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ANALYSIS OF TIME-VARYING LOW-FREQUENCY MAGNETIC-FIELD EMITTED FROM THE SHIP'S INVERTER-FED INDUCTION MOTOR

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Abstract − This paper focuses on the analysis of low-frequency magnetic-field emissions (MFEs) in ship's environment, in reference to admissible levels for exposures to time-varying electromagnetic field (EMF), proposed by International Commission on Non-Ionizing Radiation Protection (ICNIRP). It concerns the special case of simultaneous exposure to multiple frequency fields, when a summation formula (from ICNIRP guidelines) has been applied. Due to a time-varying behavior of the sinusoidal components of the magnetic flux density (MFD), the time-frequency analysis based on the short–time Fourier transform (STFT) was performed. The level of the magnetic field intensity was evaluated, in reference to the standard for occupational environments, which takes into account the people's protection against the excessive emission of the low-frequency magnetic field. The selected results of the off-line analysis of the recorded magnetic flux density near by the ship's inverter-fed induction motor are presented.

Keywords low-frequency magnetic field, exposure to time-varying magnetic field

1. INTRODUCTION

In the ship's environment, where the high concentration of the numerous electrical and power electronics equipment is present, the significant levels of the time-varying electromagnetic field (EMF) emissions occur [1]. Especially, induction motors supplied from the PWM (Pulse Width Modulation) inverters behave as effective sources of the low-frequency magnetic-field emissions (MFEs), which produce a wide spectrum of harmonics components (derived from the main fundamental frequency of power supply voltage), but also a considerable amount of non-characteristic harmonics (derived from the voltage frequency at the output of inverter and its switching frequency) and their inter-harmonics. The operation of these devices is the reason of occurrence of the violent changes of magnetic fields, which have influence on technical equipment, causing in many cases their abnormal functioning, and also can affect the health of the ship's crew.

Due to the above-mentioned reasons, emission limits have been defined by international committees both for the functional aspects [2], and for limiting human exposure to EMF emissions [3].

This paper concerns the problem of estimation of the exposure level to time-varying low-frequency magnetic-field on board the vessel, in reference to admissible levels for the occupational exposure, proposed by International Commission on Non-Ionizing Radiation Protection (ICNIRP) [3]. In the special case of simultaneous exposure to multiple frequency fields, a summation formula defined in ICNIRP guidelines can be applied [3]. The formula determines the requirements for protection against multi frequency steady-state MFEs. In order to identify the time-varying signal in time intervals and its spectrum distribution, a joint time-frequency-domain method of analyzing was used. Instantaneous values of the summation formula were estimated with the short–time Fourier transform (STFT) of the digitized magnetic-flux density (MFD) time series acquired by measurement [1].

2. TIME-FREQUENCY ANALYSIS OF MFD WAVEFORM

The short–time Fourier transform is the most widely used method for examining non-stationary signals [4], [5]. The STFT involves a compromise between the time and frequency resolutions of the resulting time-varying spectral descriptions of the data. This resolution problem could be suppressed by using alternate methods, i.e., the wavelet transform (WT), which in contrast to the fixed analysis window size in the STFT, uses longer windows for low frequencies and shorter windows for higher frequencies. The ability of wavelets to focus on short time intervals for high-frequency components and long intervals for low-frequency components improves the analysis of certain types of non-stationary data – in particular, transient data that have a finite duration, which is covered by the available window length [6]. Although the WT method provides better analysis, the computational complexity places a limitation on its use in real-time measuring system.

If frequency contents of an analyzed signal don't change rapidly, then the STFT can be successfully applied to obtain a joint time-frequency-domain representation of MFD emissions. The major advantage of this approach is its low computational complexity.

