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Level-Based Classification of Electromagnetic Effects in Certification Tests of Electric Rolling Stock

Purpose. To develop a conceptual framework for interpreting the results of electromagnetic compatibility (EMC) certification tests of electric rolling stock using a multi-level classification system. The study aims to establish a structured method for distinguishing different states of electromagnetic influence based on measured parameters of amplitude and duration, thereby improving the representation and understanding of test data within existing certification procedures. **Methodology.** Existing approaches to electromagnetic compatibility testing and data interpretation in railway applications were analyzed to identify limitations in differentiating levels of electromagnetic influence. A structured method for precise classification is proposed, based on normalized comparison of interference characteristics. The developed framework defines transition zones between safe and potentially critical operating conditions and allows flexible adaptation of threshold parameters depending on test conditions. This ensures compliance with certification requirements while enhancing the diagnostic depth and informativeness of the results. **Findings.** A multi-level classification system for electromagnetic interference has been developed, providing a comprehensive representation of EMC test results. The approach enables identification of transitional states and trends toward critical operating conditions that are not detectable under a dichotomous evaluation scheme. It allows a more accurate interpretation of test outcomes, supports early diagnostics of instability, and provides a quantitative basis for assessing the operational resilience of railway systems. **Originality.** A systematic, multi-level framework for interpreting EMC test results of electric rolling stock has been developed. Unlike conventional methods limited to threshold verification, the proposed approach accounts for the dynamics of parameter variations and their interdependencies, enabling predictive analysis and a more complete understanding of electromagnetic behavior under various operating conditions. **Practical value.** The developed methodology enhances the accuracy, transparency, and reliability of certification testing for electric locomotives, multiple-unit trains, and other electrically powered rolling stock. It contributes to safer and more efficient railway operation by providing engineers and certification authorities with a comprehensive analytical framework for assessing electromagnetic compatibility. The approach is applicable for optimizing design solutions, refining certification criteria, and supporting the modernization of railway infrastructure.

Key words: electromagnetic compatibility; multi-level classification; certification testing; rolling stock; interference analysis; traction current; predictive diagnostics; monitoring; operational safety; risk assessment

Introduction

Modern railway systems are characterized by a rapid increase in the level of digitalization and integration of electronic components. In train control and centralized traffic control systems, microprocessor-based controllers, converters, diagnostic units, and communication systems are widely used. This enhances their functionality but simultaneously complicates the electromagnetic operating environment. The growing density of electronic devices within the limited spaces of rolling stock increases the number of potential sources of interference, while the transition to hybrid and digital power supply circuits strengthens the requirements for electromagnetic compatibility (EMC). Under these conditions, ensuring the stability and reliability of electronic system operation becomes a critical factor for traffic safety.

Certification testing of electric rolling stock for electromagnetic compatibility occupies a key position in the railway transport safety assurance system. Such tests are conducted to confirm the ability of electric locomotives, electric multiple units, and other types of electrically powered rolling stock (hereinafter referred to as ERS) to operate within a complex electromagnetic environment without causing mutual interference with infrastructure elements – including signaling, interlocking, and power supply systems, as well as communication equipment [1, 2, 7, 16].

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The purpose of these tests is to determine whether the electric rolling stock generates inadmissible electromagnetic emissions affecting surrounding equipment, while maintaining its own immunity to external electromagnetic fields.

Certification tests are carried out in accordance with international standards such as IEC 62236, CLC/TS 50238–2, and EN 50728, which define the measurement procedures, control parameters, and permissible levels of electromagnetic disturbances [5, 6, 8, 9, 10–13, 14].

During testing, both radiated and conducted emissions, as well as the electromagnetic immunity of systems under various power supply and load conditions, are assessed. The results obtained make it possible to confirm compliance with established norms and thereby ensure the safe and reliable operation of ERS as part of the railway system. However, the existing practice of interpreting test results is primarily based on a binary principle – the tested object is either considered compliant with the requirements or not [4, 15].

This approach, based on a dichotomous evaluation model (or binary classification scheme), ensures the formal completion of certification procedures but does not always reflect the full complexity of electromagnetic interactions occurring under real operating conditions.

Despite its simplicity and clarity, the dichotomous evaluation system has significant limitations in terms of analytical informativeness. It does not allow identification or recording of intermediate states where the level of electromagnetic influence approaches the permissible limits but has not yet formally exceeded them. In such cases, the equipment is considered “compliant”, although the actual interference level may already pose a potential threat to the stable operation of signaling and control systems. The absence of gradations between acceptable and unacceptable states leads to the loss of valuable diagnostic information, limits predictive capabilities, and reduces the effectiveness of preventive measures. This, in turn, highlights the need to transition toward more detailed and informative methods for interpreting the results of certification testing.

