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Statistical analysis of electromagnetic interference between AC traction current and track circuits

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ABSTRACT
The statistical analysis of traction current harmonics in rail circuits has been provided with the aim to develop statistical evaluation methods of electromagnetic compatibility between the AC traction current and rail circuits.

KEYWORDS: electromagnetic compatibility, AC traction current, track circuits

1. Introduction

The ensuring of electromagnetic compatibility of AC traction current with railway signaling systems is an important scientific and practical problem. The interest in it recently increased in connection with the occurrence of new types of rolling stock with asynchronous traction engines and microelectronic traffic control systems [1,2]. The evaluation of electromagnetic interference between the AC traction current and rail circuits (RC) is a complex and time consuming procedure due to a bundle of random factors that influence a form and value of the traction current in the rail lines, including the number of locomotives in a feeding zone, their operation mode, traction voltage fluctuation, variations of rail line-ground admittance etc. So the electromagnetic interference parameters also as parameters of rail circuit receivers (detectors) have a stochastic character. Papers [3,4] focused on the importance of taking into account of a casual character of electromagnetic interferences and immunity level of their receptors for correct evaluation of electromagnetic compatibility (EMC) of microelectronic systems. But in most publications on electromagnetic compatibility of traction current with railway signaling systems the stochastic character of systems parameters was not taken into account.

The purpose of this work is to develop statistical methods applicable to the evaluation of electromagnetic compatibility between the AC power traction current and rail circuits.

2. Statistical analy sis

The methods and some results of locomotives traction current measurements were described in the author's previous publications [5-9]. Since the traction current is a stochastic and in generally non-stationary process, it is essential to stipulate a statistical analysis methods used in the present work.

The realization of stochastic process obtained in k measurements of traction current i_{Tk} may be expressed as the sum of the determined process $i_{Tk}{}^{D}$ specified by a locomotive control system in accordance with the appointed movement mode (regime) and stochastic process $i_{Tk}{}^{S}$ caused by random external and internal factors [10]

$$i_{Tk}(t) = i_{Tk}{}^{D}(t) + i_{Tk}{}^{S}(t) \qquad (1)$$

Random component $i_{Tk}{}^{S}$ has zero average value independent of time, and, as shown in our work, has normal (Gaussian) probability distribution, that may be easy explained on the basis of the central limit theorem of probability theory in view of plenty of independent random factors that influenced the process. The function of a sample average value (mean) of the process is equal to determined function $i_{Tk}{}^{D}$

$$E[i_{Tk}(t)] = E[i_{Tk}{}^{D}(t) + i_{Tk}{}^{S}(t)] = i_{Tk}{}^{D}(t) \qquad (2)$$

Therefore for a stochastic process with the alteration time that is much longer then the period of rail circuit signal current the random component may be removed using a low-frequency filtration, polynomial approximations or evaluation of time average of fragments sampled from the process realization [10]. For our investigations the low-frequency filtration of the traction current was provided by a computer program.

To calculate an average in time value of the current, the traction current oscillograms were quantized on sample sets.

Some sample sets that were measured at similar locomotive operation modes were considered as ensemble of independent process realizations for the evaluation of signal average as an arithmetic mean of the observation functions.

Samples length was determined according to the inequality

$$T_H < T_{Ek} < T_{iTk}{}^{S} \qquad (3)$$

where $T_{iTk}{}^{S}$ is the oscillation time of stochastic function, T_H - the maximal period of traction current interferences that are able to cause a failure in rail circuits operation (for rail circuits with signal current frequency 25 Hz and a filter pass band 25±6 Hz, T_H =26.32 ms and the sample length for statistical analysis was taken not less then $10^2\ T_H$).

The sample period digitization was determined according to the inequality

$$\mathrm{D}t_d = {}^{1}\!/_{2f_C} < {}^{1}\!/_{2f_{HM}} \qquad (4)$$

where f_C is a Nyquist frequency.

The verification of stationary of the chosen samples was carried out by the first and second statistical moments. The verification of the hypothesis about similarity of dispersions in different samples of stochastic function was carried out by Kokren criterion [10], and the verification of the hypothesis about a normal distribution electromagnetic interference value was carried out by χ^2 – Pirson's criterion.