The STFT algorithm partitions the time-domain input discrete signal into several disjointed or overlapped blocks by multiplying the signal with a window function (sliding window) and then applies the discrete Fourier transform to each block. A type and a length of the sliding window affect the time-frequency resolution of the STFT. The window length should be small enough so that the windowed signal block is essentially stationary over the window interval and large enough so that the Fourier transform of the windowed signal block would provide a reasonable frequency resolution. A discrete-time STFT of the digitized MFD time series is defined as [7]

$$STFT\,[k,n]=\sum_{i=kdM-\frac{L}{2}}^{kdM+\frac{L}{2}-1} x_k[i]h^*[i-kdM]e^{-j2\pi ni/N}, \quad (1)$$

where $x_k[i]$ denotes the k th windowed segment of the digitized MFD waveform $x[i]$, $h[i]$ denotes the sliding window, L is the window length, dM is the step size to move the sliding window, N is the number of the frequency bins (number of blocks).

When dM is greater than or equal to the window length L, no overlap exists between sliding windows.

In the performed analysis the tapering signal was obtained using the Blackman window given by [4]

$$h[i]=0.42-0.50\cos(\frac{2\pi i}{L})+0.08\cos(\frac{2\pi i}{L}). \quad (2)$$

The Blackman window is a good general purpose window because of its high side-lobe rejection [4]. Since the accuracy in the amplitude is important, a window with a wide main lobe is appropriate. As it was mentioned above, a tapering window used to suppress a side-lobe leakage also increases the width of the main lobe of the spectral window. To counteract this undesirable effect, overlapped processing techniques can be used [6]. A common selection in overlapped processing is assumption that the overlap $(L-dM)$ is equal 0.5. This will retrieve about 90% of the stability lost due to the tapering operation but also will double the required number of FFT operations [6]. Overlap of the sliding window makes the STFT smoother along the time axis. However, overlap requires more computation time and memory. If the signal length is large and the spectral content evolves slowly, it is not necessary to overlap the sliding window [4]. The functions in (1) and (2) are used to determine the spectral components of the MFD emissions.

To reduce spectral leakage effects related to non synchronous sampling conditions, STFT spectral estimates obtained by (1) should be corrected by means of suitable frequency interpolation of the spectral lines [8]. The key step for the estimation of the basic parameters of a single component (A_k, f_k) is the determination of the position along the frequency axis of the measured component δ_k between the two largest local DFT coefficients X_k and X_{k+1} surrounding the component itself [8].

Let $f_k = k\Delta f$ be frequency and $|X_k[f_k]|$ amplitude estimates of the k th spectral line as calculated by STFT, Δf is the frequency resolution of the time window. Then, the spectral-line frequency and amplitude after interpolation are [9]

$$\hat{f}_k=(k+\delta_k)\Delta f, \qquad -0.5<\delta_k\le 0.5 \quad (3)$$

$$\left|\hat{X}_k[\hat{f}_k]\right|=D\left|X_k[k\Delta f]\right| \quad (4)$$

where δ_k and D are corrective coefficients.

As far as the Blackman window is concerned, these coefficients take the following expressions [8]

$$\delta_k\approx\frac{3-2\alpha_k}{1+\alpha_k}, \quad (5)$$

$$D=2\left|\frac{\pi\delta_k(1-\delta_k^2)(4-\delta_k^2)}{\sin(\pi\delta_k)}\right|. \quad (6)$$

The quotient α_k, is determined by [8]

$$\alpha_k=\frac{|X_k[k\Delta f]|}{|X_k[(k+1)\Delta f]|}=\frac{3-\delta_k}{2+\delta_k}. \quad (7)$$

The computer processing algorithms were realized in LabVIEW programming environment.

3. REFERENCE LEVELS AND SUMMATION FORMULA

For exposure to low-frequency magnetic fields, the magnetic flux density B is the parameter used by the ICNIRP for the definition of the reference levels of protection from induction effects of currents in tissues that can be electrically stimulated. The reference levels for general public and occupational exposures to time-varying magnetic fields are illustrated in Fig. 1. The limits recommended by the ICNIRP are linked to considerations on the effects of exposure to harmonic sinusoidal fields.

