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Choice of STFT and WT Parameters for Monitoring of EMI in Track Circuits

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Abstract—**The article considers the problem of the correct choice of the parameters of the short-time Fourier transform and the continuous wavelet transform to ensure monitoring of electromagnetic interference in rails in order to ensure the electromagnetic compatibility of traction current with track circuits. The problem of correct choice of parameters for the time-frequency analysis of currents in track circuits lies in the strict requirements of the standards for the accuracy of measuring the magnitude, frequency, and duration of disturbances, as well as in the specifics of the measured current parameters and in restrictions inherent in the short-time Fourier transform and continuous wavelet transforms on the accuracy of measuring harmonic parameters. The specificity of currents in rails is associated with a large dynamic range of harmonics, a wide frequency range and the proximity of harmonics in the spectrum to each other, which makes it difficult to distinguish weak harmonics against the background of more powerful ones, as well as in the non-periodic and random nature of current. The paper considers the technology of the correct choice of parameters of the short-time Fourier transform and the continuous wavelet transforms. The results of the work were approved during testing of new types of trains.**

Keywords—electromagnetic interference, electromagnetic compatibility, traction current harmonics

I. INTRODUCTION

The problem considered in the paper is related to ensuring electromagnetic compatibility (EMC) of traction current with railway signaling systems, namely with track circuits (TCs), which are used in traditional train control systems as train location sensors, as well as a channel for transmitting information about the state of the track to the driver's cab. The most common traction power supply system consists of overhead power supply conductors connected to power supply substations and traction rails, which are used as a path for returning traction current back to the substation [1]. Thus, the signal currents of the TCs and automatic locomotive signaling (ALS) flow in the rails along with a return traction current, which leads to a strong distortion of the signal current due to electromagnetic interference (EMI) from the traction current. Reducing the influence of traction current on signal currents is provided by such well-known methods as the use frequencies for signal current that differ from the frequencies of the main harmonics of the traction current, the use of filters at the inputs of TCs receivers, the equalization of the electrical resistances of two traction rails, etc. Also, new types of signaling systems before commissioning on railways must be tested for EMI immunity, and new types of rolling stock must be tested for EMC with signaling systems in accordance with the requirements of norms and standards. In addition, EMI in track circuits is periodically measured during operation in accordance with the maintenance schedule [2], [3], but in most cases such measurements are carried out manually. The recent use of automated information and control systems as an add-on to traditional train control systems makes it easy to create embedded systems for continuous monitoring of the parameters of signal currents in rails based on widely used data acquisition systems (DAQ). The parameters of the signal current during monitoring must be controlled in the time and frequency domains. However, when measuring parameters in the frequency domain, it is often not taken into account that the current in the rails is a non-periodic random process, and, accordingly, the discrete Fourier transform is not applicable for its analysis. For the time-frequency analysis of non-periodic signals, the windowed short-time Fourier transform (STFT) is used, which makes it possible to measure the parameters of the harmonics contained in the traction current [4]-[6], but for short-term localized EMI in the signal current of TCs, the STFT does not give good results. For example, STFT does not provide the required accuracy in determining the parameters of short-term interference with a frequency close to the frequency of the amplitude-modulated current of ALS in short pauses between pulses with a duration of 0.12 s [2]. The wavelet transform (WT) uses time-localized wave-like oscillations, the scale and position of which are changed during the analysis, which makes it possible to identify short-term disturbances in the signal [7]-[9]. But the problem lies in the strict requirements of the standards for the accuracy of measuring the magnitude, frequency, and duration of disturbances, as well as in the specifics of the measured current parameters and restrictions inherent in the STFT and WT on the accuracy of measuring harmonic parameters. The specificity of the currents in the rails lies in the large dynamic range of harmonics that need to be controlled, a wide frequency range and the proximity of the harmonics in the spectrum to each other, which makes it difficult to distinguish weak harmonics against the background of more powerful ones. In addition, current in rails is non-periodic and has a random character.

The purpose of this work is to develop and test a methodology for choosing the parameters of the STFT and WT for monitoring interference in track circuits. Section II of the article briefly describes the object of investigation and considers the methodology for choosing the STFT and WT parameters for monitoring harmonics in rails. Section III gives an evaluation of the measurement accuracy of harmonic parameters based on the method under consideration.