Purpose

The objective of this research is to develop a conceptual framework for a multi-level approach to the interpretation of EMC test results for electric rolling stock. The proposed approach is aimed at enhancing the informational value of electromagnetic impact assessment without requiring any modifications to the existing regulatory framework. It supplements the current binary evaluation system with more detailed interpretive levels, thereby providing a deeper understanding of the actual electromagnetic stability of the tested objects.

The primary goal of the study is to establish a method that enables the identification of transitional zones between acceptable and critical operating conditions, the evaluation of EMC parameter dynamics under various power supply scenarios, and the utilization of the resulting data to refine engineering decisions and improve certification requirements.

This research does not intend to revise existing standards but rather focuses on advancing analytical and interpretative methods within the framework of current requirements. The main attention is given to the interaction between electric rolling stock and signaling, interlocking, and communication systems, where ensuring electromagnetic compatibility is of critical importance for traffic safety and the operational stability of infrastructure elements.

To enhance the informativeness of EMC test result analysis, a multi-level classification system for electromagnetic impact states is proposed. Unlike the traditional dichotomous model, the suggested approach introduces four evaluation levels that reflect not only compliance with normative limits but also the degree of proximity to threshold values and instances of their exceedance.

Such differentiation allows for the consideration of transitional states, the detection of trends indicating the deterioration of the electromagnetic environment, and timely responses to potentially hazardous conditions. Each level represents the degree of parameter deviation from permissible values and characterizes the potential risk to the operation of signaling and control systems, as well as other electronic components of the electric rolling stock.

Methodology

Analysis parameters. The parameters considered in the analysis include the root mean square (RMS) amplitude of the harmonic components of current I, representing the intensity of electrical disturb-

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ances, and the duration of disturbance t (in seconds), representing the time interval during which the amplitude exceeds the threshold value.

For quantitative interpretation of the levels of electromagnetic influence, normalized quantities of current and duration of interference are introduced:

– I_{lim} – normative (limit) value of current, A,

– t_{lim} – normative (limit) value of duration, sec.

The values of I_{lim} and t_{lim} are obtained from the standardized tables of harmonic current components for different power supply systems of electric locomotives and electric multiple units – namely, 3 kV DC, 25 kV AC at 50 Hz, and combined systems. These data are based on the requirements of the corresponding standard, which defines the permissible levels of harmonic components and the limiting values of electromagnetic disturbances within the relevant frequency bands associated with the nominal signal frequencies of signaling and interlocking equipment (Table 1) [1, 3, 5].

Table 1

Permissible values of harmonic current components for electric locomotives and electric multiple units

Power supply system	Harmonic frequency band, Hz	Nominal signal frequency, Hz	RMS harmonic current in band, max
3 kV DC	19–21 21–29 29–31	25	11.6 1.0 11.6
	40–46 46–54 54–60	50	5.0 1.3 5.0
	4 507–4 583	4 545	0.2
	5 517–5 593	5 555	0.2
25 kV AC (50 Hz)	15–21 21–29 29–35	25	4.1 1.0 4.1
	65–68	75	4.1
	4 462–4 538	4 500	0.2
	5 462–5 538	5 500	0.2

Continuation of Table 1

Power supply system	Harmonic frequency band, Hz	Nominal signal frequency, Hz	RMS harmonic current in band, max
3 kV DC and 25 kV AC (50 Hz)	167–184	175	0.4
	408–432	420	0.35
	468–492	480	0.35
	568–592	580	0.35
	708–732	720	0.35
	768–792	780	0.35
	4 962–5 038	5000	0.2

The tables provided in the standard specify the root mean square (RMS) current levels calculated for all harmonic components simultaneously present within a given frequency band, for a disturbance duration exceeding 0.3 seconds. This duration criterion serves as the regulatory basis for determining the limiting value of disturbance duration t_{lim}, which is used for the normalization of exposure duration in the proposed classification system [3, 5].

The main evaluation parameters are as follows:

– harmonic component current – I;

– maximum permissible current – I_{lim};

– disturbance duration – t;

– maximum permissible duration – t_{lim}.

