Monitoring of distortions and interferences in ASK-modulated currents of railway signaling systems

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Abstract. The problem considered in the work concerns the automation of the monitoring of ACK signals, which are widely used in railway signaling systems, namely in track circuits, due to the simplicity of their generation. Due to the low interference immunity of ACK signals under the influence of traction current and other electromagnetic sources at the railways, malfunctions can occur in the operation of train control systems. To prevent possible failures in the operation of track circuits, measurements of the signal parameters on generators and receivers of track circuits are periodically carried out. Such measurements are mainly made manually, therefore they are expensive and do not provide the necessary accuracy of the results. The problem of automating the control of signals in track circuits is related to the correct choice of characteristic features of signal distortions in order to identify excessive distortions that can lead to failures in the operation of track circuits. The article discusses methods for analyzing the signal current in the time and frequency domains to detect signal distortions. It is shown that in addition to the current measurements of the rms voltage of signals in track circuits, it is necessary to monitoring the voltage levels in the pulses and pauses of the signals, as well as the spectral composition of the signals.

1 INTRODUCTION

Amplitude Shift Keying (ASK) is a type of amplitude modulation (AM) that represents binary data as changes in signal amplitude. ASK signals are widely used in railway signaling systems due to their ease of implementation [1]. The binary Amplitude Shift Keying uses in operation only two levels – low level (LL), usually zero value, and certain high level (HL). The ASK modulator block comprises of the carrier frequency signal generator, the binary sequence from the message signal which change amplitude of the carrier current using control electrical switch in accordance with binary sequence and the bandpass filter.

ASK currents are used in coded track circuits (TCs) and automatic locomotive signaling (ALSN), which is a type of cab signaling, as well as in tone track circuits (or audio frequency track circuits) [1]. Track circuits are designed to detect the presence or absence of a train on a certain section of the railway track and, therefore, are the main and safety-important components of automatic train control systems. In the track circuit, the rails are used as conductors of the signal current, which flows from the generator located at the supply end of the TC to the receiver located at the other (relay) end of the track circuit. The current passes from the generator through a transformer, matching and protective devices into the rails and further from the rails through a tract transformer and matching and protective devices enters the receiver. The receiver determines the state of the controlled block of the railway section according to the current parameters of the received signal. The ALS is a railway safety system that provides track status information to the train cab. In simplest case these system displays the trackside signal aspect (typically, green, yellow or red), indicating whether it is safe to proceed movement or not. The three types of coded current which correspond to three codes – "green", "yellow", and "red yellow" using in coded track circuits and ALS are modulated by code binary sequence with three, two or one pulses (Fig. 1).

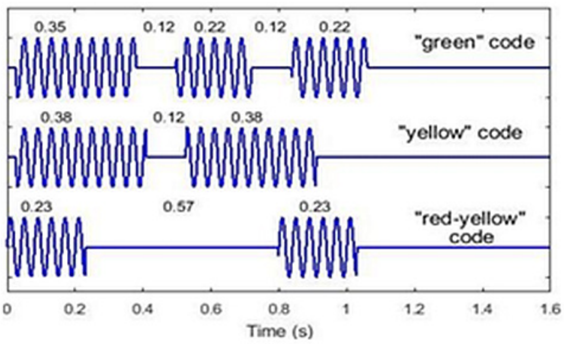

Fig. 1. The time dependences of the codded track circuits currents for "green", "yellow", and "red yellow" signals.

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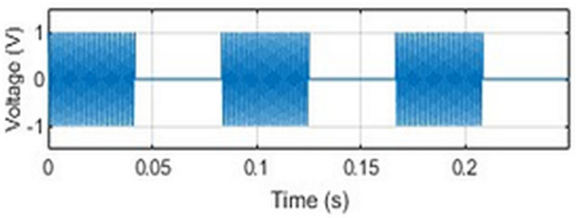

Fig. 2. The time dependence of the tone frequency traction current.

