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COMPARATIVE ANALYSIS OF EXPERIMENTAL AND CALCULATION METHODS FOR DETERMINATION OF THE TRACTION CURRENT HARMONICS DISTRIBUTION IN RAILS

Introduction

The problem of ensuring of the electromagnetic compatibility (EMC) of traction power supply with railway signalling systems is quite well analyzed in many scientific publications [1-10].

EMC of electrified railways with low-current signalling and communication lines was achieved during their evolution both by reducing interference from rolling stock and by improving the noise immunity of signalling systems.

Nevertheless failures of track and train signaling devices caused by interference in rails still occur [6, 7]. Recent times some of failures in railway signalling systems were caused by operation of new types of rolling stock equipped with electronic static converters with pulse-width modulation which create interference in track circuits with frequencies up to several tens of kHz. To ensure the EMC of new types of trains with signalling systems, they must be subjected to acceptance testing, during which the measurements of electrical interference from them in rails should be carried out for all modes directed by European and national regulations [8]. These acceptance tests are carried out with one train at the railway section, while in further operation the several trains can be simultaneously in operation at the same section. Also it is necessary to evaluate interference in track circuits for all train operating modes predetermined by norms and standards, taking into account possible simultaneous variations of several outer factors (for example, resistance of track ballast) that can adversely affect train movement safety. Therefore, computer simulation is widely used to investigate the causes of failures in the operation of signaling systems caused by electromagnetic interference [1-7].

To ensure electromagnetic compatibility of new types of rolling stock with track circuits,, it is necessary to supplement the experimental results with computer simulation results.

The real values of traction current harmonics generated by train in rails, which measured during tests, can be used for simulation of the distribution of interference in rails.

Methods and some results of measurements of the disturbances from train in rails were considered by author in previous works [7, 8]. The mathematical model of the propagation of traction current harmonics in the rails generated by several trains was considered in [6].

The purpose of the work

The purpose of this work is to perform the comparative analysis of experimental and calculation methods for determination of the distribution of traction current harmonics in rails.

This paper is organized as follows. Section 2 gives brief consideration of the method of traction current harmonics measurements in rails, section 3 describes technique of modelling of the traction current harmonics distributions in rails, section 4 presents the results of comparative analysis of experimental and calculation methods for determination of the distribution of traction current harmonics in rails, and section 5 concludes the work.

Method of traction current harmonics measurements in rails

AC electrified railway section was chosen for the measurements at a sufficiently large distance from the traction substation to reduce the background current in the traction network. Traction current was measured in circuit of the inter-throttle jumper with using an inductive contactless sensor (Rogowski coil). The signal current sensor was digitized using a 10-bit analog-to-digital converter (ADC) with a sampling frequency of 5 kHz and then was registered using computer.

To investigate the distribution of traction current in the rails, the special marks ("flags") were set up at a certain distance (100, 300 and 500 m) from the point of measurement along the track. The moments of passing the train past the "flags" were recorded in a computer due to a sound signal from the train, as well as visual observation. The train was moving in the measuring section in a quasi-stationary mode with an average speed of about 48 km/h. The dependence of the traction current on time as the train approaches the measuring point is shown in fig. 1.

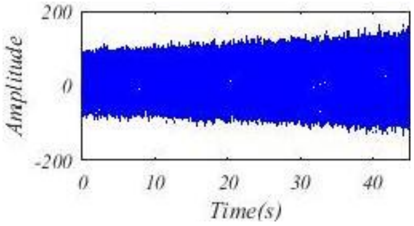

Fig. 1. The dependence of the traction current on time as the train approaches the measuring point.

Fragments of time dependence of the traction current during train passage of track points with distance for the measuring point: 500 m *(a)*, 300 m *(b)*, 100 m *(c)* and 5 m *(d)*. are shown in fig. 2. The spectrograms for these fragments of the traction current obtained using the FFT with a Hann window of 2 s length are shown in Fig. 3.

The frequencies of maximum traction current harmonics in fig. 3 are 25, 150, 300 and 425 Hz (except the main harmonic of the traction current 50 Hz).