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II. CHOICE OF THE STFT AND WT PARAMETERS

A. *Brief Description of the Object of Investigation*

The power supply of electric rolling stock is carried out from electrical substations via overhead wires. The return traction current flows from the rolling stock to the substations along the rails and partly along the ground due to the low electrical conductivity between the rails and the ground. For interval control of train traffic, the track is divided into block sections, within which track circuits are organized, which are used as train location sensors. Traction current harmonics with frequencies close to the frequencies of the signal current and values and durations exceeding certain limits can cause failures in TCs operation. These limits depend on the types of track circuits, and may vary in different countries [12], [13].

B. *Choice of the STFT and ADC Parameters*

The choice of parameters of the main DAQ blocks, namely, the signal conditioning circuit, ADC, antialiasing filter, STFT-processor is described in detail in [4]-[6], [14]. Therefore, this paper considers only the choice of some ADC parameters that are directly related to the accuracy of measuring the weak harmonics parameters in the traction current spectrum. The main errors associated with the ADC itself include offset error, gain error, differential linearity error, integral linearity error, and total unadjusted error [14]. The offset and gain errors of an ADC is easily corrected by calibration. Some other errors can be compensated. Therefore, the paper considers only the choice of the ADC resolution (the number of its bits), the value of which largely determines the dynamic range of the system and the signal-to-noise ratio (SNR). The SNR of the ADC-STFT system in the ideal case, when only quantization noise is taken into account, is defined as [14]

$$SNR = 6.02n + 1.76 + 10\log_{10}\left(N_W / 2 \right) \ \text{(dB)}, \qquad (1)$$

where n is the number of the ADC bits, N_W is the length of window in number of samples. The dynamic range of current is defined as the ratio of the value of the largest harmonic I_1 to the value of the smallest harmonic $I_{\min}$ according to expression (in dB) $D_{\mathrm{TC}} = 20\log_{10}\left(I_1 / I_{\min} \right)$, and for the alternating traction current with the value of the largest harmonic I_1 of 300 V and the value of the smallest harmonic of 0.2 A [12], the dynamic range of the system must be at least 63.5 dB. To ensure the measurement of the smallest harmonic with a relative error δ, the dynamic range of the ADC, taking into account only the quantization noise, must be at least

$$D_{\mathrm{ADC}} \geq D_{\mathrm{TC}} + 20\log_{10}(2\delta) + D_0 \ \text{(dB)}, \qquad (2)$$

where D_0 takes into account the headroom of the ADC input current to protect against possible accidental increases and additional unpredictable factors [14]. From (2) it follows that to ensure the measurement error of the lowest harmonic of 5%, the resolution of the ADC must be at least 14 bits. The parameters of the windowed STFT, in particular the type of the window function, also strongly affect the accuracy of measuring weak harmonics. The wide dynamic range of currents in the rails requires the use of a window function with small side lobes and a large roll-off in the frequency domain.

But such types of window functions tend to have a wider main lobe, which reduces the resolution in the frequency range [4]-[6]. Since these requirements for a window function conflict with each other, the trade-off is necessary for its correct choosing. The use of windows leads to errors associated with coherent power gain, which can be taken into account using the known correction parameter, but the error associated with the picket fence effect cannot be taken into account, since its value is not determined only by the type of window [4]-[6]. The resolution of the windowed STFT in the frequency domain is defined as [6]

$$\Delta f = F_{\mathrm{S}} / N_{\mathrm{W}}; \qquad (3)$$

where F_{S} is the sampling rate. Since the simultaneous increase the resolution in time and frequency domain is not possible due to the uncertainty principle $(\Delta t\,\Delta f = 1)$, a trade-off is necessary when setting these two parameters. The resolution of the monitoring system in the time domain must be at least 0.3 s [12], which, in accordance with the uncertainty principle, corresponds to a frequency resolution of not more than 3.3 Hz. This frequency resolution is insufficient to analyze harmonics in the frequency range from 19 Hz to 31 Hz. The frequency resolution in this case can be improved by zero-padding of the measured current and time domain resolution can be improved by increasing window overlap [4].