There are two code sequence with different period (1,6 s and 1.72 s), which are used alternately in adjacent TCs. The carrier current for these coded signals usually has frequency of 25 Hz, 50 Hz or 75 Hz. The receiver of the ASK code current consists of bandpass filter of carrier frequency, ASK demodulator, threshold device and decoder that counted number pulses per period, and relay [1]. Tone frequency track circuits (TFTC) use ASK signals with carrier frequencies of 420, 480, 580, 720 and 780 Hz (TFTC-3) or 4545, 5000 and 5555 Hz (TFTC-4) [1] modulated at 8 Hz or 12 Hz (Fig. 2). The current from the tone frequency generator, located remotely from the controlled section of the rails, usually in the control room at the station, flows through the filter, cable, track transformer, rails, as well as the devices of the receiving end of the TC, namely the other track transformer, cable to the input of the receiver, located also in control room.

The TFTC receiver consists of bandpass filter of carrier frequency, ASK demodulator, threshold device, bandpass filter of modulating frequency, low pass filter and relay [1]. Asynchronous ASK demodulator, used in receivers, consists of a half-wave or full-wave rectifier, a low pass filter, and a comparator. When the signal exceeds the threshold value HL, then bit "1" is provided at demodulator output, and when the signal is less than the threshold value LL, then bit "0" is achieved.

The ASK current flowing in the rails is distorted due to the inductive and capacitive components of the resistance of rails, cables, track transformers and other elements of track circuits, as well as due to the strong influence of the traction current flowing in the rails [2]. Traction current harmonics with frequencies in the passband of the track receiver filter affect its operation. If ASK signal current disturbances are higher than certain permitted level the signal current can be wrong decoded which can lead to train movement accidents.

The problem of safe operation of track circuits has again become relevant in recent years due to the use of new types of rolling stock equipped with electronic static converters with pulse-width modulation, which create conducted and radiated interference in a wide frequency range [2, 3], as well as due to an increase in train speed [4], the use of new microprocessor-based train traffic control systems, and also taking into account the prospect of using new lines with a European gauge of 1435 mm [5, 6], which can be placed parallel to existing conventional tracks of 1520 mm gauge [7, 8].

To ensure the functional safety of the TC, the ASC currents in the rails should be periodically monitored by the maintenance personnel by direct measurements in the rails and/or during planned test trips of a specially equipped car-laboratory, in which coils located on the bottom of the train serve as a current sensor, the signal from which is amplified and recorded by a computer [9]. According to the existing ALS maintenance methods, which are currently used mainly on railways, the recorded signal is visually analyzed by the operator to identify problem sections where the signal parameters differ significantly from the normative ones. This signal processing technology is laborious, inefficient and does not provide the required accuracy.

Automatic detection and identification of problem segments of the ALS signal is an important task. The fast Fourier transform (FFT) is often used to detect interference in the ALSN signal, but the real ASK signal is not stationary, contains strong random noise, and therefore the FFT is not suitable for its spectral analysis [10-12].

Dennis Gabor [13] proposed the Short-Time Fourier Transform (STFT) for spectral analysis of non-stationary signals that applies FFT to signal divided into segments of certain length where the signal could be admitted as stationary one. The use of STFT for spectral analysis of ASK signal has some limitations; in particular, one of them is associated with a trade-off between the FFT window length and the frequency band width caused by the use of a fixed-length window [14, 15].

In recent decades, wavelet theory has become a powerful signal processing tool, widely used for non-stationary signal analysis in many practical applications [16-19]. Wavelet transform (WT) allows us to simultaneously analyze the signal characteristics in both time and frequency domains, but unlike STFT, wavelet analysis uses a different time window, the length of which depends on the frequency being analyzed. The effectiveness of WT for the analysis of power quality has been discussed in many papers.

To automate the detection of signal current disturbances, it is necessary to reveal the main features of disturbances and interference both in the time and frequency domains.

Modern computerized train control systems make it possible to automatically measure the rms voltage and current of the ASK signals in track circuits. These measured values must be within the permissible limits defined by the regulations. However, in practice when this condition is met, failures in the operation of track circuits are often observed due to distortions in the ACK signal, in particular, caused by interference in the rails, which does not allow correctly decoding the ASK signal. Thus, in addition to measuring the electrical parameters of ASK signals in rails, it is necessary to control their shape and spectral composition.

