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[1.] Richard DRAHOŠ, [2.] Ervin LUMNITZER

METHODOLOGY FOR MEASUREMENT AND ASSESSMENT OF EXPOSURE TO PULSED MAGNETIC FIELDS

[1-2.] Technical university of Košice, Faculty of mechanical engineering, Institute of Safety, Quality and Environmental Science, Department of Environmental Studies, Slovakia

Abstract: The paper deals with the methodology for pulsed low frequency magnetic fields measurement for the purpose of employees assessment of health risks in relation to exposure to magnetic field. Experimental measurements of pulsed magnetic field using oscilloscopic method in time domain and frequency method in the frequency domain was performed. The advantages and disadvantages of these methods to determine employees exposure were evaluated.
Keywords: Pulsed low frequency magnetic fields, time domain, frequency domain, exposure to pulsed magnetic field

1. INTRODUCTION

The employees health protection in respect of the (human) exposure to electromagnetic fields and health risks preventions from the exposure to electromagnetic field is provided in Directive 2004/40/EC [1] EP&C, which is included in juridical system of the majority of EU member states. The employees exposure to magnetic field is described by magnetic flux density B (magnetic field strength H) and induced current density J.

The employees exposure to pulsed low frequency magnetic fields (f <65 kHz) is caused for example by operating of electrical equipment for resistance welding, pulse magnetization and demagnetization and magnetic properties testing, etc.

The method for measurement and assessment of employees exposure to pulsed low frequency magnetic field (hereinafter referred to as "pulsed M field") is significantly different from the method for measurement and assessment of employees exposure to periodical M field.

The evaluation of test operator (employee) exposure to pulsed M field during the test equipment operation (magnetic structurescope) was performed by oscilloscopic method in the time domain under terms of standard EN 62226-2-1:2005 [2] and by frequency method in the frequency domain.

ASSESSMENT OF EMPLOYEES HEALTH RISK

The employees health protection at workplace with presence of M fields is ensured by compliance with the limit rms (peak) values of induced current density for head and trunk $J_{L,rms}$ ($J_{L,pk}$). In frequency range from 1 Hz to 10 MHz, limit values of the induced current density for head and trunk J_L are based on proven adverse exposure effects of the M field on the central nervous system tissues (in the head and trunk of the body) and the limit values are frequency dependent [1]. Limit peak value of the induced current density $J_{L,pk}$ are determined by multiplying the $J_{L,rms}$ rms value by factor $\sqrt{2}$.

The directly measurable action rms values of magnetic flux density $B_{a,rms}$ were derived from limit rms values of induced current density for the head and trunk $J_{L,rms}$. In the case of exposure to pulsed M field, induced current density $J_{L,pk}$ limit peak value is applied at the equivalent frequency f_e, which is calculated as $f_e = 1/(2t_p)$, where t_p is the pulse duration [in seconds].

2. PULSED MAGNETIC FIELD GENERATION

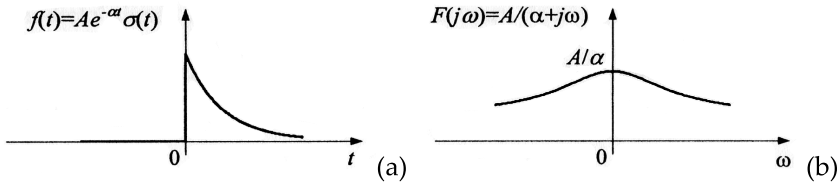

Fig. 1: Idealised pulse in time domain (a) and in frequency domain (b) [3]

The pulsed M field is generated at the surroundings of conductor (usually coil) with pulsed electric current flow. Fig. 1 shows idealized pulse (infinitely rapid rise and exponential decrease) in the time domain (Fig. 1a) and the corresponding Fourier's transformation in the frequency domain (Fig. 1b) [3].

3. METHODS OF MEASUREMENT & ASSESSMENT OF EXPOSURE TO MAGNETIC FIELD

The methods for measurement and assessment of employees exposure to M field according to the time characteristic of magnetic flux density B are differentiated to the measurement of periodical (harmonic, non-harmonic) M fields and non-periodical (pulsed) M fields.

3.1 Periodical magnetic fields

The measurement and assessment of exposure to M field is relatively simple in case of a periodical M field, i.e. field with the possibility of performing harmonic analysis with discrete spectrum.