Since most of the traction current measurements were

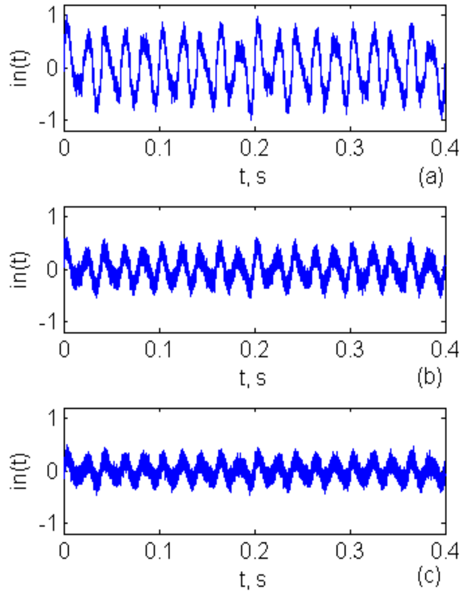

Fig. 1. Time domain plots of a traction current, in locomotive power circuit (a), in rail lines at 1 km (b) and 2 km (c) distance from locomotive
Source: [own work]

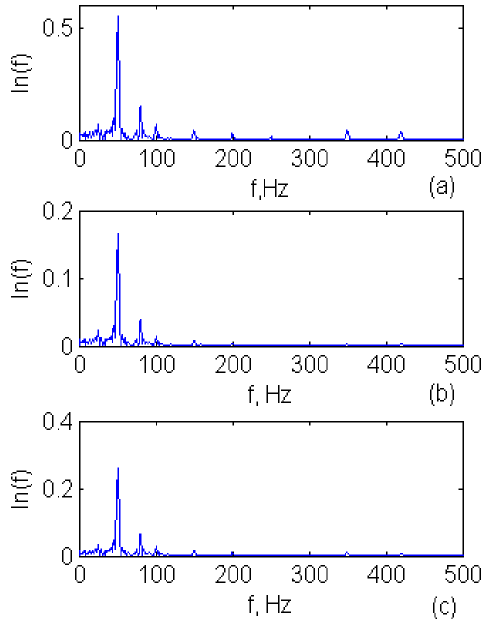

Fig. 2. Frequency domain plots of a traction current, in locomotive power circuit (a), in rail lines at a distance of 1 km (b) and of 2 km (c) from the locomotive
Source: [own work]

carried out in the locomotive during its movement, it is necessary to prove the application of these results to the analysis of electromagnetic processes in track circuits. The time and frequency domain plots of traction current measured in a locomotive and in rail lines at a distance from locomotive of 1 and 2 km are shown in Fig. 1 and 2. The amplitude of the traction current, as well as amplitudes of its harmonics were decreased with increasing distance to the locomotive. The harmonics attenuation rate during traction current propagation from locomotive along rail lines increased with frequency of harmonics that is evident when taking into account reactive components of the rail line impedance. Appreciable harmonics in a spectrum of the traction current in rail lines, which were additional in comparison with the current measured in locomotive circuits have not been observed. Therefore the rail lines parameters were practically linear at values of traction current that were set during measurements.

Mutual and auto correlation (covariation) functions of the traction current measured in a locomotive circuit $i_L(t)$ and in rail lines $i_R(t)$ were determined by the expressions [10]

$$K_{LR}(\tau)=\frac{1}{T_E-\tau}\int_0^{T_E-\tau}\left[i_L(t)-m_L(t)\right]\left[i_R(t+\tau)-\right.$$
$$\left.-\,m_R(t+\tau)\right]f(i_L,i_R,t,t+\tau)dt \quad (5)$$

$$K_{LL}(t,\tau)=\frac{1}{T_E-\tau}\int_0^{T_E-\tau}\left[i_L(t)-m_L(t)\right]\left[i_L(t+\tau)-\right.$$
$$\left.-\,m_L(t+\tau)\right]f(t,t+\tau)dt \quad (6)$$

where $m_L(t)$ and $m_R(t)$ are the average values of stochastic functions.

For discrete samples

$$i_L(n)=i_L(t_n)=i_L(n\cdot\Delta t) \quad (7)$$

$$i_R(n)=i_R(t_n)=i_R(n\cdot\Delta t) \quad (8)$$

obtained on a realization interval, the covariation functions were calculated by the expressions [10]

$$K_{LL}(m)=\begin{cases}\dfrac{1}{n-|m|}\sum\limits_{n=1}^{N-|m|} i_L(n)i_L^*(n+m), & m\ge 0\\ K_{LL}(-m), & m<0\end{cases} \quad (9)$$

$$K_{i_Li_R}(m)=\begin{cases}\dfrac{1}{n-|m|}\sum\limits_{n=1}^{N-|m|} i_L(n)i_R^*(n+m), & m\ge 0\\ K_{i_Li_R}(-m), & m<0\end{cases} \quad (10)$$

The analysis carried out has shown high enough level of correlation between the current in a locomotive power circuit and in rail lines.

3. EMC in rail circuits

The statistical analysis of electromagnetic compatibility of rail circuits and traction current was provided for all frequencies of signal current used in the railways, but in this work only some results for the voice-frequency rail circuits with signal current 420 Hz are presented.

