzer@tugraz.at

Katrin FRIEDL
TU Graz / IFEA – Austria
katrin.friedl@tugraz.at

Maria AIGNER
TU Graz / IFEA – Austria
maria.aigner@tugraz.at

ABSTRACT

Today many powerful programs for the calculation of magnetic and electric fields concerning one or more sources (e.g. high voltage overhead power lines, cables, transformer, electric appliances, base loads,…) are available. The crucial problem is that these programs are designed for the calculation of electromagnetic fields concerning one fundamental frequency and cannot consider sources with different frequencies or harmonics, as required in the “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)” published by ICNIRP. This publication demonstrates a quick and efficient method to consider electric and magnetic fields of several sources with different fundamental frequencies including harmonics.

INTRODUCTION

As required in the “Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)” by ICNIRP (International Commission on Non-Ionizing Radiation Protection [1]) simultaneous exposure to fields of different sources and frequencies including harmonics have to be considered and therefore a new and easy applicable method has been developed. Equations (1) and (2) are the base for further considerations and are taken from the ICNIRP Guidelines [1] where electric and magnetic fields for frequencies up to 10 MHz are individually handled.

\[ \sum_{i=60\text{Hz}}^{10\text{MHz}} \frac{H_i}{H_{L,i}} + \sum_{i=60\text{Hz}}^{10\text{MHz}} \frac{H_i}{H_{B,i}} \leq 1 \]  

(1)

\[ \sum_{i=60\text{Hz}}^{10\text{MHz}} \frac{E_i}{E_{L,i}} + \sum_{i=60\text{Hz}}^{10\text{MHz}} \frac{E_i}{E_{B,i}} \leq 1 \]  

(2)

EXPOSITION RATIO: ER

The exposition ratio is defined by the value of the field strength divided by the reference value (treatment for the magnetic field see equation (1) and treatment for the electric field see equation (2)).

One Source and One Frequency

The exposition ratio for the magnetic field in space free of magnetic materials can be calculated using the magnetic flux density or the magnetic field strength applying the following expression (3).

\[ ER_{B,j} = \frac{H_j}{H_{L,j}} = \frac{\mu_0 \cdot H_j}{B_{L,j}} \]  

(3)

The exposition ratio for electric fields is defined by equation (4).

\[ ER_{E,i} = \frac{E_i}{E_{L,i}} \]  

(4)

The reference values comprise the protection aim concerning the occupational ([1], Table 7) and the general public exposure ([1], Table 6). Table 1 shows some characteristic reference levels for the electric field strength and the magnetic flux density published by ICNIRP for the general exposure. Exemplarily the reference levels for a fundamental frequency of 16.7 Hz, 50 Hz and 250 Hz under consideration of the general public exposure are listed in Table 2.
ERB,j exposition ratio for the magnetic field considering one source and one frequency j
ERE,i exposition ratio for the electric field considering one source and one frequency j

One Source with Several Frequencies
The following step includes the summation of the exposition ratio including several frequencies for one source.

$$\begin{align*}
ER_B &= \sum_{j=1Hz}^{10MHz} \frac{H_{L,j}}{\mu T} = \sum_{j=1Hz}^{10MHz} \frac{B}{\mu T} \quad (5) \\
ER_E &= \sum_{i=1Hz}^{10MHz} \frac{E_{L,i}}{\mu T} = \sum_{i=1Hz}^{10MHz} \frac{E}{\mu T} \quad (6)
\end{align*}$$

ERB exposition ratio for the magnetic field considering one source and several frequencies j
ERE exposition ratio for the electric field considering one source and several frequencies i
H_{L,j} magnetic field reference value according to [1], for a frequency range from 65 kHz to 10 MHz equal to the constant value b
E_{L,j} electric field reference value according to [1], for a frequency range from 1 MHz to 10 MHz equal to the constant value a