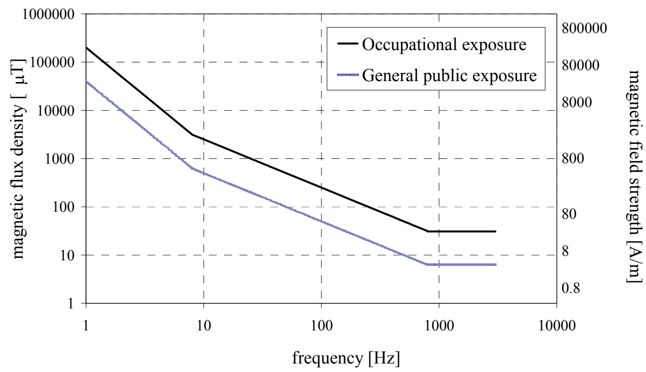

Fig. 1. Reference levels for general public and occupational exposures to time-varying low-frequency magnetic fields (unperturbed rms values) [3].

In case of simultaneous exposure to multi frequency steady-state MFEs the following requirement, based on summation formula defined in ICNIRP guidelines [3], can be applied to the field levels

$$\sum_{i=1Hz}^{65kHz} \frac{B_i(t)}{B_{L,i}} + \sum_{j>65kHz}^{10MHz} \frac{B_j(t)}{B_0} \le 1 \qquad (8)$$

where i and j are summation indexes running over the finite set of the MFD sinusoidal components, $B_{L,i}$ and B_0 are reference levels defined in [3]. The term $B_k(t)$, $k = i, j$ denotes the time-varying magnitude of the k th frequency component of the MFD.

According to [3], safety conditions are ensured if the inequality in (8) is satisfied at any time instant.

Estimation of the magnitude of the k th frequency component of the MFD $B_k(t)$ in (8), is obtained by spectral analysis of the digitized MFD time series acquired by measurement.

4. MEASUREMENT EXPERIMENT

The measurements of the magnetic field emissions were performed onboard the Gdynia Maritime University research-training vessel, near by the bow thruster motor fed from the inverter, during maneuvering and the sea voyage [1]. Bow thruster is assembled in the fore part of the ships' hull and has constant pitch propeller. Using the control levers at the wings of the bridge, it is possible to change the speed and direction of the revolutions of the propeller, and in this way to move the bow of the ship during maneuvering. The bow thruster is driven with squirrel cage asynchronous motor fed by the PWM frequency converter (Fig. 2). The IGBT (Isolated Gate Bipolar Transistor) inverter was operating at 2 kHz (possible 4 kHz) switching frequency. The inverter output frequency was adjusted in the frequency range from 0 to 50 Hz.

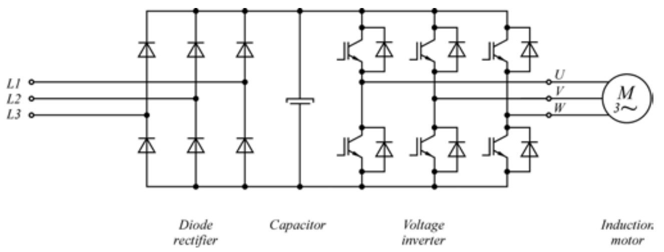

Fig. 2. The diagram of PWM frequency converter

Measurements were performed in the bow thruster compartment with the ESM-100 H/E field meter, which was fixed on the wooden bar (Fig. 3), about 1 m from the bow thruster motor.

The results of the preliminary measurements of MFD emissions, which are caused by the running inverter fed the ship's bow thruster motor, confirmed that MFD spectrum depends strongly on frequency [1]. The magnetic field spectrum spreads out mainly in low frequency range below 2 kHz [1]. The presented below exemplary results of measurements and analyzing were performed within the frequency range from 5 Hz up to 2 kHz.

