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Characterization of magnetic field measuring instruments in presence of non-sinusoidal magnetic fields

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Abstract- The behaviour of the low and medium frequency environmental magnetic field meters is investigated with reference to the possible approaches that can be implemented to evaluate compliance with the field exposure limits. The investigation is carried out both numerically and experimentally, in presence of sinusoidal and distorted waveforms, which are produced by the systems for the generation of reference magnetic fields up to 100 kHz set up at the Istituto Nazionale di Ricerca Metrologica of Torino. The adoption of different methods in the evaluation of the compliance to the exposure prescription may lead to different or even apparently inconsistent evaluations, when operating in presence of both sinusoidal and non-sinusoidal fields. By taking into account the different meter characteristics and output quantities, suitable checks of the measuring instruments with complex magnetic field waveforms of known frequency spectrum should be performed by adopting specific measurement procedures.

I. Introduction

The conformity to the prescriptions related to the protection of both the population and the workers from possible damages due to exposure to electric and magnetic fields is often assessed carrying out measurements with suitable field meters. To verify compliance with the exposure limits, the measured electric and magnetic fields have to be compared with reference levels, which are expressed as a function of frequency in terms of rms field values [1].

If the low and medium frequency range (up to a few hundred kilohertz) is considered, the magnetic field emissions, generated by sources operating both in domestic and in industrial environment (household appliances, switching power supply, arc and resistance welding devices, induction heating equipments, etc), have to be measured by instruments with a suitable frequency bandwidth. An example of magnetic flux density time behaviour, generated during a spot resistance welding operation, is shown in Fig. 1, together with its harmonic spectrum.

The check of the measuring instruments is usually performed by carrying out a calibration at power frequency, over the implemented measurement ranges. A verification of the frequency response with a sinusoidal signal, in a limited number of frequency points (e.g. bandwidth minimum, medium and maximum frequency value), should at least be performed when the meter has to be used in presence of fields with non negligible harmonic content, such as the one shown in Fig.1.

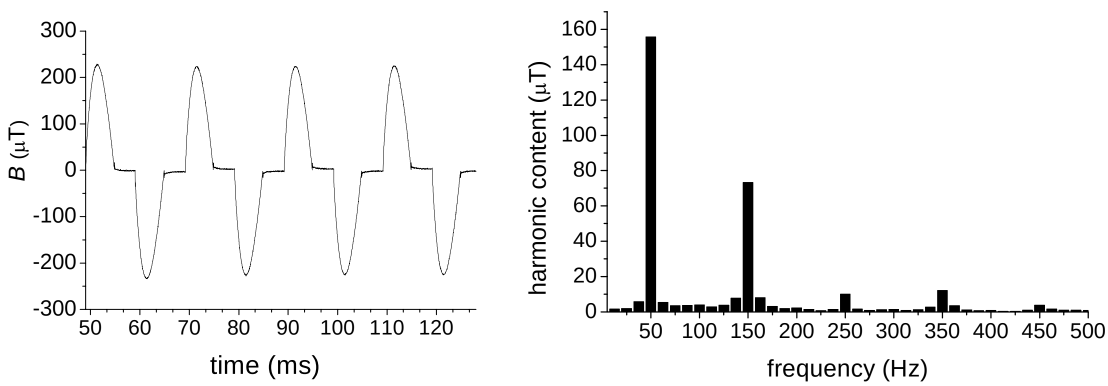

Fig. 1 – Magnetic flux density measured during spot resistance welding and related harmonic content.

In the case of distorted fields, the verification of the conformity to the exposure prescription is more complex and different approaches can be adopted, which are based on the time or frequency domain analysis of the measured fields [2]. The measuring instruments of most recent production can give, besides the indication of the true rms value of the magnetic flux density, other output quantities, which directly or indirectly enable the evaluation of the conformity to the exposure prescriptions. The behaviour of these instruments should then be properly checked with reference to these additional output quantities, taking into account the expected measurement conditions and making use of suitable reference systems.

In the following, after a brief description of the approaches that can be implemented for the exposure evaluation, the characteristics of the Istituto Nazionale di Ricerca Metrologica (INRIM) systems for the generation of reference low and medium frequency magnetic fields are discussed; the paper then focuses on the analysis of the responses of such instruments in presence of different types of waveform to be measured. The investigation is carried out both numerically and experimentally, by producing sinusoidal and distorted waveforms in the frequency range from some hertz to 100 kHz.