The rms magnetic flux density values B_{rms} are measured at individual harmonic frequencies by applying frequency-selective method. The assessment of employees exposure is done by comparing the measured magnetic flux density B_{rms} rms values with action rms values of magnetic flux density $B_{a,rms}$ at each individual harmonic frequencies. Consequently the assessment of employees simultaneous exposure to multiple frequency M fields (at harmonic frequencies) is done, where for compliance this additive formula must be fulfilled

$$\sum_i B_{\mathrm{rms,\,i}} \Big/ B_{\mathrm{a,\,rms,\,i}} \leq 1 \tag{1}$$

In case of exceeding of action values $B_{a,rms}$, the rms values of induced current density $J_{n,rms}$ for non-uniform M field are calculated (real case of human exposure) by the procedure described in the technical standard [2]. The assessment of employees exposure is done by comparing rms values of induced current density $J_{n,rms}$ with limit rms values of induced current density for head and trunk $J_{L,rms}$ at each respective harmonics frequencies. Consequently the assessment of employees simultaneous exposure to multiple frequency M fields (at harmonic frequencies) is done, where for compliance this additive formula must be fulfilled

$$\sum_i (J_{\mathrm{n,i}} \Big/ J_{\mathrm{L,i}}) \leq 1 \tag{2}$$

3.2 Non-periodical (pulsed) magnetic fields

The measurement and assessment of employees exposure to pulsed M field is much more complicated because the frequency spectrum of the magnetic flux density B is not discrete but continuous. The actual magnetic flux density B measurement of M pulses is complicated by the fact that the duration of each pulse is usually very short. The assessment of employees exposure to pulsed M field can be performed by oscilloscopic method (in time domain) or theoretically by frequency method (in frequency domain).

3.2.1 Oscilloscopic method

This method enables to show time characteristic of magnetic flux density B. The peak value of the induced current density J_{pk} is determined by applying the time derivation of the magnetic flux density dB / dt. The peak value of the induced current density $J_{u,pk}$ caused by uniform M field is determined with application of numerical calculation 2D model [2] according to the formula

$$J_{\mathrm{u,pk}} = 0{,}5 .\, r .\, \sigma .\, (\mathrm{d}B / \mathrm{d}t) \tag{3}$$

where r - is the radius of equivalent disk (the substitution of body - trunk and head) [m], σ - is the average (homogenous) conductivity of living tissues [S.m^{-1}], dB/dt - is the magnetic flux density time derivation.

This analytical model is based on assumptions of highly simplified body geometry – head and trunk of the body is substituted by equivalent disk with radius r = 0.2 m, with homogenous average electrical conductivity of tissue σ = 0.2 Sm^{-1} and uniform applied M field.
The formula (3) is then simplified:

$$J_{u,pk} = 0{,}02.(dB/dt) \quad (4)$$

The non-uniform M field (real scenario of employeers exposure) the peak value of the induced current density $J_{n,pk}$ is determined according to the formula

$$J_{n,pk} = K.J_{u,pk} = K.0{,}02.(dB/dt) \quad (5)$$

where K - is the coupling factor, dependent on the type of M field source and the distance between the source and evaluation area (measurement point) [2].
The assessment of employees exposure to pulsed M field is done by comparing calculated peak values of $J_{n,pk}$ with a limit peak value $J_{L,pk}$ at equivalent frequency f_e.

3.2.2 Frequency method

The frequency domain method is based on the measuring and time waveform capturing of the pulsed M field and subsequent application of the Fast Fourier transformation (FFT) algorithm.
The magnetic flux density wideband (WB) rms values $B_{WB\,(x,y,z),rms}$ in the particular orthogonal axis (x, y, z) are detected by integration of the displayed frequency characteristic of magnetic flux density and then a final rms value $B_{WB,rms}$ is calculated according to the following formula

$$B_{WB,rms} = \sqrt{B_{WBx}^2 + B_{WBy}^2 + B_{WBz}^2} \quad (6)$$

The equivalent frequency f_e is calculated as $f_e = 1 / (2.t_p)$, where t_p is the pulse duration in seconds. The pulse duration is evaluated from the equipment technical documentation or the equipment settings. In case that it is not possible to find out the pulse duration (it is quite common in practice), the pulse duration has to be evaluated from time waveform of pulse obtained by oscilloscopic method.
The assessment of employees exposure to pulsed M field is done by comparing the calculated magnetic flux density $B_{WB,rms}$ values with action rms values of magnetic flux density $B_{a,rms}$ at equivalent frequency f_e.