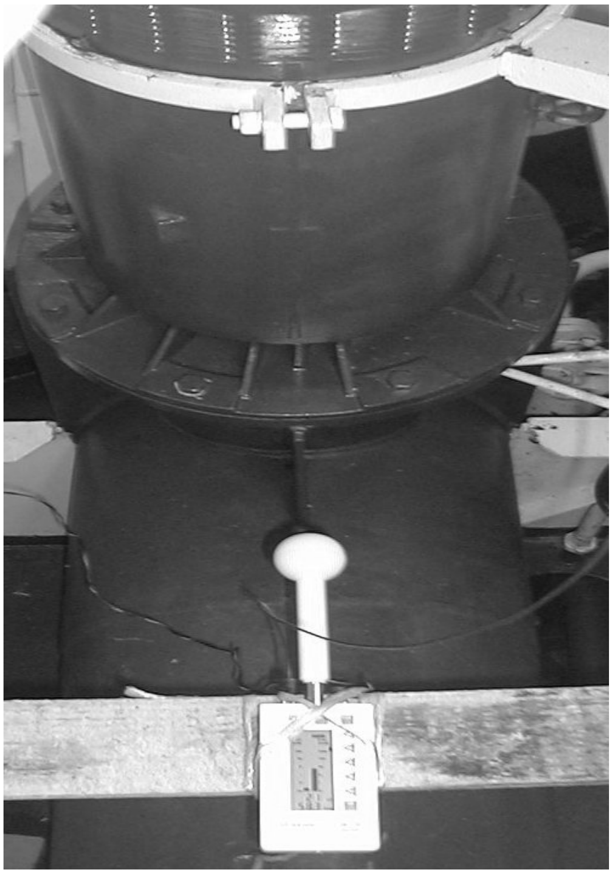

Fig. 3. The ESM-100 H/E field meter located close to the bow thruster motor

Data recording of MFD emissions was carried out with a/d converters of the data acquisition board (DAQ), with 16-bit resolution and sampling rate up to 20 kS/s, which were connected to the analogue outputs of an isotropic field meter. ESM-100 H/E field meter, which was applied in this system, enables the measurements of MFD in the measuring ranges from 1 nT to 20 mT. Four wide-band analogue outputs of this meter afford possibilities for measuring the time waveforms of the magnetic fields, separately in the three orthogonal directions, in the output voltage range from 0 to 600 mV. Discrete signals were off-line analyzed with LabVIEW software.

In the low frequency range (below 2 kHz), the formula (3) is modified as follows

$$\sum_{m=1}^{M_1} \frac{B_m(t)}{B_{L,m}} + \sum_{l=M_1+1}^{M_2} \frac{B_l(t)}{B_r} \le 1. \qquad (9)$$

The upper index M_1 determines a sinusoidal component with frequency less than or equal 800 Hz for general public and 820 Hz for occupational exposure. The upper index M_2 corresponds to a sinusoidal component with frequency less than or equal 2 kHz. The field reference level B_r in (4) equals 6.25 μT for general public and 30.7 μT for occupational exposure respectively [3].

4. RESULTS OF ANALYSIS

The experimental data, collected during the measurement experiment were processed with the virtual instrument. The length of the sliding window was equal 2048 samples, what results in frequency resolution of 0.97 Hz. The step size and the number of the frequency bins were equal 2048 samples as well. No overlapping between sliding windows was used.

The instantaneous values of the MFD waveform obtained during the sea voyage, when the bow thruster wasn't running are presented in Fig. 4. The level of the magnetic field background existing near by the bow thruster motor is shown. On the time-frequency plane obtained when the STFT was applied, the basic component 50 Hz and its odd harmonics are identified; due to the ship's supply system (Fig. 5). According to the requirement (9) the instantaneous values of the summation formula were computed for the case of the sea voyage. The result is shown in Fig.6. It can be noticed that safety conditions are ensured at the whole time of this part of experiment.