The following normalized parameters are introduced:

$$k_I = \frac{I}{I_{\text{lim}}};$$

$$k_T = \frac{t}{t_{\text{lim}}},$$

where k_I resents the relative exceedance of the current amplitude with respect to the permissible value and k_T denotes the relative exceedance of the disturbance duration.

Thus, the introduction of the variables k_I and k_T makes it possible to construct a classification system in which the system states are evaluated comprehensively according to two key characteris-

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tics – the magnitude of the harmonic current components and the duration of their impact. This provides a precise and unambiguous determination of the risk level associated with electromagnetic disturbances.

Levels of Stability and Risk. To analyze system stability, it is proposed to distinguish four stability levels depending on the amplitude and duration of electromagnetic disturbances.

Level 1 (Safe – Green) – the zone of stable operation, where both the amplitude of harmonic current components and the disturbance duration are significantly below the regulatory limits.

Condition of membership:

$$k_I \in (0, k_{I1}] \wedge k_T \in (0, k_{T1}],$$

where k_{I1} is the amplitude threshold coefficient defining the upper boundary of the safe zone and k_{T1} is the time threshold coefficient defining the maximum disturbance duration for this level.

Using the limiting current amplitude $I_{\lim}$ and limiting duration $t_{\lim}$, the amplitude and duration corresponding to the safe level are determined as:

$$I_1 = k_{I1} \cdot I_{\lim}; \quad (1)$$

$$t_1 = k_{T1} \cdot t_{\lim}. \quad (2)$$

The values I_1 and t_1 represent the actual boundaries of the safe zone, within which the system operates stably and the observed disturbances do not have a significant impact on the equipment or signaling devices.

Level 2 (Advisory – Yellow) – the early warning stage, in which the amplitude of harmonic current components and the duration of the disturbance approach critical values but remain within the permissible range.

Condition of membership:

$$k_I \in (k_{I1}, k_{I2}] \wedge k_T \in (k_{T1}, k_{T2}],$$

where k_{I2} is the amplitude threshold coefficient defining the upper boundary of the advisory level and k_{T2} is the time threshold coefficient defining the maximum allowable duration for this level.

The real amplitude and duration for the advisory level are calculated as:

$$I_2 = k_{I2} \cdot I_{\lim}; \quad (3)$$

$$t_2 = k_{T2} \cdot t_{\lim}. \quad (4)$$

The values I_2 and t_2 define the boundary of the region in which the system still operates correctly but is approaching a state that requires monitoring and possible intervention to prevent transition into critical modes.

Level 3 (Pre–Critical – Red) – the heightened alert zone, where the amplitudes of harmonic components and the duration of disturbances are close to the limiting values but do not yet exceed the normative limits $I_{\lim}$ and $t_{\lim}$.

At this stage, the system operates in a condition close to the critical state, requiring increased attention and parameter monitoring.

Condition of membership:

$$k_I \in (k_{I2}, 1] \wedge k_T \in (k_{T2}, 1].$$

Thus, the «Pre–Critical» level denotes a condition in which the influence of harmonic components and their exposure time reach the admissible limits, indicating the need for control and possible load reduction to avoid transition into the critical zone.

Level 4 (Critical – Black) – the danger zone, in which the amplitudes of harmonic components and the duration of disturbances exceed the regulatory limits.

This condition indicates that the system has exceeded the permissible values, which may lead to malfunctions in equipment or signaling and interlocking systems.

Condition of membership:

$$k_I \in (1, \infty) \wedge k_T \in (1, \infty).$$

Therefore, the "Critical" level corresponds to the state in which system parameters surpass the allowable norms, and operation occurs under conditions of potential danger to stability and reliability of the equipment.

To ensure the consistency of classification, the normalization coefficients for amplitude and duration are selected so as to satisfy the inequalities:

$$0 < k_{I1} < k_{I2} < 1; \quad (5)$$

$$0 < k_{T1} < k_{T2} < 1. \quad (6)$$

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This guarantees a logical progression from the safe zone to the critical state. Such a dependence reflects the coherent variation of parameters: as the amplitude of harmonic components increases and the duration of the disturbance grows, the system gradually transitions to a higher risk level.

This relationship reflects the coherence in the variation of parameters: as the amplitude of the harmonic components increases and the duration of exposure grows, the system gradually transitions to a higher risk level.