4. MEASUREMENT OF PULSED M FIELD

The pulsed M field measurement was carried out at the operation area of the magnetic structurescope (coercimeter) during detection of permanent magnets properties. The pulsed M field was generated by magnetizing coil supplied with pulsed electric current with required time waveform. The magnetic structurescope generated series of three pulses and magnetometer detected the response.

4.1 Oscilloscopic method

The measurement in the time domain was carried out using a measuring coil FESP 5133-7/41 with a diameter of 133 mm. The time waveform of voltage u(t) and instantaneous voltage values U_{RX} at the input of oscilloscope ETC M595 were measured in the three orthogonal axis (x, y, z) positions of measuring coil. The oscilloscope has allowed recording the time waveform of the pulses to the connected PC with control software (ETC Roll mode ver. 2.02).
The values of the magnetic flux density B [dBpT] in the orthogonal axis (x, y, z) are determined as the sum of voltage values U_{RX} [dBμV] at the input of the oscilloscope and the conversion factor CF [dB(pT/μV)] of used measuring coil. Fig. 2 shows the time waveform of a single pulse, i.e. electric voltage u_z(t) of the measuring coil oriented in the z direction at a distance of employee trunk position during the work.

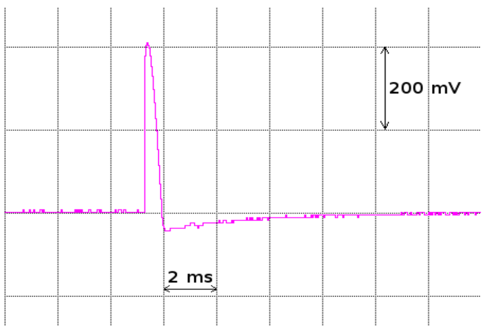

Fig. 2: Voltage tome waveform at the input of oscilloscope u_z(t) - axis z

4.2 Frequency method in the frequency domain

The measurement in the frequency domain was done with field analyzer NARDA EHP-50C. The system consists of three orthogonal oriented electric filed probes and three orthogonal coils for M field measurement. The analyzer has recorded the rms values of magnetic flux density B, which has been transmitted via fiber optic cable to the display unit NBM 550 or PC control software EHP-TS (Windows platform).

The continuous magnetic flux density B frequency spectrum has been detected using Fast Fourier Transformation (FFT). The isotropic measurement of the magnetic flux density B is based on the composed sequences:

- ✓ the magnetic flux density B measurement during defined time interval at the x-axis position, FFT algorithm running and spectrum data saving,
- ✓ the magnetic flux density B measurement during defined time interval at the y-axis position, FFT algorithm running and spectrum data saving,
- ✓ the magnetic flux density B measurement during defined time interval at the z-axis position, FFT algorithm running and spectrum data saving.

And then consequently is resultant frequency spectrum calculated.

It is clear that the presentation of resultant spectrum is time consuming, because the sequence duration is depended on the width of the display range (SPAN). The repetition rate of the sequence is approximately one second in the fastest case.