The aim of the work is to select the main features of the ASK signals that can be used for the timely detection of excess distortion and interference in them that can lead to failures in the operation of track circuits, as well as the choice of methods for digital processing of the current in rails that can be used for continuous monitoring of the ASK signals.

2 SELECTIONS OF SAFETY-CRITICAL PARAMETERS OF ASK SIGNALS AND TECHNIQUES FOR THEIR MONITORING

2.1 Measurement technique and results

For continuous monitoring of current in rails, it is advisable to use embedded data acquisition systems (DAS), the structure of which is widely described in the literature [21-24]. DAS includes, as usual, a signal conditioning circuit, an ADC, an antialiasing filter, and signal processing module (PC in simple case) used for analyzing ASK signals in time and frequency domains. The choice of the main components of the DAS is described in numerous literature sources [12, 15, 23, 24].

For research, ASK signals were recorded in the rails using a measuring system that includes a current sensor, a device for matching signal levels and overvoltage protection, an antialiasing filter, a 14-bit ADC and a computer with appropriate software. The choice of component parameters and measurement techniques are described in [15, 24]. The currents in the rails were measured by two methods: directly in the rails and by using a railway measuring car-laboratory. The currents in the rails were recorded directly in the code and tone track circuits at track transformers and at the input of the TC receivers. ALS currents were recorded using a railway car-laboratory during its test trips along a certain railway section. From the measured data, some sections of the TFTC and ALS currents with characteristic features for the analysis were chosen (Fig. 3 and Fig. 4).

The RMS values of the measured ASK signals are presented in Table 1. Normative RMS voltage for considered tone track circuit is from 0.4 to 1.0 V, and normative RMS current for ALSN signal should be at least 1.4 A at the receiving end of track circuits. Thus, the parameters of these ASK currents are in permissible limits.

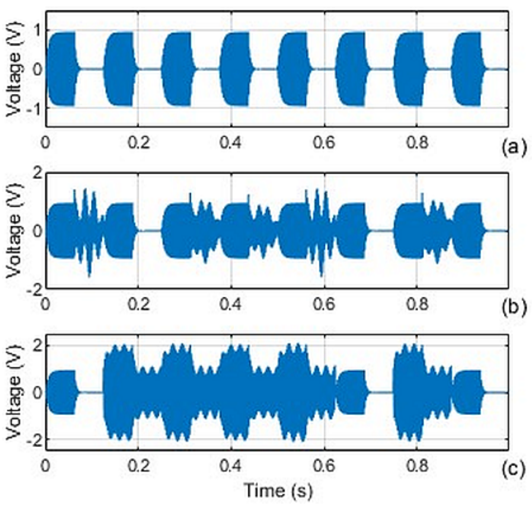

Fig. 3. Time dependences of the TFTC signal with low distortion (a), with swells in some signal pauses (b) and with interference (c).

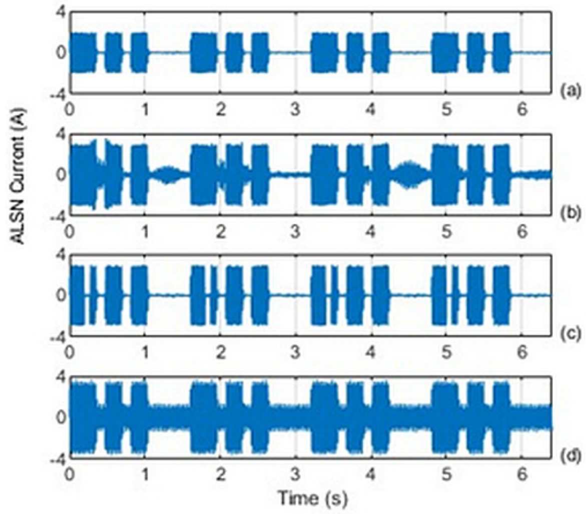

Fig. 4. Time dependences of the ALS current with low distortion (a), swells in some signal pauses (b), with split pulses (c) and with interference (d).

Table 1. The RMS values of the ASK signals.