The classification function for the risk level $L(I,t)$ takes the following form:

$$L(I,t)=\begin{cases}1, I \le I_1 \wedge t \le t_1 \\ 2, I_1 < I \le I_2 \wedge t_1 < t \le t_2 \\ 3, I_2 < I \le I_{\text{lim}} \wedge t_2 < t \le t_{\text{lim}} \\ 4, I > I_{\text{lim}} \wedge t > t_{\text{lim}}\end{cases}. \quad (7)$$

Findings

The input parameters for the classification are I_{lim} and t_{lim} – the limiting values of current and disturbance duration as regulated by the relevant standards [1, 3, 5].

The coefficients k_{I1}, k_{I2}, k_{T1}, k_{T2} are determined either experimentally or set by a specialist during testing, allowing the classification system to be adapted to actual operating conditions and the specific characteristics of the equipment.

This approach provides methodological flexibility: by adjusting the coefficient values, it is possible not only to modify the boundaries of existing classification levels but also to introduce additional levels if required for a more detailed assessment of system status, provided that the consistency of the inequalities between coefficients is maintained.

The proposed classification system enables the automatic determination of the criticality level of electromagnetic disturbances based on the measured amplitude and duration parameters I and t.

Figure 1 presents a binary representation of certification test results. The colored areas indicate regions corresponding to permissible and non-permissible values, providing a clear visual representation of the system's compliance with electromagnetic compatibility requirements.

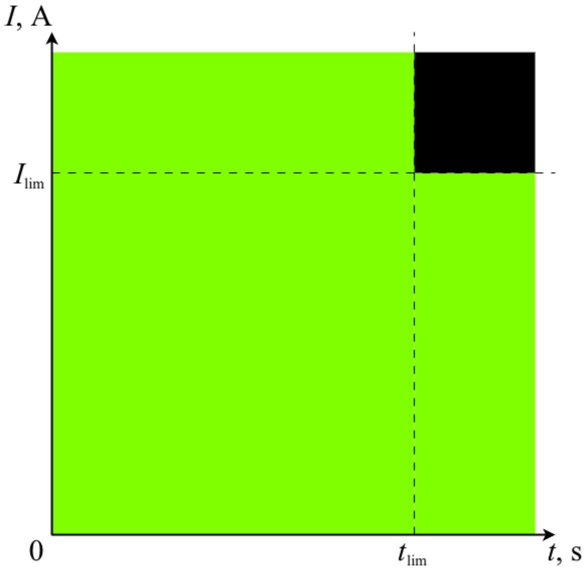

Fig. 1. Binary representation of certification test results showing compliance and non-compliance regions

Despite its visual clarity, the binary representation does not reflect the degree of proximity of the parameters to the threshold values and does not allow for a detailed assessment of the system state. In the figure, this is manifested as abrupt transitions between permissible and non-permissible zones, which complicates the analysis of trends and hidden dependencies in the data.

To increase informational content, a multi-level approach is employed, enabling a more precise classification of test results.

Figure 2 presents a multi-level representation of certification test results. Unlike the binary scheme, the multi-level approach provides a more detailed classification of the data, distributing parameter values across several ranges (Level 1–4) depending on the degree of compliance with regulatory requirements.

The use of color coding allows for a visual assessment not only of compliance or non-compliance but also of the degree of proximity of parameters to threshold values. This visualization method makes the structure of the results distribution more transparent, facilitating the analysis of trends, the identification of transitional areas, and the detection of potential risk zones.

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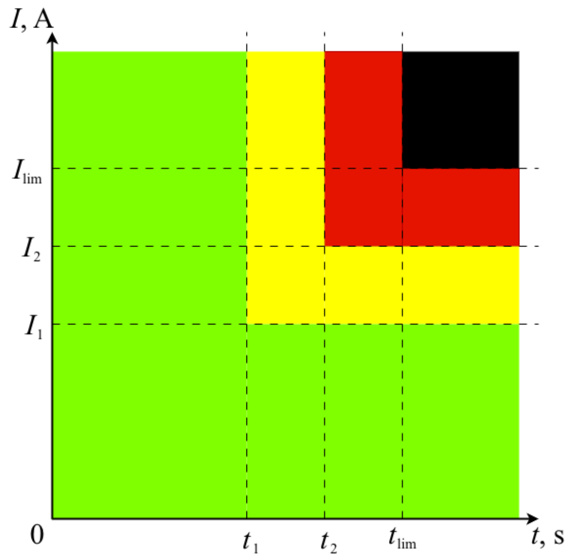

Fig. 2. Level-based representation of certification test results with color-coded Levels 1–4

Thus, the multi-level approach provides a foundation for a more flexible and informative interpretation of test results, offering enhanced support for engineering and certification decisions. When processing real test data, this approach enables a transition from the dichotomous "compliant / non-compliant" evaluation to a multi-level classification system, reflecting both the degree of proximity of parameters to threshold values and the dynamics of their change over time.