Modelling of traction current harmonics distributions in rails

The distribution of the return traction current harmonics in rails for AC and DC feeding systems and their influence on the track circuits is modeled usually by using the multiconductor transmission line (MTL) model Voltage and current of the traction current harmonics in MTL with the $n+1$ conductors are described by well-known set of $2n$ first-order partial differential equations [6].

$$\frac{\mathrm{d}\bar{\dot{U}}_f(x)}{\mathrm{d}x} = -\underline{Z}_f \bar{\dot{I}}_f(x),$$

$$\frac{\mathrm{d}\bar{\dot{I}}_f(x)}{\mathrm{d}x} = -\underline{Y}_f \bar{\dot{U}}_f(x),$$

where $\bar{\dot{I}}_f$ and $\bar{\dot{U}}_f$ are a $n\times 1$ column vectors containing the currents $\dot{I}_{fii}$ in i -line $(i=1..n)$ and voltages $\dot{U}_{fij}$ between i and j -lines $(j=1..n)$ of harmonics with frequency f; $\underline{Z}_f$ and $\underline{Y}_f$ denote matrices of size $n\times n$ of series impedance and shunt admittance per-unit-length (p.u.l). These matrixes are symmetric.

Since the strict solution of the differential equation system is difficult due to the need to specify the boundary conditions for all the lines of the traction system, some reasonable assumptions are usually made to simplify the task.

In this paper a single-track railway section was considered, which significantly simplifies the task.

The contact network consisting of a contact and a messenger wires, was represented at equivalent circut as one wire with an equivalent height of suspension above the rails and equivalent impedance according to expression [6]

$$\underline{Z}_{KM} = \frac{\underline{Z}_K \underline{Z}_T - \underline{Z}_{KT}^{\,2}}{\underline{Z}_K + \underline{Z}_T - 2\underline{Z}_{KT}},$$

where $\underline{Z}_K$, $\underline{Z}_T$ are impedances (p.u.l.) of contact wire and messenger wire, respectively; $\underline{Z}_{KT}$ is a mutual impedances (p.u.l.) of contact and messenger wires.

Since in the considered task the distribution of the traction current harmonics in the rails is the object of interest, the two rails were represented in the equivalent circuit as a one conductor with equivalent impedance

$$\underline{Z} = \left(\underline{Z}_1 + j\omega\underline{M}_{12}\right)/2 \ ,$$

where $\underline{Z}_1$ is the impedance (p.u.l) of a single rail, $\underline{M}_{12}$ is a mutual impedances (p.u.l.) of two rails, ω is a cyclic frequency, $j = \sqrt{-1}$ is imaginary unit.

In the considered model, the background noise in the rails can be neglected (this assumption is confirmed by measurements), therefore only interference from the train under test was considered during simulation. Therefore, the electric equipment of the train is represented at the equivalent circuit as a parallel-connected resistor and current source. The interference from an electric train is represented in differential equations as a vector of currents $\dot{\boldsymbol{J}}_T = \left\{\dot{J}_{hn}\left(f_n\right)\right\}$ with components corresponding to the values of the traction current harmonics which are injected into the rail at the point x_l corresponding to the train coordinate.

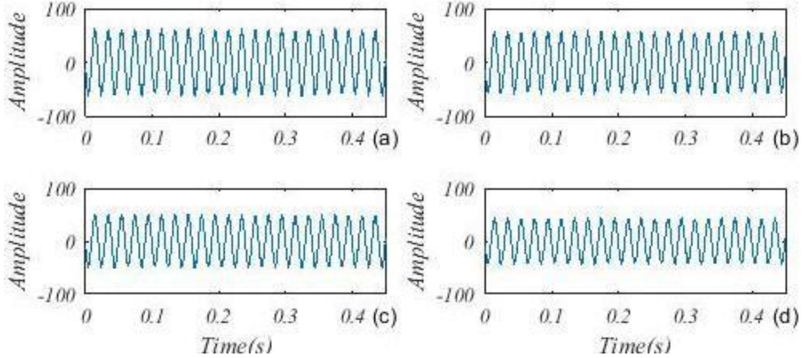

Fig. 2. Fragments of time dependence of the traction current during train passage of track points with distance for the measuring point: 500 m *(a)*, 300 m *(b)*, 100 m *(c)* and 5 m *(d)*.

