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АВТОМАТИЗОВАНІ ТА ТЕЛЕМАТИЧНІ СИСТЕМИ НА ТРАНСПОРТІ

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A. V. ZUBKO[1*], V. I. SHCHEKA[2*]

[1*]Dep. «Automation and Telecommunications», Ukrainian State University of Science and Technologies, SEI DIIT, Lazaryana St., 2, Dnipro, Ukraine, 49010, tel. +38 (056) 373 15 04, e-mail andrii.v.zubko@gmail.com, ORCID 0009-0001-1861-5017
[2*]Dep. «Automation and Telecommunications», Ukrainian State University of Science and Technologies, SEI DIIT, Lazaryana St., 2, Dnipro, Ukraine, 49010, tel. +38 (056) 373 15 04, e-mail v.i.shcheka@ust.edu.ua, ORCID 0000-0002-2184-2827

Consideration of the Upper Error Bound of Measurement Complex in the Analysis of Digitized Signals

Purpose. This work aims to: enhancing the reliability of certification tests for new rolling stock by integrating measurement system error considerations into the data analysis process; ensuring a more precise evaluation of compliance with safety and performance standards, minimizing the risk of undetected defects that could emerge during operation; improving risk assessment by reducing measurement uncertainties, thereby strengthening the decision-making process for rolling stock approval. **Methodology.** Analyzing existing approaches to certifying new rolling stock in accounting for measurement system errors. Developing a method for systematically integrating these errors into the data analysis process to enhance result accuracy. Assessing the impact of this approach on certification reliability and its effectiveness in identifying potential operational risks before deployment. **Findings.** An improved certification process incorporating measurement system error considerations has been proposed. The study demonstrates that this approach significantly reduces the probability of overlooking defects that may only become apparent during operation, thereby increasing the overall reliability of certification tests. **Originality.** A method for assessing the reliability of certification test data while considering measurement system errors has been developed. It has been proven that integrating these data into the test analysis process improves the accuracy of predicting the operational reliability of rolling stock and enhances the overall effectiveness of certification procedures. **Practical value.** The proposed approach enhances railway transport safety by ensuring a more reliable and accurate certification process for new rolling stock. This is particularly relevant in the context of Ukraine's railway fleet modernization, including the introduction of Hyundai Rotem and Tarpan electric trains, as well as Škoda locomotives. By refining certification procedures, this methodology contributes to safer and more efficient railway operations.

Key words: certification testing; digital signal analysis; safety; interference; electromagnetic compatibility; traction current; harmonic

Introduction

Railway transport plays an important role in the economy, infrastructure development, and ensuring the sustainable movement of goods and passengers in Ukraine. To enhance productivity, specifically by increasing passenger and freight transportation volumes, Ukraine's railway systems are continuously being modernized.

Some modernization efforts focus on improving transportation safety, while others aim to enhance management systems, including monitoring and planning improvements. These advancements help optimize transportation operations and increase the number of trips within a given period.

Such modernization efforts are feasible, but they largely depend on train speeds across the country's railway network. Increasing train speeds significantly boosts the overall capacity of the railway system. Higher travel speeds open new possibilities for improving management systems. These and many

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other factors influence the quantity, quality, and, most importantly, the safety of transportation. While ensuring safety remains the top priority for Ukraine's railways, increasing train speeds is a key factor in improving their efficiency.

Speed enhancement is achieved through the modernization or replacement of certain locomotive components and systems, such as braking systems, control systems, power circuits, and cooling systems. Increasing engine power while maintaining locomotive stability and safety on the tracks plays a crucial role in achieving higher speeds. [5]

Since early 2012, Ukraine's railway network has undergone modernization efforts aimed at increasing train speeds. During this period, the following new locomotives and electric trains were introduced:

– Hyundai Rotem: Electric trains from Hyundai Rotem began operation in 2012;

– Škoda: Škoda locomotives also entered service in 2012;

– Tarpan: «Tarpan» electric trains, produced by the Kryukov Railway Car Building Works, began operation in 2014.