Practical application. Example calculation for frequency 420 Hz. To demonstrate the operation of the classification system, the following coefficients are proposed for the first two levels.

Level 1 (Safe):

$$k_{I1} = 0.9;$$

$$k_{T1} = 0.9.$$

Level 2 (Advisory):

$$k_{I2} = 0.95,$$

$$k_{T2} = 0.95.$$

The coefficients k_{I1}, k_{I2}, k_{T1} and k_{T2} were selected to satisfy the conditions (6) and (7).

For a frequency of 420 Hz, the following limiting values are established [1, 3, 5]:

$$I_{\lim} = 0.35 \text{ (A)};$$

$$t_{\lim} = 0.3 \text{ (sec)}.$$

Using the proposed coefficients k_{I1} and k_{T1}, the actual threshold values I_1 and t_1 for Level 1 are calculated according to formulas (1) and (2):

$$I_1 = k_{I1} \cdot I_{\lim} = 0.9 \cdot 0.35 = 0.315 \text{ (A)};$$

$$t_1 = k_{T1} \cdot t_{\lim} = 0.9 \cdot 0.3 = 0.27 \text{ (sec)}.$$

Using the proposed coefficients k_{I2} and k_{T2}, the actual threshold values I_2 and t_2 for Level 2 are calculated according to formulas (3) and (4):

$$I_2 = k_{I2} \cdot I_{\lim} = 0.95 \cdot 0.35 = 0.333 \text{ (A)};$$

$$t_2 = k_{T2} \cdot t_{\lim} = 0.95 \cdot 0.3 = 0.285 \text{ (sec)}.$$

Figure 3 presents the calculation results for 420 Hz using a linear scale, on which the boundaries of all classification levels are visually represented.

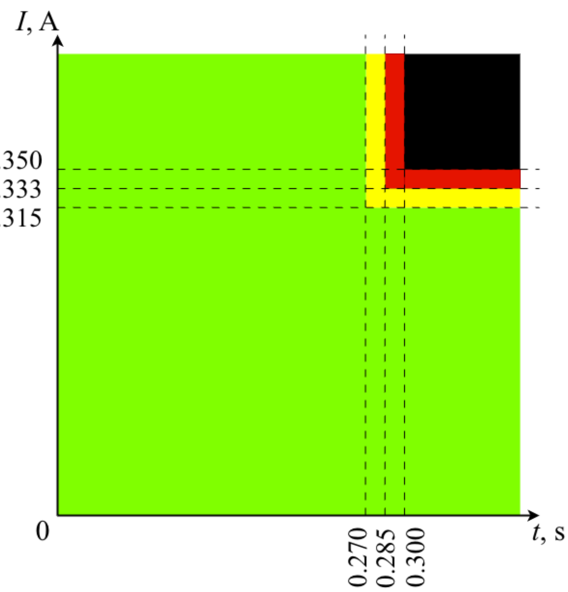

Fig. 3. Level-based visualization for 420 Hz showing calculated classification boundaries on a linear scale

Thus, the classification level zones for a frequency of 420 Hz are determined according to formula (7):

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$$L_{420}(I,t)=\begin{cases}1, I\le 0.315\wedge t\le 0.27\\ 2, 0.315<I\le 0.333\wedge 0.27<t\le 0.285\\ 3, 0.333<I\le 0.35\wedge 0.285<t\le 0.3\\ 4, I>0.35\wedge t>0.3\end{cases}$$

Originality and practical value

The proposed methodology for interpreting electromagnetic compatibility test results differs from traditional approaches by replacing the binary evaluation model – "compliant / non-compliant" – with a multi-level classification system. This approach allows for the consideration of the degree of proximity of parameters to threshold values, the duration of disturbances, and cumulative effects, providing a more detailed assessment of the system state during certification testing.

The scientific novelty of this work lies in the implementation of a multi-level analytical model that introduces several gradations of system state – from safe (green) to critical (black). This enables a more precise and informative differentiation of test results compared to the conventional dichotomous scheme.