The plots of Figs. 7, 8 and 9, corresponding to the case of the vessel during maneuvering, present the time waveform of the MFD, acquired in the same measurement place and its STFT spectrograms. On the time-frequency plane there are components resulting from the inverter output frequency (especially 20 Hz, 30 Hz, 50 Hz) (Fig. 9), their harmonics, as well as, the steady-state harmonic components of 50 Hz existing in examined signal during the whole observation time. This plot evidences the time-varying spectral components related to the output frequency of the inverter and its harmonics, which changes during the experiment. The magnitude and the frequency of the all components are clearly identified. The time frequency representation confirms a non-stationary character of the investigated MFD emissions. The calculated MFD spectral contents should be compared with the appropriate reference levels in compliance with the requirements of protection from exposure to time-varying EMF. The results of the signal spectrum evaluation, obtained with the FFT procedure was presented in Fig. 10. It can be noticed that the calculated values of the MFD emissions don't exceed the reference levels in the examined range of frequency (see also Fig. 1). But this way of a compliance testing doesn't take into account an influence of the simultaneous exposure to fields of different frequencies. According to the requirement (9) the instantaneous value of the summation formula was computed over the whole duration of the measurement by applying the STFT procedure.

The instantaneous values of the summation formula are shown in Fig. 11. It is observed that safety conditions aren't ensured at the whole time. The inequality in (9) isn't fulfilled at few time intervals (Fig. 12). The main spectral component at 30 Hz and its related harmonics, as well as the stationary 50 Hz harmonic components simultaneously occur in the first time interval [67, 234] s, associated with high levels of the instantaneous value of the summation formula (Fig. 12). In the next intervals, where the limit of 1 is exceeded, there are frequency components mainly related

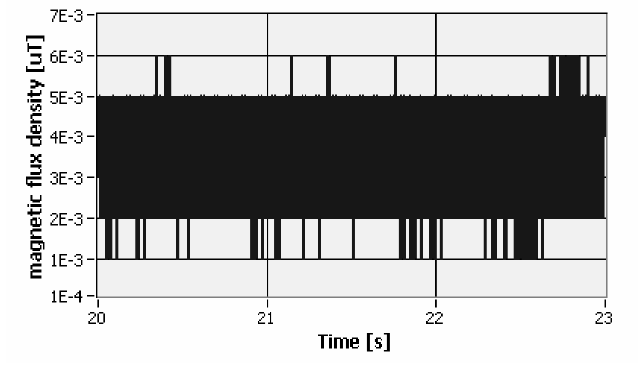

Fig. 4. The time waveform of the MFD near by the bow thruster motor, recorded during the sea voyage, for the time interval equal 3 s.

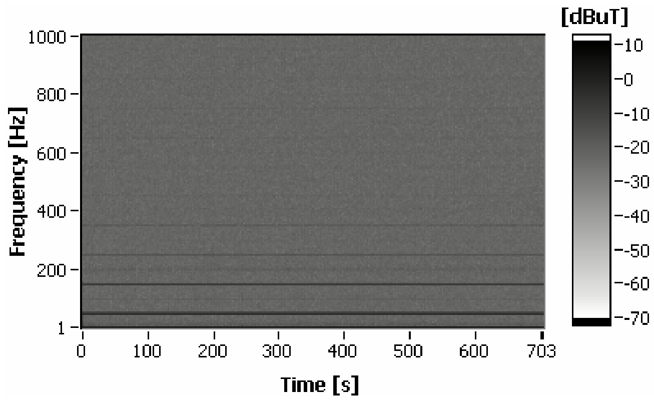

Fig. 5. The time-frequency plane of the MFD magnitude, obtained by using STFT with the Blackman window in the frequency range from 1 Hz to 1000 Hz. The window length, the step size and the number of the frequency bins is equal 2048 samples.