These modernization efforts have improved the efficiency of railway transport, ensuring faster and more comfortable transportation of both passengers and cargo.

Purpose

The study focuses on the certification testing process of railway rolling stock, with particular emphasis on assessing electromagnetic compatibility with railway automation and telemechanic systems. The article examines existing approaches to conducting tests, data analysis, and evaluating compliance with international standards. One of the key aspects of this research is the issue of insufficient consideration of measurement system errors during the digital analysis of signals, particularly the return traction current.

Measurement inaccuracies play a crucial role in the certification process, as even minor deviations can affect the results and lead to incorrect assessments of electromagnetic impact levels. In most cases, data on measurement uncertainty is recorded in test protocols; however, it is not always factored into the final data processing. This creates a risk where measured values may be close to the maximum permissible limits, but without accounting for possible deviations, potentially leading to an incorrect approval of rolling stock for operation.

This study aims to substantiate the need for a more precise approach to certification testing, incorporating the influence of measurement system errors, especially in critical scenarios. Such an approach will not only enhance result accuracy but also provide an additional layer of safety when introducing new rolling stock into service. A proper analysis of electromagnetic compatibility is a key factor in ensuring the reliability of railway infrastructure and preventing potential risks to signaling, communication, and automatic train control systems.

The process of conducting certification tests. Introducing a new rail vehicle is a complex and highly responsible process. Testing is conducted to determine the feasibility of operating new rolling stock on the railway network while adhering to all safety regulations and measures for passenger and freight transportation.

These tests assess the safety level of using new rail vehicles. Inspections are carried out by all railway departments, including the locomotive depot, signaling and communications service (SCS), track service, and power supply service. These departments conduct a detailed analysis and testing to ensure the new equipment meets all safety and operational requirements.

Certification studies by the signaling and communications service focus on identifying potential risks that a new rail vehicle may pose to station, track, or level crossing equipment. Particular attention is given to verifying the electromagnetic compatibility of the new equipment with locomotive control systems, such as automatic block signaling (ABS), automatic train signaling (ATS), microprocessor interlocking (MPI), and electric interlocking (EI). Additionally, tests are conducted to assess potential interference with communication systems, including dispatching and station communication, ensuring that interactions with new locomotives do not cause operational disruptions. [1, 4]

In tests assessing electromagnetic compatibility with SCS devices, special attention is given to return traction current, which flows back to the traction substation through the rails. Significant distortions in return traction current can adversely affect the operation of signaling and communication de-

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vices, potentially leading to system failures, violations of safe transportation regulations, and risks to passenger and personnel safety, as well as the integrity of transported goods.

Rolling stock electromagnetic compatibility tests are conducted following the rules and standards of international railway electromagnetic compatibility regulations [6–10]. These standards establish permissible levels of return traction current for different frequency ranges depending on the type of current (DC or AC) and dictate the procedures for measurement and data analysis.

Before data collection, all measuring devices undergo accuracy verification in accredited metrology laboratories. This procedure determines the accuracy of each device and assesses the overall measurement system's potential margin of error.

During testing, current levels are monitored to ensure they do not exceed permissible values within the specified frequency ranges outlined by the standards. Studies are conducted across all locomotive operating modes: coasting, braking, acceleration, idle, traction, and regeneration. If return traction current studies reveal violations (exceeding permissible limits according to the established standards), the locomotive is not approved for operation until the parameters are brought into compliance with regulatory requirements, as confirmed by subsequent testing.

The digitization of return traction current is performed using a combination of devices, including current sensors (such as Rogowski coils, current clamps, etc.), an amplification and conversion unit, an analog-to-digital converter (ADC), a data storage device, and a personal computer (PC). Once data is collected, the process of digital analysis and signal processing begins.