Signal features	RMS voltage for TFTC signal (V)	RMS current for ALSN signal (A)
Low distortion	0.47	1.43
Swells in pauses	0.54	1.53
Interference	0.92	1.84
Split pulses	-	1.40

2.2 Choice of methods for monitoring currents in rails and their analysis in the time domain

To ensure reliable operation of the TC, the main parameters of the ASK signals, such as the duration of pulses and pauses, as well as the RMS values of signals in pulses and pauses, must comply with regulatory requirements. To do this, it is necessary to transform the ASK signals in the same way as demodulation (detection) of them in a track receiver, that is, to find the signal envelope by eliminating carrier frequency oscillations [25]. In this paper, two classical methods for signal envelope estimation are considered, such as the analytical envelope estimation method based on Empirical Mode Decomposition (EMD) [26, 27] and the root-mean square (RMS) method [25].

2.3 Analytic envelope estimation method

The ASC currents flowing in the rails are non-stationary, so it is convenient to use the Hilbert-Huan transform (HHT) to analyze them in the time domain [26, 27]. A key part of the analytic envelope estimation method is the EMD, with which any complicated data set can be decomposed into a finite number of Inner Mode Functions (IMFs) using the Hilbert Transform (HT) [26, 27]. Intrinsic mode functions give instantaneous frequencies as functions of time, which identify embedded signal structures. The procedure for extracting IMF is called sifting [26]. The sifting process is as follows:

- determine all local extrema in the signal;
- connect all local maxima with a cubic spline line as the upper envelope.

Since the ASK signal is rectified during demodulation, the lower envelope of the signal corresponds to the abscissa axis, which is realized by determining the signal modulus [26]. For a real band-limited signal $x(t)$, if $x(t) \in L^2(R)$ and its Fourier transform is $X(f)$, then its Hilbert transform is defined by [27]

$$\hat{x}(t) = H\left[x(t)\right] = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{x(\tau)}{1-\tau} d\tau , \qquad (1)$$

where P is the Cauchy principal value. From this equation we can determine the analytic signal $m(t)$ as

$$m(t) = x(t) + j\hat{x}(t) = \left| m(t) \exp\left(j\varphi(t)\right) \right| . \qquad (2)$$

The analytic signal is useful for envelope detection since its modulus $m(t)$ and time derivative of the phase $\varphi(t)$ can serve as estimates for the amplitude envelope and instantaneous frequency of $x(t)$ under certain conditions. The envelopes of real-valued signals are constructed by spline interpolation from extrema sequences in the EMD algorithm.

2.4 Root-mean square (RMS) envelope estimation

The RMS method for estimating the time evolution of signal energy allows one to obtain an estimate of the amplitude envelope by applying it with a sliding window, as shown in the equation [25]

$$RMS(t) = \sqrt{\frac{1}{T} \sum_{i=1}^{N} w(t_i) x(t_i)^2} , \qquad (3)$$

where $x(t_i)$ is the i th sample of the signal centered around t_i, $w(t_i)$ is the sliding window of length T, N is the number of samples. Usually a rectangular window is used, but other choices are also possible [25]. The analysis step t imposes a trade-off between the temporal sampling rate of the envelope and how much information it represents. Small values of window length react sooner to sudden changes in amplitude, while presenting ripple in more steady regions and larger values smooth out the ripples but tend to lag behind abrupt energy changes.

2.5 Choice of the envelope detection technique

In order to select a suitable method for determining the envelopes of the ASK signals under study, the envelopes were determined for two signals, namely the ALS and TFTC signals, using the analytical envelope estimation method and the RMS method. Fig. 5 shows the ALSN signal that corresponded to green code with a carrier frequency of 50 Hz, and Fig. 6 shows the TRC signal with a carrier frequency of 580 Hz.