II. Assessment of the conformity to the exposure limits

The measurement of the environmental time-varying magnetic fields is generally aimed at the evaluation of the human exposure. To this end, reference levels expressed in terms of measurable quantities have been indicated at international level by the International Commission on Non-Ionising Radiation Protection Association (ICNIRP), both for the population and the workers [1]. These reference levels are expressed as rms value of pure sinusoidal fields as a function of the frequency. The ICNIRP guidelines have been adopted by the European Community with its Council Recommendation of 12 July 1999, with reference to the population, and more recently with the Directive 2004/40/EC for the workers. In the case of sinusoidal fields, compliance with the prescriptions is assured if the measured rms magnetic flux density is lower than the indicated reference level.

In the case of multiple sources and/or distorted fields, compliance with the ICNIRP prescriptions, with respect to possible induced electrical stimulation effects, can be verified according to the relationship:

$$T_0 = \sum_{f_i=1Hz}^{65kHz} \frac{B(f_i)}{B_{\lim}(f_i)} + \sum_{f_i>65kHz}^{10MHz} \frac{B(f_i)}{b} \leq 1 \qquad (1)$$

where T_0 is the resulting exposure index, $B(f_i)$ is the magnitude of the field component at the frequency f_i, $B_{lim}(f_i)$ is the corresponding indicated reference level and b is equal to 30.7 µT for the workers and 6.25 µT for the population.

By multiplying the two terms of (1) by a reference level $B_{\lim}(f_{\mathrm{ref}})$ for an arbitrary frequency f_{ref}, a weighted magnetic flux density B_w is obtained:

$$B_W = B_{\lim}\left(f_{ref}\right) \cdot T_0 = \sum_i W\left(f_i\right) \cdot B\left(f_i\right) \leq B_{\lim}\left(f_{ref}\right) \qquad (2)$$

where the weighting function $W(f_i)$ is the ratio between the magnitude of the field component and $B_{lim}(f_{\mathrm{ref}})$. The weighted magnetic flux density can then to be compared with the reference level $B_{\lim}(f_{\mathrm{ref}})$ at the considered reference frequency f_{ref}. In the case of non-sinusoidal phase-coherent waveforms (e.g. distorted or pulsed periodical fields), the use of (1) leads to a conservative evaluation of the exposure compliance.

On the basis of electrophysiological considerations, an alternative approach has been proposed. According to it, a complex weighting function $W_c(f_i)$ can be implemented both by an analog first order high pass filter or a piecewise linear complex function [2, 3, 4]. The amplitude and phase of the two weighting functions are compared in Fig 2. The high pass filter can be implemented by a resistive and capacitive circuit; when the worker exposure is considered, the time constant is set to 194 µs, which corresponds to a cut-off frequency of 820 Hz. Compliance to the exposure prescriptions is assured if the index given by the ratio of the weighted magnetic flux density peak value $B_{w,p}$ to the reference level peak value $B_{\lim,p}(f_{\mathrm{ref}})$ is lower than unity.

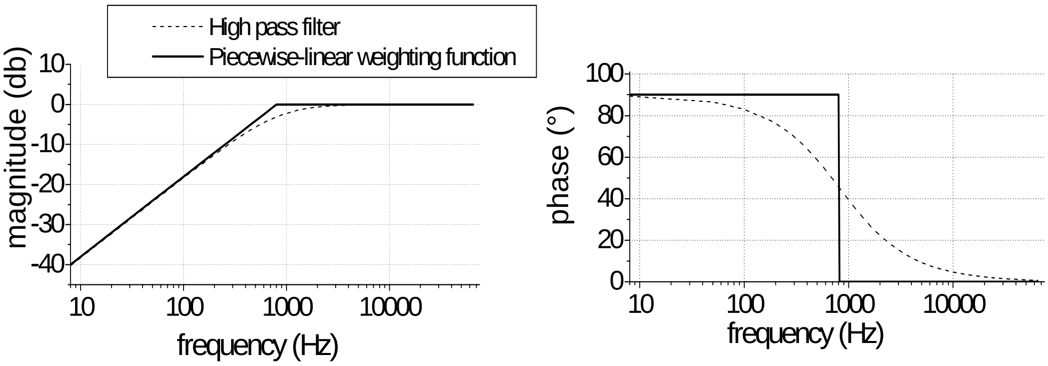

Fig. 2 – Piecewise linear and first order high pass filter magnitude and phase weighting functions (reference frequency f_{ref} = 50 kHz).