The methodology is based on standardized normalized indicators of disturbance amplitude and duration and incorporates them within the framework of a level gradation system. This allows for comparison of measured results with regulatory limits, accounting for the degree of proximity to critical values, and forming a more accurate representation of EMC status throughout operational use.

The practical significance of the methodology lies in its ability to enhance the accuracy of analysis and the reliability of EMC diagnostics while remaining fully compatible with existing standards. The limiting values $I_{\lim}$ and $t_{\lim}$ are retained, while the introduced adjustable coefficients k_{I1}, k_{I2}, k_{T1}, k_{T2} allow the level boundaries to be adapted to real testing conditions, providing flexibility and scalability for different electric rolling stock systems and infrastructure.

Particularly important is the application of this method in operational monitoring. Data visualization in the form of level maps and zonal diagrams enables clear and timely representation of the EMC state.

This provides opportunities for:

– early detection of potential issues before parameters exceed threshold values,

– support for maintenance and preventive decision-making,

– integration into existing monitoring systems, where state levels can be updated automatically.

Thus, the methodology offers a scientifically grounded interpretation of test results and can be applied both in certification procedures and operational monitoring, providing an informative tool for assessing the EMC status of modern railway systems.

Conclusions

The developed methodology is aimed at improving the process of evaluating electromagnetic effects that arise during testing and certification of electric rolling stock. In modern power supply and control systems, even moderate electromagnetic disturbances can have a noticeable impact on the operation of electronic control units, safety systems, and diagnostic modules. This highlights the necessity of employing reliable and detailed analytical methods.

The proposed multi-level approach transcends the traditional dichotomous evaluation framework by introducing a graded classification system that accounts not only for the exceedance of regulatory limits but also for the degree of proximity of parameters to critical thresholds. This enables a more nuanced differentiation of the system's condition and allows for the identification of pre-failure or potentially adverse scenarios before actual malfunctions occur.

The introduction of a tiered classification provides additional opportunities for forecasting the development of electromagnetic processes, assessing high-risk zones, and correctly interpreting the cumulative effects of interference. The methodology can be integrated into modern automated systems for monitoring and data analysis, thereby enhancing the accuracy of control, the speed of diagnostics, and the overall operational reliability of equipment.

Thus, the proposed approach represents an effective and scientifically grounded tool that ensures a comprehensive assessment of electromagnetic compatibility and contributes to improving the safety, resilience, and functional reliability of electrical systems in electric rolling stock.