TOTAL EXPOSITION RATIO: TER
The summation of ERB and ERE, respectively leads to the total exposition ratio TERB and TERE for all considered sources including several frequencies (i.e. harmonics). The total exposition ratio for magnetic fields TERB and the total exposition ratio for the electric field TERE are calculated by summing up ERB and ERE, respectively (see equation (7) and (8)). All sources n and all relevant frequencies and harmonics have to be considered.

$$\begin{align*}
TER_B &= \sum_n^n ER_B \quad (7) \\
TER_E &= \sum_n^n ER_E \quad (8)
\end{align*}$$

n number of sources
TERB total exposition ratio for the magnetic field for n sources under consideration of j frequencies
TERE total exposition ratio for electric field for n sources under consideration of i frequencies

HARMONIC FACTOR kH
To simplify the calculation of the ER of a source which shows harmonics in current and voltage a harmonic factor kH is useful. In the following the calculation of the harmonic factor kH for the magnetic flux density is demonstrated, kH for the electric field can be derived similarly. The harmonic factor considers the physiological effect of harmonics and represents the impact of them in currents or voltages related to the fundamental frequency.

**Harmonic Factor kH for Magnetic Fields**
The formula for ER (equation (5)) can be transformed as shown in equation (9).

$$ER_B = \sum_{j=1Hz}^{10MHz} \frac{B_{L,j}}{\mu T} = \sum_{j=1Hz}^{10MHz} \frac{B}{\mu T}$$

$$ER_B = \sum_{j=1Hz}^{10MHz} \frac{B_{L,j}}{\mu T} = \sum_{j=1Hz}^{10MHz} \frac{B}{\mu T} \quad (9)$$

$$ER_B = \frac{ER_{B,ff}}{k_H} \quad (10)$$

B_{L,j} magnetic flux density at frequency j in µT
B_{L,ff} magnetic flux density reference level at frequency j in µT
B_{ff} magnetic flux density for the fundamental frequency in µT
E_{L,j} magnetic flux density reference level for the fundamental frequency in µT
ER_{B,ff} exposition ratio for the magnetic field considering the fundamental frequency of one source
ERB exposition ratio for the magnetic field considering several frequencies of one source

If the magnetic flux density is linearly dependent from the currents of a source (see equation (11)), the harmonic factor kH can be calculated directly from the RMS-values of the harmonics I ν of currents (see equation (12)) which are obtained by a Fourier analysis.

$$I_j = \frac{I_{1j}}{I_{1}} = \frac{I}{I_{1}}$$

$$k_H = \sum_{\nu=1}^{H} k_{H,\nu} = \sum_{\nu=1}^{H} \frac{I_{\nu}}{I_{1}}$$

Ij RMS-value of the current harmonic at frequency j in A
Iν RMS-value of the current of the harmonic order in A
I1 RMS-value of the fundamental frequency in A
kH,ν harmonic factor kH,ν for each harmonic order ν

In the following example a current of 1000 A (fundamental frequency) is considered with typical current harmonics up to the 7th order (see Table 3). After calculating the harmonic factors kH,ν for each harmonic frequency they are summed up to the harmonic factor kH (see Table 3).

<table>
<thead>
<tr>
<th>ν</th>
<th>Iν</th>
<th>I1</th>
<th>kH,ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>1000</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>700</td>
<td>0.70</td>
</tr>
<tr>
<td>5</td>
<td>350</td>
<td>700</td>
<td>0.50</td>
</tr>
</tbody>
</table>
APPLICATION OF THE NEW METHOD

The calculation of the total exposition ratio of several sources including various currents and harmonics can be split into following steps (see Figure 1).

The first step is the determination of the immission point followed by the identification of the influencing sources (e.g. railway, overhead power line, cable, electrical appliances, base load, reserve). Based on the position of the emission point P_i correlated to the location of the source, the flux density value B or the exposition ratio ER_{B,ff}(P_i) for the fundamental frequency can be determined. This value can be calculated either by a commonly used program or read from a precalculated normalized figure or table (for a specific current). By using such a normalized figure (example see Figure 3) or table, the value of ER_{B,ff}(P_i) has to be transformed to the relevant current. If harmonics occur, the harmonic factor k_H has to be calculated and considered. Finally the ER of this source can be computed.