Methodology

To ensure the safety of railway rolling stock and railway automation and telemechanic systems, a digital data analysis is conducted following field tests. Particular attention is given to the analysis of the return traction current signal, which is verified for compliance with electromagnetic compatibility requirements. These requirements are outlined in the international standard IEC 62236-3-1:2018, specifically in subsection 6.1 and clause 6.2.2. Compliance with these standards is critically important for preventing potentially hazardous situations arising from electromagnetic interference between new rolling stock and existing automation systems. [8, 11].

Although data on the measurement system's margin of error is recorded in the test protocol, it is often not considered during digital analysis, as a certain level of error is deemed acceptable. However, when assessing the safety of new rolling stock, it is necessary to account for the worst-case scenario. This means that the measurement system's error should be taken into consideration during signal analysis, especially when the digitized signal level is close to the maximum permissible current threshold. In such cases, there is a risk that measurement uncertainty could lead to an exceedance of this threshold.

Consider a test signal example that clearly illustrates this issue. The Fig. 1 presents a section of the digitized signal, which serves as an analog of a real return traction current signal of a locomotive.

Without digital processing, it is difficult to determine whether the signal contains harmful interference that exceeds the maximum allowable current level within specific frequency ranges. To enhance clarity, a band-pass filtering method will be applied to the original signal using the MATLAB development and simulation environment. As an example, we will examine interference at a frequency of 420 Hz.

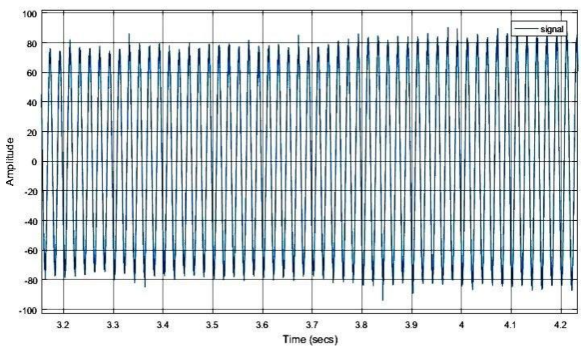

Fig. 1. The original signal of the locomotive's return traction current

According to testing standards, the frequency range should be between 408 and 432 Hz, the maximum allowable amplitude must not exceed 0.35 A, and the duration should be no less than 0.3 seconds.

For the analysis, a Chebyshev Type II infinite impulse response (IIR) band-pass filter will be used. The transfer function of this filter is defined according to equation (1):

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$$H(z)=\frac{B(z)}{A(z)}, \quad (1)$$

where z is a complex variable, $z=e^{jw}$, and w represents the frequency in radians; $B(z)$ and $A(z)$ are polynomials in z with coefficients corresponding to the numerator and denominator of the filter's transfer function [3].

To achieve a sharp attenuation characteristic, a 44th-order filter was modeled. The transfer function of this filter is presented in equation (2), and the amplitude-frequency characteristic is shown in Fig. 2.

$$H(z)=\frac{b_0+b_1z^{-1}+b_2z^{-2}+...+b_{44}z^{-44}}{1+a_1z^{-1}+a_2z^{-2}+...+a_{44}z^{-44}} \quad (2)$$

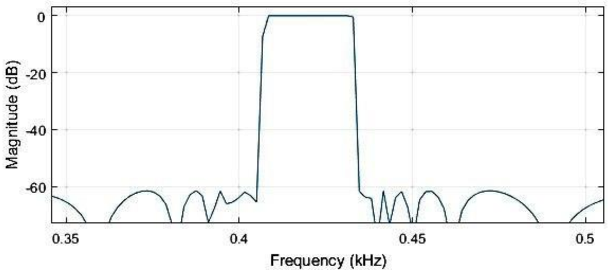
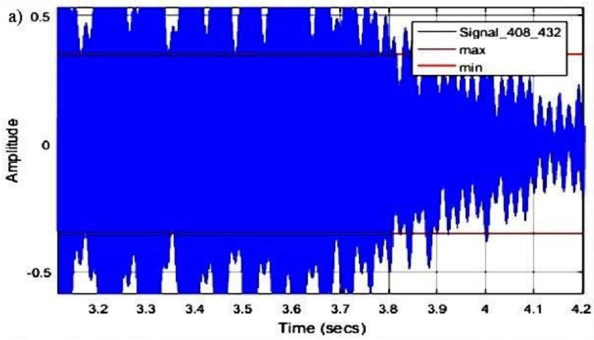