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LIST OF REFERENCE LINKS

1. Гаврилюк В. И., Щека В. И., Мелешко В. В. Испытания новых типов подвижного состава на электромагнитную совместимость с устройствами сигнализации и связи. *Наука та прогрес транспорту*. 2015. № 5(59). С. 7–15. DOI: https://doi.org/10.15802/stp2015/55352
2. Журавльов А. Ю., Саблін О. І., Щека В. І., Ящук К. І. Підвищення завадостійкості рейкових кіл в умовах впливу тягового струму. *Транспортні системи та технології перевезень*. 2024. № 27. С. 35–40. DOI: https://doi.org/10.15802/tstt2024/307339
3. Analysis of the basic parameters for maintaining the technical and operational compatibility of the 1520 mm and 1435 mm gauge rail systems at the border of the Commonwealth of Independent States (CIS) and European Union (EU). *Organisation for Cooperation between Railways (OSJD). European Union Agency for Railways (ERA) Contact Group*. Brussels, 2011.
4. Andreas A. *Digital Filters: Analysis, Design, and Signal Processing Applications.* Columbus : McGraw Hill, 2018. 976 p.
5. *CLC/TS 50238-2:2020. Railway applications. Compatibility between rolling stock and train detection systems. Part 2: Compatibility with track circuits*. [Effective from 2020-07-10]. Official edition, 2020. 43 p.
6. *EN 50728:2024. Railway applications. Rolling stock. Testing for electromagnetic compatibility with track circuits*. [Effective from 2024-12-13]. Official edition, 2024. 98 p.
7. Garczarek A., Stachowiak D. Measurements and Analysis of Electromagnetic Compatibility of Railway Rolling Stock with Train Detection Systems Using Track Circuits. *Energies*. 2025. Vol. 18. Iss. 11. P. 2705. DOI: https://doi.org/10.3390/en18112705
8. Havryliuk V. I. Modelling of the return traction current harmonics distribution in rails for AC electric railway system. *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*. (Amsterdam, 27–30 August 2018). Amsterdam, 2018. P. 251–254. DOI: https://doi.org/10.1109/EMCEurope.2018.8485160
9. Hu H., Liu Y., Li Y., He Z., Gao S., Zhu X., Tao H. Traction power systems for electrified railways: evolution, state of the art, and future trends. *Railway Engineering Science*. 2023. Vol. 32. Iss. 1. P. 1–19. DOI: https://doi.org/10.1007/s40534-023-00320-6
10. *IEC 62236-1:2018. Railway applications. Electromagnetic compatibility. Part 1: General.* [Effective from 2024-02-09]. Official Edition, 2018. 44 p.
11. *IEC 62236-2:2018. Railway applications. Electromagnetic compatibility. Part 2: Emission of the whole railway system to the outside world*. [Effective from 2018-02-09]. Official Edition, 2018. 86 p.
12. IEC 62236-3-1:2018. *Railway applications. Electromagnetic compatibility. Part 3-1: Rolling stock. Train and complete vehicle*. [Effective from 2018-02-15]. Official Edition, 2018. 63 p.
13. IEC 62236-3-2:2018. *Railway applications. Electromagnetic compatibility. Part 3-2: Rolling stock. Apparatus*. [Effective from 2018-02-15]. Official Edition, 2018. 69 p.
14. Pous M., Azpurua A. M., Oliva J., Aragon M., Gonzalez I., Silva F. Full Time Domain EMI Measurement System Applied to Railway Emissions According to IEC 62236-3-1/EN 50121-3-1 Standards. *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*. (Amsterdam, 27–30 August 2018). Amsterdam, 2018. P. 260–266. DOI: https://doi.org/10.1109/EMCEurope.2018.8485173
15. Salles R., Asplund R., Ronnberg S. Mapping and assessment of harmonic voltage levels for railway traction supply stations in Sweden. *Electric Power Systems Research*. 2025. Vol. 239. 111195. DOI: https://doi.org/10.1016/j.epsr.2024.111195
16. Zubko A. V., Shcheka V. I. Consideration of the Upper Error Bound of Measurement Complex in the Analysis of Digitized Signals. *Science and Transport Progress*. 2025. No. (2(110). P. 5–12. DOI: https://doi.org/10.15802/stp2025/331095

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Рівнева класифікація електромагнітного впливу у сертифікаційних випробуваннях електрорухомого складу

Мета. Розробка концептуальної основи для інтерпретації результатів сертифікаційних випробувань електромагнітної сумісності (ЕМС) електрорухомого складу із застосуванням багаторівневої системи класифікації. Розробка структурованого методу розрізнення різних станів електромагнітного впливу на основі виміряних параметрів амплітуди та тривалості. Покращення представлення та розуміння даних випробувань у рамках існуючих сертифікаційних процедур. **Методика.** Проаналізовано існуючі підходи до випробувань електромагнітної сумісності та інтерпретації даних у залізничних застосуваннях для виявлення обмежень у диференціації рівнів електромагнітного впливу. Структурований метод точної класифікації на основі нормалізованого порівняння характеристик перешкод. Визначення перехідних зони між безпечними та потенційно критичними режимами роботи, можливість гнучкої адаптації порогових параметри залежно від умов випробувань. Забезпечення відповідності сертифікаційним вимогам та підвищення діагностичної інформативності результатів. **Результати.** Розроблено багаторівневу систему класифікації електромагнітних перешкод, що забезпечує повне представлення результатів випробувань ЕМС. Ідентифікація перехідних станів та тенденції до критичних режимів, які не виявляються при використанні дихотомічної оцінки. Підвищення точності інтерпретації результатів випробувань, підтримка ранньої діагностики нестабільності та основа для кількісної оцінки експлуатаційної стійкості залізничних систем. **Наукова новизна.** Розроблено систематизовану багаторівневу методику інтерпретації результатів випробувань ЕМС електрорухомого складу. На відміну від традиційних методів, обмежених перевіркою порогових значень, запропонований підхід враховує динаміку змін параметрів та їх взаємозалежності, що дозволяє здійснювати прогнозний аналіз та отримувати більшого уявлення про електромагнітну поведінку в різних умовах експлуатації. **Практична значимість.** Розроблена методика підвищує точність, прозорість та надійність сертифікаційних випробувань електровозів, електропоїздів та іншого електричного рухомого складу. Сприяє більш безпечній та ефективнішій експлуатації залізниць, надаючи інженерам та сертифікаційним органам повну аналітичну основу для оцінки електромагнітної сумісності. Застосовування для оптимізації проєктних рішень, удосконалення сертифікаційних критеріїв та підтримки модернізації залізничної інфраструктури.