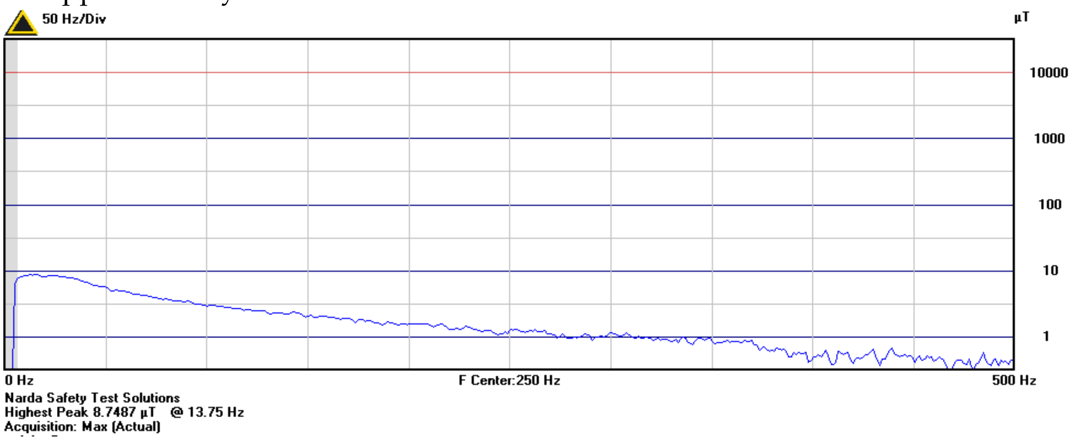

Fig. 3: Frequency spectrum of generated pulses - axis x

The measurements were performed using EHP-TS software, which enables measuring only in one defined axis and consequently reducing the time of measurements to hundreds of milliseconds. The measurement has proved that the analyzer could not capture all the generated pulse even in shorter measurement sequence. Therefore the HOLD-Max function of analyzer was activated while measuring 10 pulses series. Fig. 3 shows the frequency spectrum of pulses in x axis coil position.

4.3 Measurement results and exposure assessment

Table 1 gives the calculated values of employees exposure parameters to pulsed M field generated by magnetic structurescope (coercimeter) during detection of permanent magnets properties.

Table 1: The results of exposure to M field measurements

Frequency method $B_{WB,rms}$ [◎T]	Oscilloscopic method $J_{n,pk}$ [mA/m^2]
38,3 (f_e = 833 Hz)	4,07 (f_e = 833 Hz)

The comparison of the calculated magnetic flux density value with action value and induced current density value with limit value is as follows:

- ✓ calculated (measured) magnetic flux density $B_{WB,rms}$ rms value exceeded the action rms value of manetic flux density $B_{a,rms}$ = 30,7 µT at frequency f_e = 833 Hz,
- ✓ calculated induced current density $J_{n,pk}$ peak value did not exceed the limit peak value of induced current density for head and trunke $J_{L,pk}$ = 14,14 mA.m^2 at frequency f_e = 833 Hz.

5. COMPARISON OF M PULSED FIELD MEASUREMENT METHODS

5.1 Oscilloscopic method with measuring coil

The method is time consuming due to the separate measurements in three axis as well as demanding to the technicians professional qualification in the process of signal processing and calculation procedures.

The practical application of this method, especially in the case of pulses with extremely short rise time and longer fall time, evokes the question if magnetic flux density *B* derivation should be calculated at the rise time or fall time of the pulse.

The shorter time variation of magnetic flux density value is the cause of higher value of induced current density. The longer time variation of magnetic flux density value is the cause of lower value of induced current density.

This question remains unanswered concerning the quantification of induced current density evaluation of exposure to M pulsed field.

Note: According to the regulation valid in Czech Republic the filter with prescribed weighting function has to be connected between the coil (probe) and oscilloscope while measuring M pulsed fields [4]. The role of the filter is to reduce the pulse rise time of the magnetic flux density *B*, i.e. reduction of dB / dt and the value of induced current density *J*. There is also a reduction of limit value of induced current density J_L referred to the Directive [1].

5.2 Frequency method

When applying this method, the problem is that technician has not confidence if the captured FFT spectrum (including the value of B_{WB}) is indeed correct (valid), i.e. whether the FFT analysis was performed on a suitable sample of whole pulse of the magnetic flux density *B*.

The analyzer NARDA EHP-50C does not allow to make any settings of FFT algorithm (the number of points / lines of resolution, the highest analyzed frequency, averaging, window weighting type, etc..). The limitation of convenient window weighting type causes the distortion of resultant frequency spectrum in the case of pulsed (transient) signals.

The solution to this problem is to capture time waveform of magnetic flux density *B* by measuring in the time domain and subsequently perform FFT analysis at laboratory by suitable software product that allows correct setting of FFT algorithm parameters (for example: SigView, LabView).

6. CONCLUSION

The measurement and assessment of employees exposure to pulsed M field requires the application of more complex measurement procedure comparing to the measurement of exposure to periodical M field.

The relevance of suitable method application for measurement of employees exposure measure parameters is related to the fact that in case of exceeding the exposure action values, the employer has to carry out the health surveillance of employers.

Furthermore if limit exposure values are exceeded, the employer shall take immediate action to reduce exposure below exposure limit values.

The conclusion of comparing both methods of performed measurement of exposure to pulsed M field is as follows:

- ✓ it is advisable to prefer oscilloscopic method in the time domain,
- ✓ the frequency domain measurement method due to the limited settings of FFT analysis parameters causes the distortion of resultant frequency spectrum. That is why this method is not suitable for employees exposure evaluation.

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