III. Characterisation of magnetic field meters

Characterization of magnetic field meters in presence of sinusoidal and non-sinusoidal fields has to be performed in stable and uniform reference fields, which should be known with an uncertainty not higher than some percent over the range of amplitudes and frequencies of interest.

A. Generation of reference sinusoidal and distorted fields

Systems for the generation of low and medium frequency reference magnetic fields have been set up at INRIM. [5, 6]. With reference to the frequencies up to 100 kHz, the magnetic flux density is produced by a Helmholtz coil system supplied by a sinusoidal or an arbitrary waveform generator connected to a stable amplifier operating from DC to 500 kHz (Fig. 3). The rms value of the current flowing through the coils is measured by recording the voltage drop across a non inductive current shunt. The relative uncertainty (coverage factor k=2) of the produced field ranges from 2.0 10^{-3} at power frequency up to $12{\cdot}10^{-3}$ at 100 kHz. In the case of distorted fields, the frequency spectrum of the generated magnetic flux density is evaluated by analyzing both in the time and frequency domain the waveform of the current flowing in the coils, recorded through a calibrated digital sampling oscilloscope. In this way, the exposure index (T_0) associated with the generated flux density, can be computed according to (1). The uncertainty of the T_0 value associated with the produced distorted field is estimated to be within 0.02.

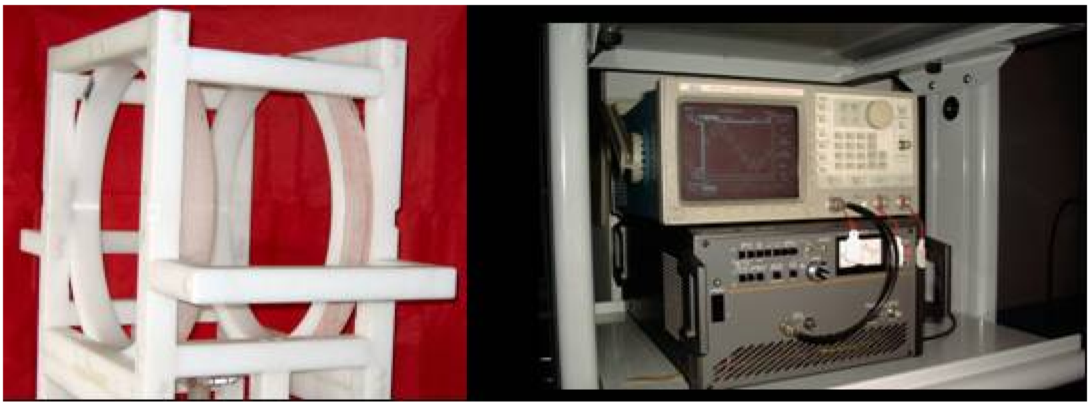

Fig. 3 – INRIM set up for the generation of sinusoidal and distorted reference magnetic fields up to 100 kHz.

B. Check of the exposure index evaluation

Evaluation of the output indication given by some field meters has been performed by investigating their behaviour both with sinusoidal and non-sinusoidal waveforms.

Fig. 4 shows the frequency behaviour of the exposure index T_{HPF} ($T_{HPF}=B_{W,p}/B_{lim,p}(f_{ref})$), given by a measuring instrument with bandwidth greater than 100 kHz, which implements the high pass filter weighting function approach. For each frequency value, the T_{HPF} given by the meter is recorded when a pure sinusoidal magnetic flux density, whose amplitude is equal to the reference level indicated in [1] for the population, is generated by the Helmholtz coil system previously described.