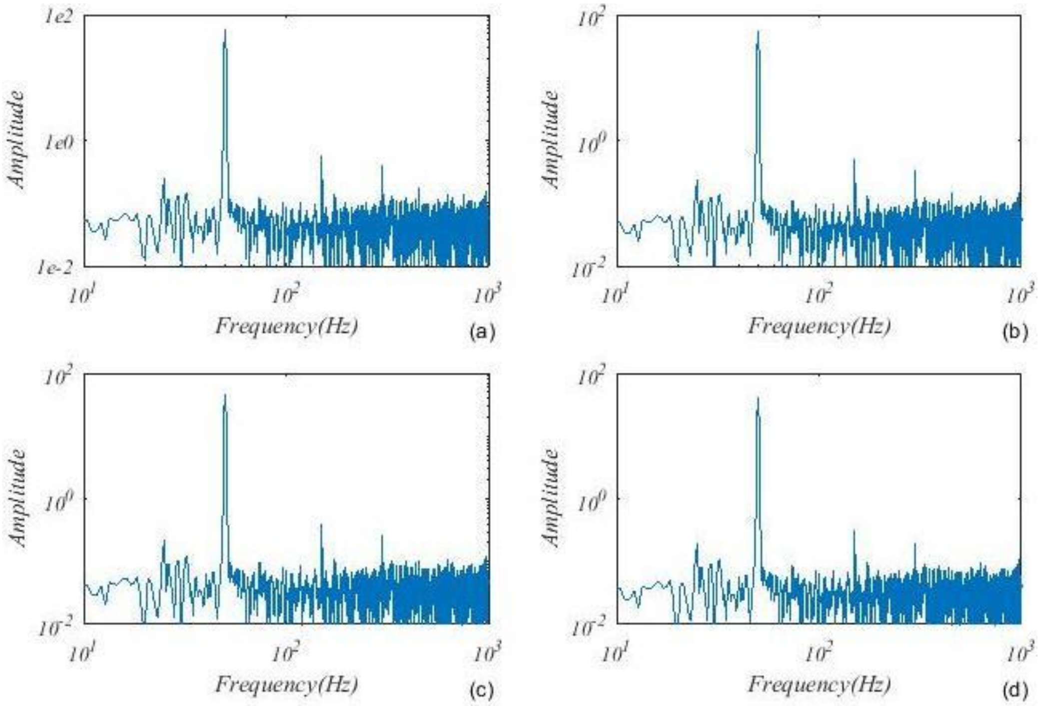

Fig. 3. The spectrograms of the traction current during train passage of track points with distance for the measuring point: 500 m *(a)*, 300 m *(b)*, 100 m *(c)* and 5 m *(d)*.

The total traction current is equal to the sum of all currents of harmonics, including the main harmonic with frequency, corresponding to the industrial frequency for AC feeding system

$$\dot{J}_T = \sum_n \dot{J}_{hn} \, ,$$

where $\dot{J}_T$ is the total traction current, $\dot{J}_{hn} = K_n\left(f_n\right)\dot{J}_T$ is the current of harmonic with frequency f_n, K_n is harmonic coefficient for harmonic with frequency f_n.

As the boundary conditions, they voltages on the traction substation busbars and the vector of the traction harmonic components generated by train were taken.

The components of the traction harmonics vector were determined by spectral analysis of the traction current, measured when the train was approaching and passing through the measurement point.

For the equivalent circuit of the traction network in the form of three conductors (contact network, rail line and ground), the solution of equation () for the required currents and voltages of each harmonic in the rail, can be found in an analytical form [6]

$$\dot{U}_{hi}\left(x, f\right) = \underline{C}_{hi}\left[\mathrm{e}^{\underline{G}\left(x - L_l - 2l_2\right)} + \mathrm{e}^{-\underline{G}\left(x - L_2\right)}\right],$$

$$\dot{I}_{hi}\left(x, f\right) = -\frac{2\underline{C}_{hi}}{\underline{Z}_{ci}}\left[\mathrm{e}^{\underline{G}\left(x - L_l - 2l_2\right)} - \mathrm{e}^{-\underline{G}\left(x - L_2\right)}\right],$$

$$\underline{C}_{hi} = \frac{\underline{C}_{1hi}\mathrm{e}^{\underline{G}L_l} + \underline{C}_{2hi}\mathrm{e}^{-\underline{G}L_l}}{1 + \mathrm{e}^{-2\underline{G}l_2}} \, ,$$

where $\underline{C}_{1hi}$ and $\underline{C}_{2hi}$ are constants of integration whose values are defined from boundary conditions; $\underline{Z}_{ci}$ is the characteristic (wave) impedance of the lines at frequency f, $\underline{G}$ is the propagation constant, L_l is the distance between train and substation, L_2 is the length to which harmonic current propagates behind the ESS (outside the feeder zone) [7].