Fig. 2. The amplitude-frequency characteristic of the bandpass filter 408–432 Hz

The results of the digital filtering performed using the modeled filter are presented in Fig. 3, *a*. The figure also shows the limit boundaries of the signal amplitude: +0.35 A and –0.35 A (max and min, respectively). The analysis of the original signal with filtering allowed for visualizing the signal characteristics within the specified limits.

The analysis of this segment revealed that, from 3.38 to 3.75 seconds (0.37 seconds), the effective value of the harmonic component is 0.349 A (see Fig. 3b). According to the international standard [8], this value does not exceed the maximum allowable limit (0.35 A), and therefore such a deviation would not be considered potentially dangerous.

a



b

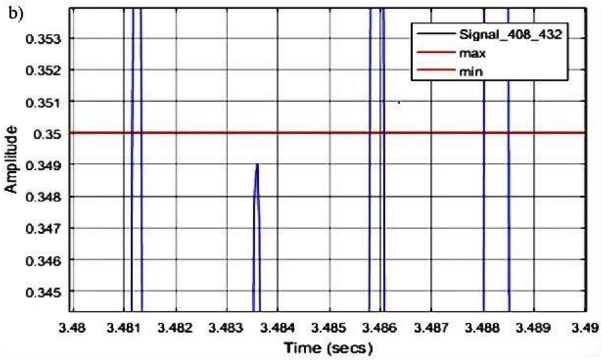


Fig. 3. The original signal after digital filtering in the range of 408-432 Hz:
a – Filtered signal,
b – Close-up of the signal's minimum peak section

Error accounting in data analysis can be carried out using two methods.

The first method involves analyzing the original measurement data, followed by accounting for the error at the final stage. For example, to correct the measurement results and obtain the maximum possible effective value considering the error (EVP), equation (3) can be used. Thus, with a measurement system error of, for instance, 1 %, the worst-case effective value would be 0.3525 A, which already exceeds the maximum permissible value.

$$EVP=\frac{EV\cdot P}{100}, \quad (3)$$

where EV is the effective value of the harmonic component; P is the measurement system error (%).

The second method involves preliminarily increasing the values of all points in the original signal by the amount of the error before starting the analysis. This approach requires the use of software such as Excel or MATLAB, as well as some coding

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skills. To implement this method, the following algorithm should be applied.

Let the set of original points be denoted as X:

$$X = \{x_1, x_2, ..., x_n\},$$

where x_i is the value of the i-th point; n is the total number of points.

The set of points with increased values will have a similar structure:

$$X' = \{x_1', x_2', ..., x_n'\}.$$

Thus, the entire set of points X is modified by the following equation (4):

$$X' = \left\{x_1 + \frac{x_1 \cdot P}{100}, x_2 + \frac{x_2 \cdot P}{100}, ..., x_n + \frac{x_n \cdot P}{100}\right\}, \quad (4)$$

where P is the measurement system error (%).

To confirm the correctness of the second method, let us first increase the values of the points in the original signal by the amount of the error (1 %) using equation (4). The new points X' are then filtered using the previously modeled band-pass filter at frequencies between 408 and 432 Hz. Next, we analyze the filter results for the section of the signal where the lowest peak of the effective value is observed (Fig. 4).