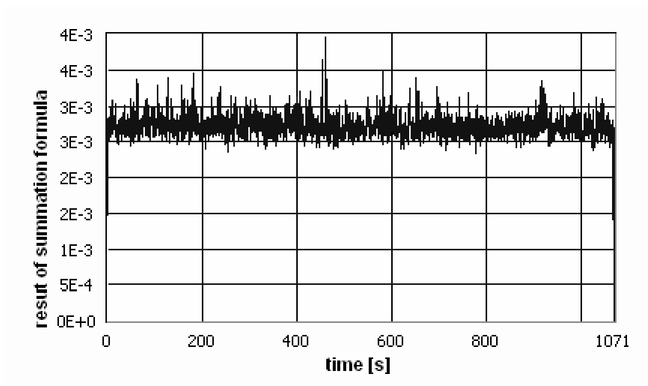

Fig. 6. The values of the summation formula defined in (9) in the time function. The linear scale of y axis was applied.

to the output frequency of the inverter, its harmonics and stationary harmonics of 50 Hz. The differences between the limiting value of the summation formula and the instantaneous values, obtained during above-presented analyzing procedure don't exceed 4 dB (Fig. 12).

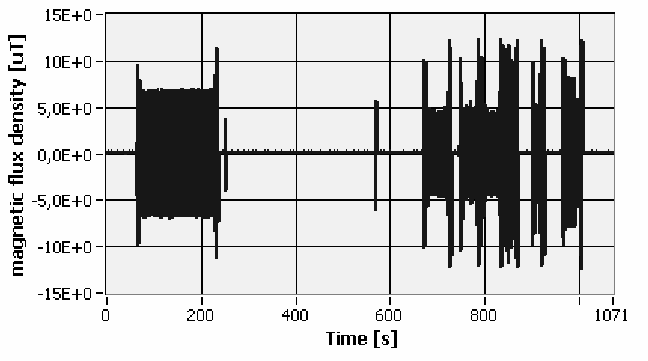

Fig. 7. The time waveform of the MFD near by the bow thruster motor, recorded during the maneuvering. The sampling frequency equal 2 kHz.

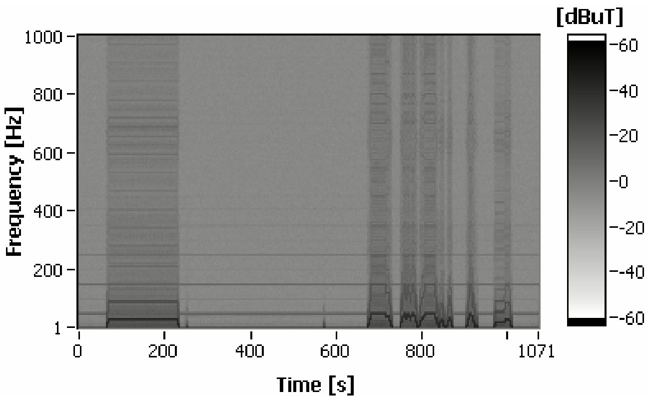

Fig. 8. The time-frequency plane of the MFD magnitude, obtained by using STFT with the Blackman window in the frequency range from 1 Hz to 1000 Hz. The window length, the step size and the number of the frequency bins is equal 2048 samples.

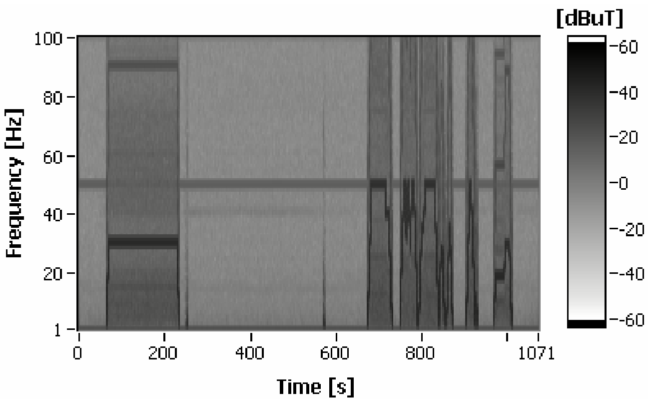

Fig. 9. The zoom of the time-frequency plane of the MFD magnitude shown in Fig. 5, in the narrow frequency range from 1Hz to 100 Hz.