Results

The simulation results of the distribution of the traction current harmonics from the train in rails with the frequencies 25, 150, 300 and 425 Hz that were prevailing in this experimen are presented in Fig. 4.

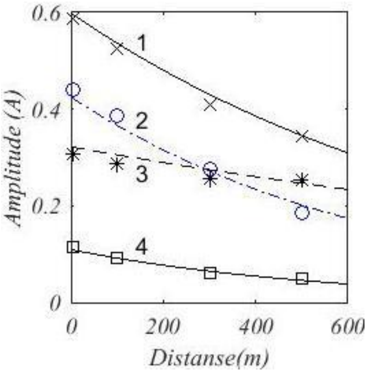

Рис. 4. Distribution of the traction current harmonics in rails with the frequencies 25 *(1)*, 150 *(2)*, 300 *(3)* and 425 Hz *(4)*. The lines correspond to calculated results, the points – to measurement results.

For the convenience of presenting both calculation and measurement results on a single graph, the coordinates origin was superposed with the instantaneous position of the train. In this case, the abscissa represents the distance from the train to the measurement point. The amplitudes of the harmonics for the four distances from the train to the measurement point are also plotted on this graph. The positions of the points obtained in the experiment are somewhat different from the calculated curves. For a comparative analysis of discrepancies in the results obtained using the methods of calculation and measurement, the relative values of the difference in the results obtained using the two considered methods are given in Table 1 for four frequencies and four distances from the train to the measuring point.

The observed discrepancies in the results are explained both by the measurement error and the calculation error. One of the main reasons for the experimental results error in this work is the inaccuracy of determining the distance from the train to the measurement point. Calculation error is related mainly with the inaccuracy of evaluation the electrical parameters of track, in particular, the track ballast resistance and the ground resistances.

Table 1

The relative difference in the results obtained by calculation and measurement methods (in percents)

Frequency, Hz	Distance, m			
	5	100	300	500
25	4.49	6.02	6.93	3.15
150	1.87	2.29	4.95	2.56
300	3.77	5.47	1.80	7.57
425	5.12	1.94	4.38	9.48

However, in general, the considered model can be used for investigation of the traction current harmonic propagation in rails from train, and their influence on the track circuits receivers for different cases including the variation of the track circuits electrical parameters, as well as the number of rolling stock units in the feeder zone. Such analysis of harmonic in rails is important for revealing the causes of failures in railway signalling system operation under simultaneous affecting on it several factors adverse to safe operation.

Conclusions

In this work the comparative analysis of experimental and calculation methods for determination of the distribution of traction current harmonics in rails have been carried out. To investigate the distribution of traction current in the rails, the special marks ("flags") were set up at a certain distance (100, 300 and 500 m) from the point of measurement along the track. The moments of passing the train past the "flags" were recorded in a computer due to a sound signal from the train, as well as visual observation. The train was moving in the measuring section in a quasi-stationary mode with an average speed of about 48 km/h. Traction current was measured in circuit of the inter-throttle jumper with using an inductive contactless sensor and registered using computer.

The distribution of the return traction current harmonics in rails for AC feeding systems were modeled by using the multi-conductor transmission line (MTL) model

Obtained results allow to confirm that, in general, the considered in the work model can be used for investigation of the traction current harmonic propagation in rails from train, and their influence on the track circuits receivers for different cases including the variation of the track circuits electrical parameters, as well as the number of rolling stock units in the feeder zone.

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Ключові слова: тяговий струм, гармоніки, завади в рейкових колах.

Ключевые слова: тяговый ток, гармоники, помехи в рельсовых цепях.

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