The measurements of turn-on voltage U_C and turn-off voltage U_B of rail circuits' receivers were provided on ten different receivers of the same type with variation of an electric power supply voltage (in allowable limits) at different external conditions (temperature, humidity, etc.). As a result, 98 independent values of both turn-on voltage and turn-off voltage have been obtained. A statistical hypothesis about normal voltage distribution was checked up χ^2 – Pirson's criterion at a 0.05 significance level. Values of a sample mean values and standard deviations of a turn-on and turn-off voltages were obtained: m_{UC} =0.349 V, m_{UB} =0.244 V, s_{UC} =0.0197 V, s_{UB} = 0.0137 V. Histograms of measured voltages U_C, U_B, and the probability density function calculated using the obtained statistical moments are presented in Fig. 3.

Fig. 3 also presents the probability density distribution function of traction current harmonic voltage with frequency 420 Hz at the input of rail circuit receivers that was obtained from a statistical analysis of the traction current. For stationary locomotive movement modes the traction harmonic voltage was enough strictly described with normal probability distribution function.

For transient modes the interference voltage distribution had a more complex character and could be described for truncated normal or exponential function as the first approximation.

The results in Fig. 3 show that there is a finite probability that the value of 420 Hz harmonic interference at the input of rail circuit receivers may become greater than the turn-on voltage and even turn-off voltage of rail circuit

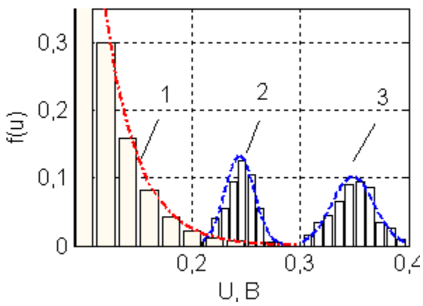

Fig. 3. The probability density distribution function of voltage of a harmonic on the input of RC receiver (a) and histograms of turn-off (2) and turn-on (3) voltages of RC receivers
Source: [own work]

receiver, when some of the most adverse factors would coincide in time during the train movement.

Failure in rail circuits may take place when the voltage at the input of rail circuit receivers in normal mode operation decreases lower than the input turn-on voltage of receivers or when the voltage at the input of rail circuit receivers in shunt or control mode operation increased higher than the input turn-off voltage of receivers.

Probabilities of these events are equal

$$P\{U_{RN} < U_C\} = \int_0^{U_C} f(U_{RN})\,dU_{RN}, \qquad (11)$$

$$P\{U_{RS} > U_B\} = \int_{U_B}^{\infty} f(U_{RS})\,dU_{RS}. \qquad (12)$$

The probability that the input receiver voltage falls within interval (U_1, U_1+dU) is equal to

$$P\{U_C \in (U_1, U_1 + dU)\} = f(U_1)\,dU, \qquad (13)$$

$$P\{U_{\hat{A}} \in (U_1, U_1 + dU)\} = f(U_1)\,dU. \qquad (1)$$

Since these events are independent in pairs, probabilities of rail circuit's failure in normal (P_{FN}) and shunt (P_{FS}) modes are equal to the product of these events probabilities

$$\begin{aligned} P_{FN} &= P\{[U_C \in (U_C, U_C + dU_C)] \cap \\ &\cap [U_{RN} < U_C]\} = \\ &= \int_0^{\infty} f(U_C) \left[\int_0^{U_C} f(U_{RN})\,dU_{RN} \right] dU_C, \end{aligned} \qquad (14)$$

$$\begin{aligned} P_{FS} &= P\{[U_{\hat{A}} \in (U_{\hat{A}}, U_{\hat{A}} + dU_{\hat{A}})] \cap \\ &\cap [U_{RS} < U_{\hat{A}}]\} = \\ &= \int_0^{\infty} f(U_{\hat{A}}) \left[\int_{U_{\hat{A}}}^{\infty} f(U_{RS})\,dU_{RS} \right] dU_{\hat{A}}. \end{aligned} \qquad (15)$$

From the obtained equations it is possible to determine the probability of rail circuits failure when concrete statistical parameters of the input receiver voltage for normal, shunt and control rail circuit's operation modes were preliminary measured.

4. Conclusion

The statistical analysis of traction current harmonics in rail circuits has been provided with the aim to develop statistical methods of electromagnetic compatibility evaluation between the AC power traction current and rail circuits. Time and frequency domain analysis of traction current in rail circuits has shown high enough level of correlation between the current in a locomotive power circuit and in rail lines. On the basis of the variance analysis of input voltages of rail circuit receivers mathematical equations were obtained that allowed to determine the probability of rail circuits failure when concrete statistical parameters of the input receiver voltage for normal, shunt and control rail circuit's operation modes were preliminary measured.

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