C. *Choice of the WT Parameters*

The continuous wavelet transform (CWT) was chosen from the available types of wavelets transform as the most suitable for time-frequency analysis of non-stationary current [7]-[9]. Since CWT uses short-wavelength oscillations, their resolution in frequency and time is determined mainly by the type and parameters of the wavelet used. For the analysis of traction currents with time-varying amplitude and frequency, as well as for the detection of local signal disturbances, the analytical Morse wavelet was chosen as the most suitable for these purposes. The Morse wavelet has the following parameters: the time-bandwidth product P^2 and symmetry parameter γ [15]. The standard deviations of the Morse wavelet in time and frequency are determined as [15], [16]

$$\sigma_t \approx \sqrt{P^2 / 2}\,; \qquad \sigma_f \approx \frac{1}{2}\sqrt{2 / P^2}\,. \qquad (4)$$

The frequency limits of the continuous analysis are defined by the lowest peak passband frequency $F_{\min}$ and the highest peak passband frequency $F_{\max}$, which are defined as

$$F_{\min} \geq 2F_N\,; \qquad F_{\max} \leq \frac{2\sigma_t F_{peakWT}}{N}, \qquad (5)$$

where F_{peakWT} is the peak frequency of Morse wavelet, N is the signal length, F_N is the Nyquist frequency. Minimum and maximum values of period limits are determined as [15], [16]

$$T_{\min} \geq 2T_S\,; \qquad T_{\max} \leq \frac{N}{2\sigma_t F_{peakWT}}, \qquad (6)$$

where T_S is the sampling period.

III. ASSESSMENT OF MEASUREMENT ACCURACY

A. *Brief Description of the Measurement Technique.*

The accuracy of the time-frequency analysis of the current in the rails by the STFT and WT with the parameters selected in accordance with the technique under discussion was assessed using real currents recorded in the rails, as well as simulated currents with known parameters, the values of which were close to the parameters of real currents. Ten different currents were simulated with harmonics at frequencies defined by standards, with a duration of 0.3 s [12] and values in the range from 0.5 to 1.5 of limit values, to which random noise was added. The sampling rate for the simulated currents was 22 kHz. The Blackman-Harris window was selected for STFT that provides the required dynamic range [8], [9]. The length of window was 13230 samples to provide a time resolution of 0.3 s. The window overlap was 50%. The Morse wavelet was chosen with a symmetry parameter of 3 and a time-bandwidth product of 120.

B. *Time-Frequency Analyzis of the Simulated Currents*

A typical spectrum of the simulated traction current obtained using STFT is shown in Fig. 1 (a). The maximum relative errors in determining the magnitudes of harmonics were 12.5% for harmonics with a frequency of 175 Hz and 12% for harmonics with a frequency of 75 Hz. Error in determining the frequency was 3.3 Hz. The obtained errors are unsatisfactory for practical application. These errors are mainly due to picket fence effect that cannot be compensated by introducing a correction factor. To reduce the error in determining the parameters of the harmonics, zero-padding to the measured current with factor of 2 was used, which made it possible to reduce the relative error in measuring harmonics magnitude to 1.9%, and the absolute error in determining the frequency to 0.11 Hz (Fig. 1 (b)).

For spectral analysis with CWT, the traction current was first filtered to reduce power harmonics at 50 Hz. Spectral analysis by CWT showed satisfactory results only for low traction current frequencies up to about 175 Hz. The relative error in determining the amplitudes of harmonics in this frequency range was less than 1%, and the absolute frequency errors were about 0.1 Hz for frequencies of 18 Hz, 33 Hz, 75 Hz and 0.6% for a frequency of 175 Hz (Fig. 2).

Thus, the above studies have shown that the time-frequency analysis of the traction current using STFT with correctly selected parameters allows obtaining the required accuracy. The use of WT for the spectral analysis of the traction current is possible only for low frequencies up to about 175 Hz.