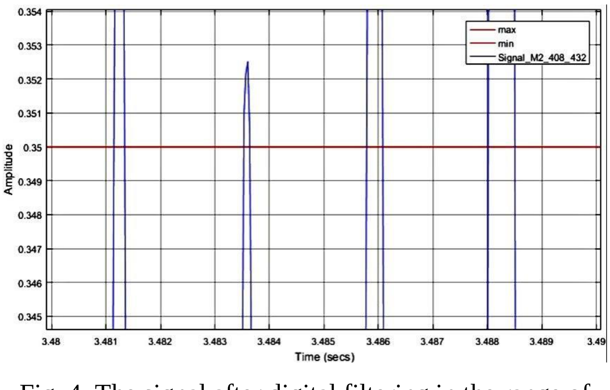

Fig. 4. The signal after digital filtering in the range of 408–432 Hz, accounting for a 1 % measurement system error

A comparison of the results from both methods shows that they align: the effective value, considering the error, is 0.3525 A, which confirms the correctness of the chosen approach. This value also exceeds the maximum allowable value and, as in the first method, represents a potentially dangerous violation.

Although the second method is more complex, it provides a more accurate assessment of the data during analysis, leading to a better understanding of potential exceedances of allowable harmonic levels under the worst-case conditions associated with measurement system errors.

This method is preferable as it allows for the consideration of actual data and helps identify potential issues that might remain unnoticed in a simple analysis of the original signals. Applying the measurement error to each data point in the signal set enables the detection of areas that could be overlooked without accounting for the error. As a result, the likelihood that previously normal signal sections may exceed the permissible limits increases. This approach allows for a more thorough analysis and identification of potential violations, which could be critical in real-world operating conditions.

Findings

The results of the study showed that ignoring the measurement system's error could lead to the omission of potentially dangerous sections of the return traction current. This is particularly critical when the signal is close to the maximum permissible levels, which could result in non-compliance with electromagnetic compatibility requirements and potential operational issues. Using a methodology that accounts for measurement errors during testing allows for a more accurate assessment of risks and helps prevent potential failures in real-world operating conditions. This approach enhances safety and reliability in the operation of railway rolling stock, preventing potential hazards that might otherwise go unnoticed in standard signal analysis.

This method can also be valuable for developing more effective monitoring and management strategies for railway systems. Including errors in the calculations not only helps avoid potential accidents but also improves overall diagnostics and equipment tuning, thus ensuring stable and safe operation throughout the entire lifecycle of the rolling stock.

Originality and practical value

The originality of the research lies in the approach to accounting for measurement system errors when analyzing locomotive return traction current. Unlike traditional methods, where such errors are often ignored, the proposed methodology allows

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for a more accurate assessment of the signal characteristics, revealing potentially hazardous deviations. This solution represents a significant advancement in the field of safety, as it enables the prediction and prevention of issues that could arise during operation.

The practical value of this approach lies in its potential to enhance the reliability and safety of railway rolling stock operation. By incorporating error consideration in signal analysis, the methodology ensures accurate evaluation of electromagnetic interference impacts and guarantees compliance with international standards. The implementation of this approach in testing and monitoring systems will help ensure a higher level of safety for new locomotives, improving operational performance and preventing potentially dangerous situations.

Conclusions

The main goal of certification testing is to ensure that new locomotives comply with regulatory requirements and do not pose a threat to traffic safety. Considering the measurement system's error margin allows for reducing the uncertainty during digital analysis, enabling a more accurate assessment of the locomotive's compliance with established standards. If any discrepancies are found during testing, the locomotive is sent for adjustments, followed by re-testing to confirm its safety and readiness for operation. [2]

Although the method of increasing the signal points by the error margin is a more complex process, its application significantly improves the accuracy of the analysis. This approach allows not only for considering the errors of the measurement system but also for identifying areas of the signal that, without accounting for the error, could remain within the acceptable range. As a result, the probability of detecting potentially dangerous areas, which could be overlooked during standard analysis, increases. Therefore, the application of this method contributes to a more detailed evaluation of harmonics and ensures a higher precision in certification.

This approach places additional demands on locomotive manufacturers, as the allowable deviations from the standard during testing are narrowed by the error margin of the measurement system. This means that additional factors must be considered to meet stringent safety standards and eliminate potential risks. Despite the increased complexity of the process, more thorough design, testing, and certification ultimately contribute to improving the safety of railway transportation.