5. CONCLUSIONS

An analysis procedure has been presented for the characterization of low-frequency magnetic-field emissions in ship's environment. It was shown that the joint time-frequency-domain representation of MFEs has been applied successfully to determine with some time resolution the moments, when the analyzed signal components of different frequencies occurred. This way, the sources of high level magnetic field can be localized in the tested environment.

Due to a time-varying behavior of the analyzed signal, instantaneous values of the summation formula were assessed, based on the on the evolutionary spectral estimates of the MFD emissions. The STFT was a good first choice to perform a time-frequency analysis because this method is simple and fast. The long-range leakage was minimized using suitable tapering windows and the short-range leakage was corrected by an interpolation formula.

The obtained results point out the few frequency ranges, where the simultaneous exposure to magnetic fields of

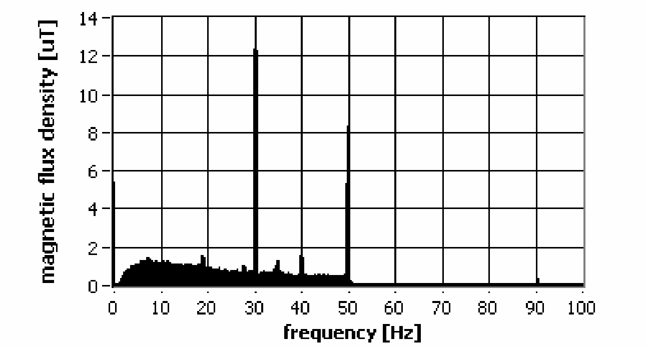

Fig. 10. The spectrum of the MFD magnitude obtained by using the Blackman window in the frequency range up to 100 Hz. The window length equal 2048 samples.

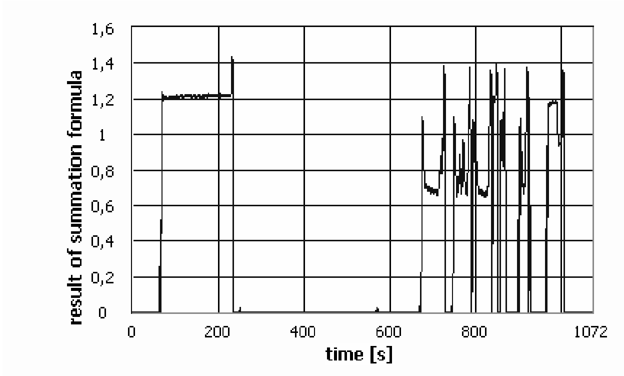

Fig. 11. The values of the summation formula defined in (9) in the time function. The linear scale of y axis was applied.

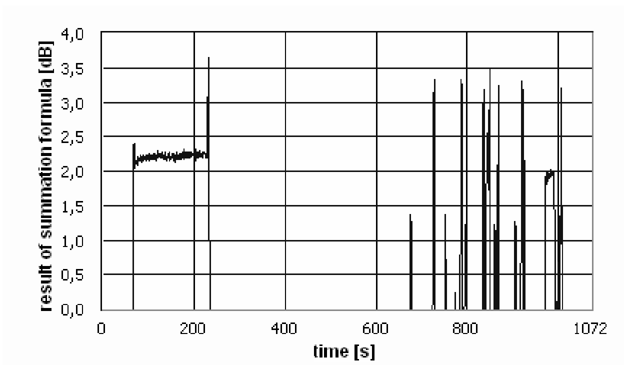

Fig. 12. The values of the summation formula that exceeded the limit of 1 (0 dB in the decibel scale).

different frequencies exceeded the limiting value of the summation formula, originally defined in the ICNIRP guidelines [6].

The presented method of analysis has been applied for the magnetic-field emissions in surroundings of the ship's bow thruster motor drive with the power frequency inverter in low frequency range below 2 kHz. The characteristics of the a/d converter adopted in the designed measuring system gives possibilities data analyzing to the upper frequency of 10 kHz. Nevertheless, the numerical analysis procedure has a general validity and may be used for the monitoring and characterization of low-frequency MFD emissions in ship's environment, in the whole bandwidth of interest.

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