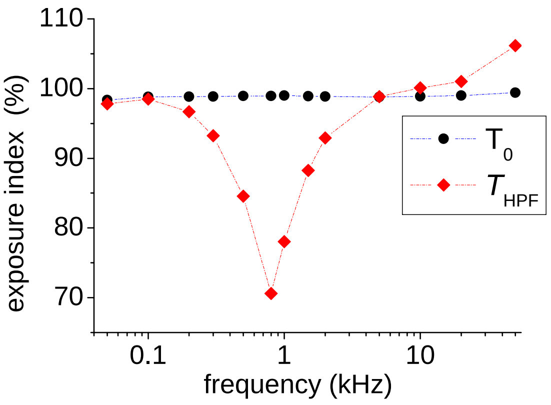

Fig. 4 – Exposure index in presence of sinusoidal fields evaluated by the same meter through conservative (T_0) and high pass filter weighting approach (T_{HPF}).

The obtained values are compared with those (T_0) conservatively evaluated by (1) as ratio between the rms value of the applied field given by the same meter and the corresponding reference level. As expected, around the cut-off frequency, values lower down to 30% can be obtained by the same meter when considering the output indications evaluated according to the high pass filter weighting approach with respect to those obtained with the conservative one. Significant differences can also be observed at frequencies higher than 10 kHz, where the results put in evidence how, for the considered meter, the values of T_{HPF} significantly overestimate the expected ones ($T_{HPF\_expected}=T_0=100\%$).
In the case of a distorted waveform, the phase value of the harmonic components can significantly modify the exposure level index evaluated by means of the high pass filter approach.
Fig. 5 shows the simulated and measured values obtained in the case of a field given by a 50 Hz fundamental (450 μT) and a third order harmonic component (16.67 μT) at the increase of the third harmonic phase displacement. The amplitude of the field components has been chosen to obtain an exposure index T_0 equal to 100%. The experimental data (T_{HPF}) are compared with the computed behaviour (T_{HPF_S}) obtained by reproducing the high pass filter behaviour (cut-off frequency 820 Hz, reference frequency 50 kHz).

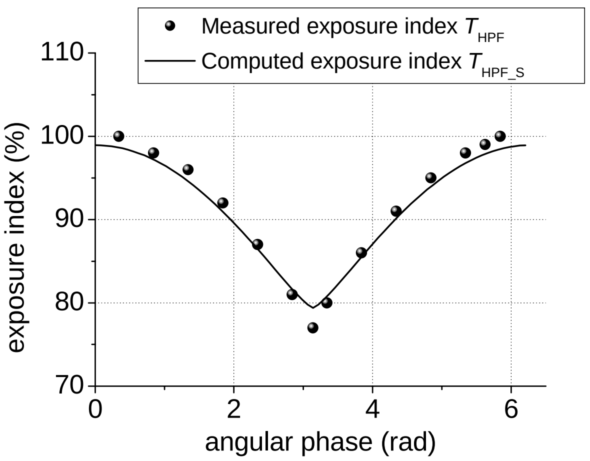

Fig. 5 – Influence of the third harmonic phase on the exposure index evaluated by the high pass filter approach.

An incorrect evaluation of the exposure index, given by a measuring instrument that performs the analysis in the frequency domain, is finally evidenced in Fig. 6. The deviation of the measured exposure index (T_{0m}) from that associated to the reference magnetic field (T_0) in presence of sinusoidal fields is strongly dependent on the considered frequency value; these deviations are due to the inadequate FFT frequency resolution, leading to a possible overestimation of the exposure index.

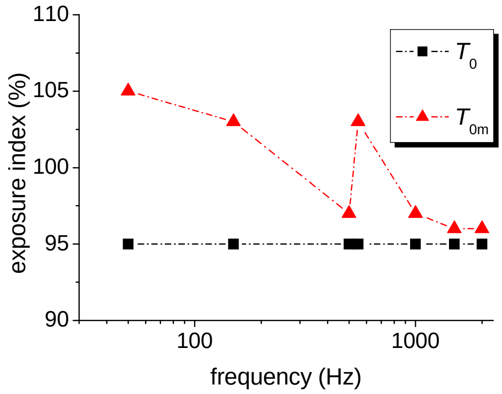

Fig. 6 - Comparison between the exposure index associated with the generated field (T_0) and that measured (T_{0m}) by a meter which performs the analysis in the frequency domain

C. Check of the filter weighting function

The magnitude and phase of the weighting function (WF) implemented in a three-dimensional magnetic field meter, equipped with analog outputs of both the measured and filtered field spatial components, are investigated. Since the WF input signal can not be directly measured, for each orthogonal spatial component the system shown in. Fig. 7 is taken into account. It is composed by three blocks: a) the probe, which converts the magnetic flux density (B_{gen}) into a voltage signal; b) a filter (FL), which attenuates both the very low frequency components, with selectable cut-off frequencies of 1 Hz, 10 Hz and 30 Hz, and those at high frequency according to the bandwidth (400 kHz); c) the high pass filter, which implements the weighting function. The system output is the voltage V_{out}.