C. *Time-Frequency Analyzis of the Real Traction Currents*

The considered STFT technique was used in testing new types of trains to measure the influence of their traction current on track circuits. Some typical measurement results are presented to illustrate the time-frequency analysis of real traction current. The traction current spectra for two conditional time points (14 s and 24 s) counted from the start of the train movement along the monitored track segment are shown in Fig. 3, where the fundamental harmonic at a frequency of 50 Hz and two multiple harmonics at 50 Hz and 150 Hz are clearly visible. Amplitudes of interharmonics with frequencies corresponding to the operating frequencies of TCs do not exceed limits (Fig. 3).

Presentation of measurement results in the form of dependences of harmonic amplitudes on time is more convenient for monitoring the trend of harmonics (Fig. 4). The dotted lines in the Fig. 4 show the harmonics limits.

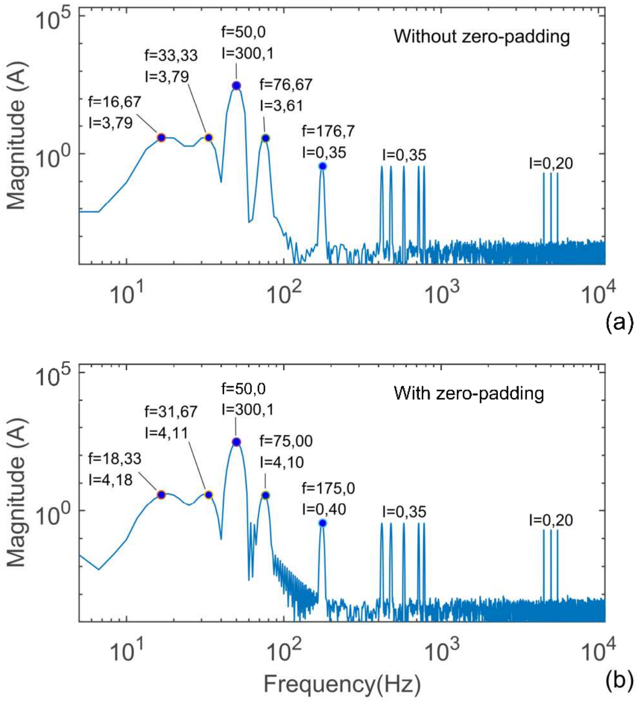

Fig. 1. Spectrum of simulated traction current obtained using STFT without zero padding (a) and with zero padding (b).

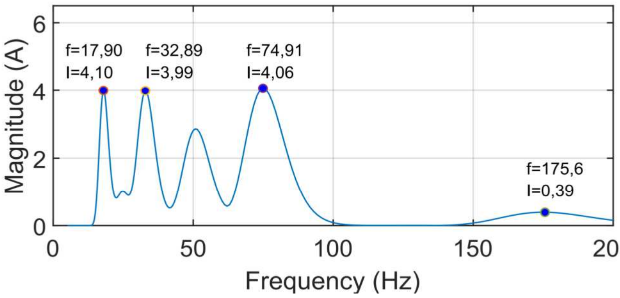

Fig. 2. Spectrum of simulated traction current obtained using CWT.

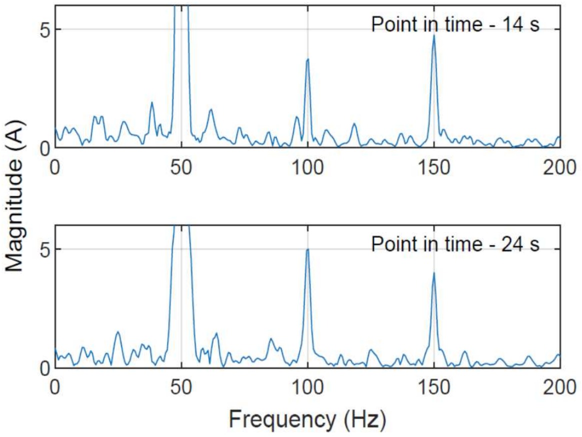

Fig. 3. Traction current spectrum in rails obtained using STFT for two time points 14 s and 24 s.