Ключові слова: електромагнітна сумісність; багаторівнева класифікація; сертифікаційні випробування; рухомий склад; аналіз перешкод; тяговий струм; прогнозна діагностика; моніторинг; експлуатаційна безпека; оцінка ризиків

REFERENCE

1. Havryliuk, V. I., Shcheka, V. I., & Meleshko, V. V. (2015). Testing new types of rolling stock for electromagnetic compatibility with signaling and communication devices. *Science and Transport Progress, 5*(59), 7-15. DOI: https://doi.org/10.15802/stp2015/55352 (in Russian)
2. Zhuravlov, A. Yu., Sablin, O. I., Shcheka, V. I., & Yashchuk, K. I. (2024). Track circuits interference resistance increase underthe traction current influence. *Transport Systems and Transportation Technologies, 27*, 35-40. DOI: https://doi.org/10.15802/tstt2024/307339 (in Ukrainian)
3. Analysis of the basic parameters for maintaining the technical and operational compatibility of the 1520 mm and 1435 mm gauge rail systems at the border of the Commonwealth of Independent States (CIS) and European Union (EU). (2011). *Organisation for Cooperation between Railways (OSJD). European Union Agency for Railways (ERA) Contact Group*. Brussels. (in English)
4. Andreas A. (2018). *Digital Filters: Analysis, Design, and Signal Processing Applications.* Columbus : McGraw Hill. (in English)
5. *Railway applications. Compatibility between rolling stock and train detection systems. Part 2: Compatibility with track circuits, 43 CLC/TS 50238-2:2020*. (2020). (in English)
6. *Railway applications. Rolling stock. Testing for electromagnetic compatibility with track circuits, 98 EN 50728:2024.* (2024). (in English)

doi: https://doi.org/10.15802/stp2025/344430

7. Garczarek, A., & Stachowiak, D. (2025). Measurements and Analysis of Electromagnetic Compatibility of Railway Rolling Stock with Train Detection Systems Using Track Circuits. *Energies*, *18*(11), 2705 DOI: https://doi.org/10.3390/en18112705 (in English)
8. Havryliuk, V. I. (27-30 August, 2018). Modelling of the return traction current harmonics distribution in rails for AC electric railway system. *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE).* (pp. 251-254). Amsterdam. DOI: https://doi.org/10.1109/EMCEurope.2018.8485160 (in English)
9. Hu, H., Liu, Y., Li, Y., He, Z., Gao, S., Zhu, X., & Tao, H (2023). Traction power systems for electrified railways: evolution, state of the art, and future trends. *Railway Engineering Science*, *32*(I). 1-19. DOI: https://doi.org/10.1007/s40534-023-00320-6 (in English)
10. *Railway applications. Electromagnetic compatibility. Part 1: General, 44 IEC 62236-1:2018*. (2018). (in English)
11. *Railway applications. Electromagnetic compatibility. Part 2: Emission of the whole railway system to the outside world, 86 IEC 62236-2:2018.* (2018). (in English)
12. *Railway applications. Electromagnetic compatibility. Part 3-1: Rolling stock. Train and complete vehicle, 63 IEC 62236-3-1:2018.* (2018). (in English)
13. *Railway applications. Electromagnetic compatibility. Part 3-2: Rolling stock. Apparatus, 69 IEC 62236-3-2:2018.* (2018). (in English)
14. Pous, M., Azpurua, A. M., Oliva, J., Aragon, M., Gonzalez, I., & Silva, F. (27-30 August, 2018). Full Time Domain EMI Measurement System Applied to Railway Emissions According to IEC 62236-3-1/EN 50121-3-1 Standards. *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*. (pp. 260-266). Amsterdam. DOI: https://doi.org/10.1109/EMCEurope.2018.8485173 (in English)
15. Salles, R., Asplund, R., & Ronnberg, S. (2025). Mapping and assessment of harmonic voltage levels for railway traction supply stations in Sweden. *Electric Power Systems Research*, *239*. 111195. DOI: https://doi.org/10.1016/j.epsr.2024.111195 (in English)
16. Zubko, A. V., & Shcheka, V. I. (2025). Consideration of the Upper Error Bound of Measurement Complex in the Analysis of Digitized Signals. *Science and Transport Progress*, *2*(110), 5-12. DOI: https://doi.org/10.15802/stp2025/331095 (in English)

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