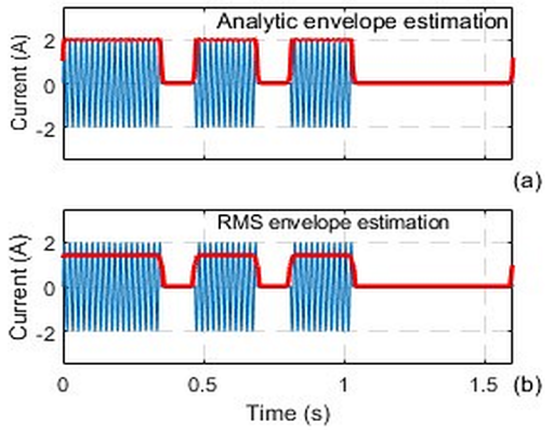

Fig. 5. The ALS current corresponded to green code with a carrier frequency of 50 Hz and their envelopes determined by analytic envelope estimation method (a) and by RMS method (b).

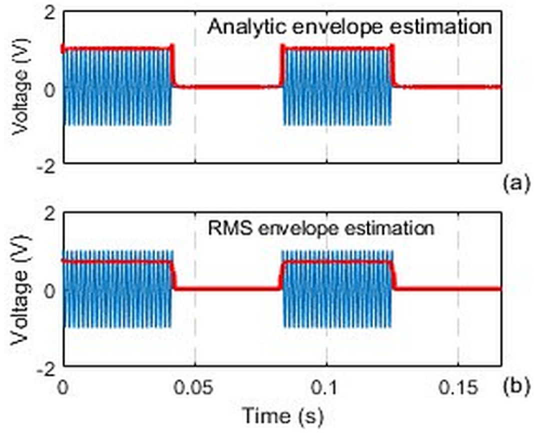

Fig. 6. The TRC signal current with a carrier frequency of 580 Hz and their envelopes determined by analytic envelope estimation method (a) and by RMS method (b).

Both methods give satisfactory results for noise-free signals (Figs. 5 and 6), but for real ACK signals with noise, the amplitude envelopes of the signal obtained by the HHT method change both during pulses and during pauses, and therefore the amplitude envelope does allow one to evaluate the response of the track circuit receiver to varying peak voltage, since the rail receiver's on-off switches are at certain RMS voltage levels. Thus, the RMS envelope estimation method is preferred.

3 ANALYSING SIGNALS IN RAILS

3.1 Analyzing signals in the time domain

The time dependences of the voltage at the input of the TCs receiver with small and significant signal distortions are shown in Fig. 7.

For reliable operation of the TC receiver, it is necessary that the RMS voltage of the demodulated signal, the RMS envelope in considered case (Fig. 8), meets certain requirements, namely, the RMS voltage in the pulses is above the threshold level HL, and the RMS voltage in the pauses is less than the value LL. For a signal with low distortion (Fig. 8(a)), this condition is met, which corresponds to requirements for reliable TCs receiver operation. For signal with significant distortions (Fig. 8(b)), the voltage envelope in pulses at some time decreases below the HL, and vice versa, the voltage envelope in pauses at some times are above the allowable LL level, which will not allow correct decoding of the ASK signal.

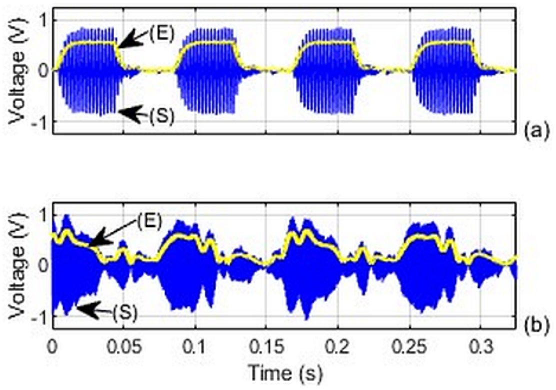

Fig. 7. Time dependences of voltages (denoted by the letter S) and their envelopes (denoted by the letter E) at the input of the TCs receiver for small (a) and significant (b) signal distortions.