The certification process is a complex and critical procedure. Any inaccuracy or negligence in checking the electromagnetic compatibility of a new rolling stock with already existing and operational railway automation systems can result in the introduction of these units into operation, thereby endangering the lives of passengers, staff, and the integrity of transported goods. Therefore, in research, especially in the transport industry, even the smallest probability of failure must be considered, and measures must be taken to prevent it, ensuring that the possibility of its occurrence is eliminated.

In the future, it is planned to conduct a detailed assessment of the feasibility of integrating the proposed methodology into existing certification systems. Special attention will be paid to its adaptability to the regulatory frameworks of other countries and international standards, such as those defined by the European Union, ISO, and IEC. This step is essential for ensuring that the methodology can be effectively applied in a global context and contribute to harmonizing certification procedures across borders. Based on the results of this assessment, additional scientific publications are planned, which will present the outcomes of the analysis and offer recommendations for practical implementation in international certification workflows. These publications will also explore potential challenges and limitations, ensuring a comprehensive approach to improving railway safety and measurement accuracy.

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А. В. ЗУБКО[1*], В. І. ЩЕКА[2*]

[1*]Каф. «Автоматика та телекомунікації», Український державний університет науки і технологій, ННІ ДІІТ, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (056) 373 15 04, ел. пошта andrii.v.zubko@gmail.com, ORCID 0009-0001-1861-5017
[2*]Каф. «Автоматика та телекомунікації», Український державний університет науки і технологій, ННІ ДІІТ, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (056) 373 15 04, ел. пошта v.i.shcheka@ust.edu.ua, ORCID 0000-0002-2184-2827

Урахування верхньої межі похибки вимірювального комплексу під час аналізу оцифрованих сигналів

Мета. Ця побота спрямована на: підвищення надійності сертифікаційних випробувань нового рухомого складу шляхом інтеграції врахування похибок вимірювального комплексу в процес аналізу даних; забезпечення більш точної оцінки відповідності вимогам безпеки та експлуатаційних характеристик, мінімізація ризику невиявлених дефектів, які можуть проявитися під час експлуатації; поліпшення оцінки ризиків за рахунок зменшення невизначеності вимірювань, що підвищує обґрунтованість прийняття рішень щодо допуску рухомого складу до експлуатації. **Методика.** Проведено аналіз наявних підходів до сертифікації нового рухомого складу з урахуванням похибок вимірювального комплексу. Розроблено методу системної інтеграції цих похибок у процес аналізу даних для підвищення точності отриманих результатів. Визначено вплив запропонованого підходу на точність сертифікаційних випробувань та його ефективність у виявленні потенційних експлуатаційних ризиків до введення рухомого складу в експлуатацію. **Результати.** Запропоновано вдосконалений процес сертифікації, що враховує похибки вимірювального комплексу. Дослідження показало, що цей підхід знижує ймовірність пропущення дефектів, які можуть проявитися лише під час експлуатації, тим самим підвищуючи загальну точність сертифікаційних випробувань. **Наукова новизна.** Розроблено метод оцінки надійності даних сертифікаційних випробувань із врахуванням похибок вимірювального комплексу. Доведено, що інтеграція цих даних у процес аналізу результатів випробувань підвищує точність прогнозування експлуатаційної надійності рухомого складу та поліпшує загальну ефективність сертифікаційних випробувань. **Практична значимість.** Запропонований підхід сприяє підвищенню безпеки залізничного транспорту завдяки забезпеченню більш надійного й точного процесу сертифікації нового рухомого складу. Це

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особливо актуально в контексті модернізації залізничного парку України, зокрема введення в експлуатацію електропоїздів Hyundai Rotem і Tarpan, а також локомотивів Škoda. Удосконалення сертифікаційних випробувань сприяє підвищенню рівня безпеки та ефективності залізничних перевезень.

Ключові слова: сертифікаційні випробування; аналіз цифрових сигналів; безпека; завади; електромагнітна сумісність; тяговий струм; гармоніки

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