For further sources this procedure has to be repeated. Furthermore TER is the sum of all relevant ER's of the considered individual sources. For another immission point P_j the whole procedure has to be repeated.

Example

The following example includes three different sources and a base load (see figure 2). The immission point is labelled with P_i (e.g. a dwelling). The first source consists of two tracks of a railway system with a boost conductor (fundamental frequency 16.7 Hz) at the distance x_1 from the emission point. The second considered source is a 400 kV overhead power line with a fundamental frequency of 50 Hz, with a distance x_2 between P_i and the line axis. The distance between the third source, a cable and the emission point is defined by x_3. Furthermore a base load with a fundamental frequency of 50 Hz is considered. Based on the situation shown in Figure 2 the total exposition ratio can be calculated as follows.

ER of Source 1, Railway System

Knowing the position of the immission point P_i in respect to the source (distance x_1 and height) the exposition ratio ER_{B,1,16.7Hz}(P_i) (see equation (14)) can be read out from Figure 3.

The evaluated value of the fundamental frequency has to be multiplied by the harmonic factor k_H (e.g. 1.08, see Table 3). If the relevant current I_{rv} is not equal to current I_N used in the normalized figure (e.g. 2000 A in Figure 3) a conversion factor k_C has to be applied (see equation (13)).

\[ k_C = \frac{I_{rv}}{I_N} \]  
\[ k_C \] conversion factor, dimensionless

\[ ER_{B,1,16.7Hz}(P_i) = 0.07 \]  
\[ ER = ER_{B,1,16.7Hz}(P_i) \cdot k_H \cdot k_C \]  
\[ = 0.07 \cdot 1.08 \cdot 1 = 0.0756 \]
ER of Source 2, Overhead Line
The following step includes the calculation of the exposition ratio for the overhead power line. The exposition ratio $ER_{B,2,50\,Hz}(I_{rv})$ can be read out from Figure 4. In this particular case the relevant current $I_{rv}$ is limited by the applied conductors (e.g. 1800 A).

\[ ER_{B,2,50\,Hz}(I_{rv}) = 0.04 \]  \hspace{1cm} (16)

\[ ER_{B,2} = ER_{B,2,50\,Hz}(P_1) \cdot k_C \cdot k_H(I_{rv}) \]  \hspace{1cm} (17)

\[ ER_{B,2} = 0.04 \cdot \frac{1800}{2300} \cdot 1.2 = 0.0376 \]  \hspace{1cm} (18)

TER
The total exposition ratio TER of the magnetic field for several sources under consideration of all frequencies can be easily calculated (see equation (7)) now:

\[ TER_B = 0.0756 + 0.0376 + 0.032 + 0.05 \]
\[ = 0.1952 \]  \hspace{1cm} (21)

This means that 19.52 % of the allowed range (100 %) in $P_1$ is utilized.

CONCLUSION
Following ICNIRP guidelines for limiting exposure to time-varying electric and magnetic fields [1] to protect people against harmful health effects relevant currents and voltages of sources including harmonics have to be considered. This leads to considerable efforts and calculations because magnetic flux densities or electric field strengths with different frequencies cannot be summed up in one step. To simplify the computation and evaluation a method using the exposition ratio and the total exposition ratio is introduced. The great advantage of this method is that precalculated results of exposition ratios of power lines, railways, cables, appliances such as machines and other electric or electronic equipment and also base loads and reserves can be considered and summed up to a total exposition ratio which can be evaluated easily. According to ICNIRP [1] the exposure to magnetic and electric fields is harmless as long as the total exposition ratio is less than 1, only if the total exposition ratio exceeds 1 the situation has to be verified in detail.

REFERENCES


[3] EN 50400:2006, “Basic standard to demonstrate the compliance of fixed equipment for radio transmission (110 MHz – 40 GHz) intended for use in wireless telecommunication networks with the basic restrictions or the reference levels related to general public exposure to radio frequency electromagnetic fields, when put into service”