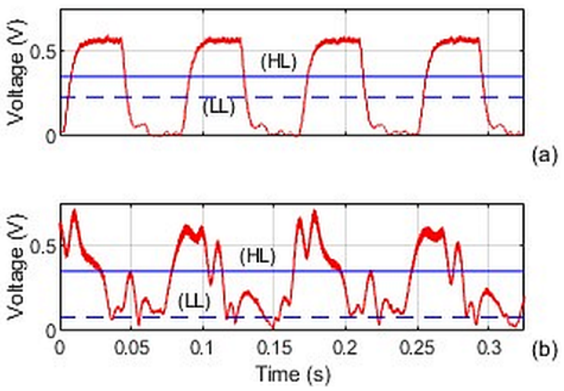

Fig. 8. The RMS voltage envelopes at the inputs of the TCs receivers and levels of voltage limits for the TC receiver: HL - upper level; LL - lower level.

In accordance with the regulations for track circuits, if the interference in the rails with frequencies lying in the passband of the TC receiver has a duration of 0.3 s or more, this can lead to its failure. In the case under consideration, the duration of the distorted ASK signal exceeds 0.3 s. The considered example illustrates the discrepancy between the RMS voltage of a signal with significant distortions in pulses and pauses with the required conditions for reliable operation (Fig. 6(b)), while the RMS voltage of the signal was within acceptable limits (Table 1).

3.2 Analyzing signals in the frequency domain

The correct choice of parameters for the time-frequency analysis of signals in track circuits to ensure the required accuracy is complicated by the large dynamic range of harmonics (in the case of AC traction more than 60 dB), and the wide range of frequencies of (from tens of hertz to ten kilohertz). Ensuring the required accuracy of spectral analysis is complicated by the non-stationarity and random strong disturbances of the measured currents, as well as the limitations inherent in time-frequency analysis associated with the impossibility of simultaneously achieving high resolution in time and frequency due to the fundamental principle of uncertainty, as well as the difficulty of distinguishing two closely spaced harmonics, especially weak ones against the background of more powerful harmonics, etc. [24]. For time-frequency analysis, the short-time Fourier transform (STFT) is widely used in practice. The correct choice of STFT parameters to obtain required accuracy of time-frequency analysis of signals was considered in [23, 24].

To illustrate the time-frequency analysis of the ACK signals, three segments of the time dependences of the voltage at the input of the TC receiver distortion, with swells in some signal pauses and with interference were selected from a large number of measured TFTC signals (Fig. 3). The spectral analysis of the signals was carried out by the STFT method with a Hann window of 1 s. The spectra of these signals are shown, respectively, in Figs. 8(a), 9(a) and 10(a). The spectra of three signals showed peaks near the signal carrier frequency of 420 Hz, as well as peaks with a traction current frequency of 50 Hz, especially noticeable for the signals in Figs. 10(a) and 11(a). Despite the fact that the waveform of these fragments of ASK signals significantly differ from each other in the time domain, their spectra don't allow us to identify features that could be used to reveal excessive signal distortions. The reason of this is related to the averaging of the features in the spectra of non-stationary signals over the entire time intervals selected for analysis (of 1 s for considered cases).

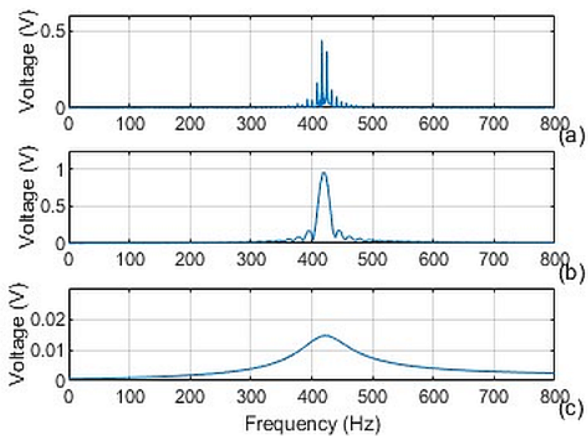

Fig. 9. Spectra of a signal with low distortions determined for interval of 1 s (a), for a signal pulse (b), for a signal pause (c).

Therefore, the spectral analysis of ASK signal need to be performed separately for pulses and pauses as in the case of time domain analysis. But due to small pulses and pauses durations (about 0.083 s) it is difficult to perform spectral analysis with required accuracy to fundamental uncertainty principal. To improve the STFT accuracy for analysis of ASK signals in rails, the STFT parameters were chosen in accordance with recommendations [21, 29]. Obtained spectra for considered three fragments of ASK current performed separately for frequencies and pauses of signals are shown, respectively in Figs. 9(b), (c), 10(b), (c) and 11(b), (c).