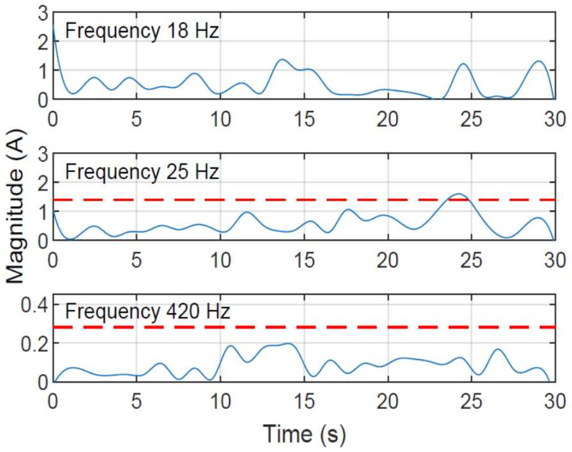

Fig. 4. Dependences of harmonics magnitudes of frequencies 18 Hz, 25 Hz, 420 Hz from time. The dotted lines show the limits for these frequencies.

D. *Time-Frequency Analyzis of the Signal Currents in TCs*

Coded track circuits use an amplitude modulated (AM) signal that can include 1, 2 or 3 pulses per period (Fig. 5(a)), which encode information about the state of the track ahead of the moving train, and this information is transmitted along the rails to traffic lights at the track and to traffic lights in the driver's cab. Due to the distortion of signal current pulses and the filling of pauses between pulses with EMI, failures in train control systems may occur. The measurement of EMI parameters in pulses and pauses of the coded current by the STFT does not provide the required accuracy due to the short duration of pulses and pauses. The first pulse in the code has a duration of 0.35 s, and the first pause is 0.12 s. Due to the uncertainty principle, the frequency resolution of an EMI in a pause, even in the ideal case, cannot be better than 8.3 Hz. Therefore, STFT is not suitable for accurate measuring EMI in pauses and pulses of coded current of 25 or 50 Hz.

In the spectrum of the TCs current, obtained using the CWT, the current of 1.99 A with a frequency of 25 Hz and the current of 0.29 A with a frequency of 50 Hz in the code signal pulse (Fig. 6 (b)), and a current of 0.02 A with a frequency of 25 Hz and a current of 0.3 A with a frequency of 50 Hz in the pause of the code signal (Fig. 6 (c)) are clearly visible.

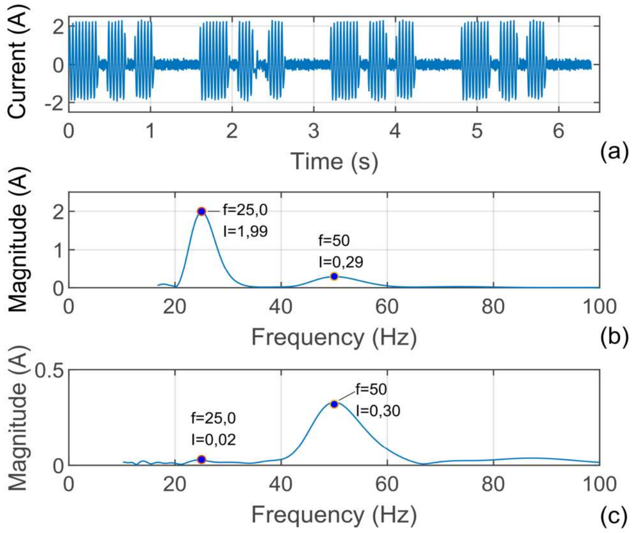

Fig. 5. Time-dependence of amplitude-modulated signal current (a), spectrum of current in a code pulse (b), and in a pause (c).

IV. CONCLUSION

The considered technique for selecting the STFT and CWT parameters makes it possible to provide the necessary input dynamic range of the current monitoring system in rails to obtain the required relative measurement error of the weakest harmonic (less than 1.9%) and the required resolution of harmonics in the time and frequency domain. The CWT is less suitable for time-frequency analysis of the traction current and shows acceptable results only for low frequencies up to 175 Hz. However, for time-frequency analysis of amplitude-modulated signal current in track circuits, CWT gives more accurate results due to the use of a short-wave signal, which makes it possible to detect local perturbations in the spectra of signal currents. Thus, STFT and CWT have their preferred areas in the analysis of traction current in rails, and if necessary, these two methods can be combined for complex monitoring of EMI in rails.

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