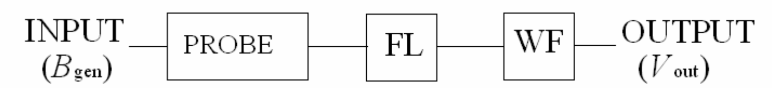

Fig. 7 - Block diagram of the meter which implements the high pass filter approach.

The considered system gain, which is a complex function, can be expressed as:

$$\overline{G} = \frac{\overline{V_{out}}}{\overline{B_{gen}}} \qquad (3)$$

A sinusoidal magnetic flux density is generated in the frequency range from 40 Hz to 20 kHz and the corresponding time behaviour of the three filtered orthogonal field components is recorded. The phase delay and the gain magnitude (G) are obtained by comparison with the behaviour of the current in the coils.

Fig. 8 shows the obtained filter gain magnitude (expressed in dB) and the related measured phase delay, with the low cut-off frequency set at 10 Hz. The expected behaviours are reported for comparison. The analysis of the phase delay curve as a function of frequency shows that the cut-off frequency associated with the implemented filter can be estimated to be about 850 Hz (instead of 820 Hz). Moreover, a significant deviation of the phase can be found both at low and high frequency. The discrepancies with respect to the prospective phase behaviour can be ascribed to the effects of the FL block; in particular, lower differences with respect to the expected behaviour are observed at low frequency, if the 1 Hz filter is used.

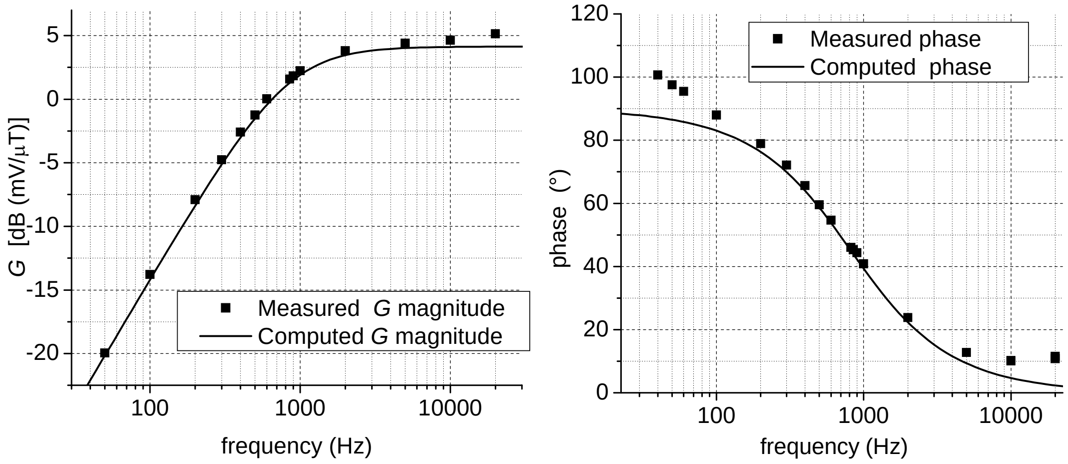

Fig. 8 – Comparison between the measured and computed magnitude and phase of the gain of the system reported in Fig. 7.

V. Conclusions

The use of magnetic flux density meters whose output indications can be related to the compliance with the indicated reference levels may lead to different or even apparently inconsistent evaluations, when operating in presence of both sinusoidal and non-sinusoidal fields. So both the approach implemented by the meter and the accuracy of the different output indications should be known as a function of the expected measuring conditions. To this end, taking into account the various output quantities that can be given by the most recent production meters, proper calibrations or at least checks of the measuring instrument should be performed, by using suitable reference generation systems and adopting specific measurement procedures.

References

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