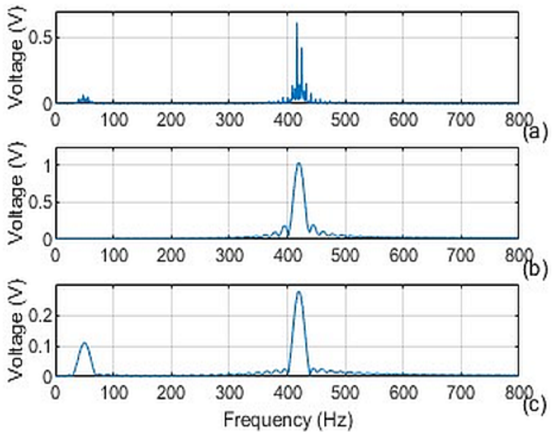

Fig. 10. Spectra of a signal with swells determined for interval of 1 s (a), for a signal pulse (b), for a signal pause (c).

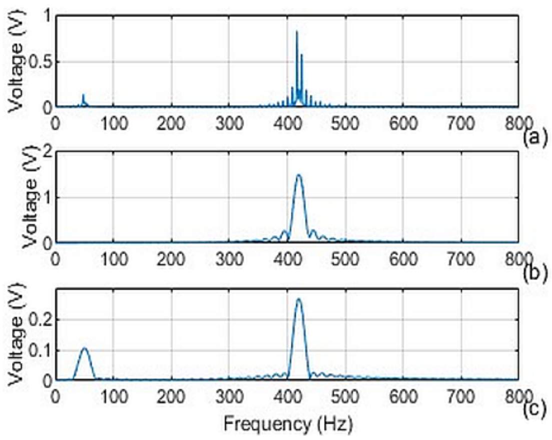

Fig. 11. Spectra of a signal with interference determined for interval of 1 s (a), for a signal pulse (b), for a signal pause (c).

The results obtained show that for a signal with low distortion (Fig. 9), the harmonic levels with a frequencies of about 420 Hz meet the requirements both in impulses and in pauses of the signal. For signals with swells and interferences (Fig. 10 and 11), the harmonic values near the carrier frequency of 420 Hz in pulses are higher than the HL value, which ensures reliable switching on of the receiver (transition to state "1"), however, in pauses, the levels of harmonics with frequencies of about 420 Hz exceed the LL voltage (0.23 V) and, accordingly, the receiver cannot switch to the "0" state in pauses.

Thus, using spectral analysis of ASK signals to detect excessive distortion in signals is preferable to analysis in the time domain, since some of the significant signal distortion observed in the time domain can be due to traction current harmonics that are not in the bandwidth of TC receivers and therefore cannot cause their failures.

But the time-frequency analysis of ASK signals separately in pulses in pauses is more time-consuming and complicated compared to the analysis of signals in the time domain. Thus, it can be recommended to carry out the current analysis of the ASK signal in the time domain at the first stage of signal monitoring, and if excessive disturbances in the ASK signal are detected, to perform the second stage using time-frequency analysis of the signal.

4 Conclusions

Methods for detecting disturbances and interference in ASC currents used in railway signaling systems are considered. The currently used methods for monitoring currents in track circuits are based on manual measurements, are expensive and do not provide the necessary accuracy of the results. In order to timely detect excessive disturbances and interference in track circuits, a technique for analyzing ACK signals in track circuits has been developed, which can be used for continuous automatic monitoring of ACK signals in track circuits. It is proposed, in addition to measuring the rms voltage of signals in track circuits, to monitor voltage levels in pulses and pauses of ASK signals, as well as the analyze the signal spectrum. The use of spectral analysis of ACK signals in track circuits gives more complete results in identifying excess interference in ACK signals compared to analysis in the time domain. But the time-frequency analysis of the ASC signals takes more time. Thus, it can be recommended to analyze the ACK signal in the time domain at the first stage, and if excess disturbances are detected, to perform the second stage using the time-frequency analysis of the signal.

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