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Influence of Commutational Interferences on the Analysis of Harmonics in the Traction Current

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Summary

Commutation phenomena related to the processes of changing the amount of power taken or returned by a vehicle affect the frequency spectrum contained within the traction current. The paper presents the influence of selected physical phenomena on the parameters taken for FFT analysis utilized for assessment of the disturbances generated into the traction network. The paper also describes the stands used for measuring disturbances generated into the traction network. The results of the measurements and calculations of the frequency response of simulated signals are presented, as well as signals measured in real conditions during traction vehicle tests, which are useful for assessing the influence of commutational interferences on the analysis of harmonics in the traction current.

Keywords: interferences, EMC, traction, interoperability

1. Introduction

The issues of electromagnetic disturbances introduced by railway power electronic devices are the subject of numerous national and international publications. The scope of issues in this area is extensive due to the variety of physical phenomena that should be taken into account when creating technical solutions (resonance phenomena, disturbances caused by non-linear characteristics of utilized components, propagation of disturbances within the power supply network treated as a long line, etc.), [6, 15], due to the diversity of solutions of the traction power supply systems used in the fixed infrastructure and due to the diversity of power control systems in traction vehicles [12, 14].

The majority of national studies and publications refer to the same issues as global publications, but, for obvious reasons, the issues concerning the 3 kV DC traction, which is utilized in Poland, are most often addressed. Due to the relatively low permissible limits of disturbances for railway signalling equipment in Poland [2], frequent subjects of the publications are: analyses and studies concerning harmonic content in the traction current [6, 7]; the issue of disturbance reduction with passive filters [16, 17] and active filters [17]; analyses and studies concerning the structure of the power supply system and power control methods utilized in traction vehicles [12, 13]; as well as analyses and tests of the magnitude of magnetic fields generated by the vehicles in terms of their influence on the track occupancy checking devices using wheel sensors [1, 2].

Current and voltage harmonics which are present in the overhead contact line have a direct effect on railway infrastructure equipment, in particular on signalling equipment. Higher harmonics in the traction current negatively affect the components of traction substations and, through traction transformers, the components of the public power grid, causing degradation of their parameters [5, 7]. Moreover, they may introduce disturbances to the devices connected to public grid and railway power networks.

The railway legal framework aimed at implementing the interoperability of the rail system in Europe requires the confirmation of compatibility between the rolling stock that is put in service and the trackside infrastructure equipment. The diversity of existing technical solutions and diversification of the railway provisions in individual European countries makes it impossible to define uniform requirements in certain areas. The solution in this respect is to introduce technical aspects in the form of "open points" which, in

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accordance with Article 5(6) of Directive 2008/57/EC, are subject to national rules in force in each Member State. The studies carried out by the Railway Research Institute on the level of disturbances generated by traction units onto the overhead contact line have provided wide-ranging knowledge in interpreting the impact of certain operational events on the recorded electromagnetic disturbance levels.

One of the important aspects is the commutation phenomena related to the processes of changing the amount of power taken or returned by the vehicle. In the context of the method of assessment of interference generated onto the overhead contact line disturbances using FFT analysis, this paper presents the influence of commutational disturbances on the results of this analysis.

2. Legal basis for testing electrical interference in Poland

2.1. European Union legislation

Legal regulations for railways result from the Treaty establishing the European Union. The aim of these regulations is to enable the inhabitants of the European Union, business entities and local governments to fully participate in the benefits resulting from the establishment of an area without internal borders, by improving the interconnections and interoperability of national railway networks as well as access to them. As far as trans-European networks are concerned, Article 155 of the Treaty provides that the Community:

- shall establish a series of guidelines covering the objectives, priorities and broad lines of measures envisaged in the sphere of trans-European networks; these guidelines shall identify projects of common interest,
- shall implement any measures that may prove necessary to ensure the interoperability of the networks, in particular in the field of technical standardisation.

The guidelines are implemented by the European Parliament. At the same time, guidelines and projects of common interest which relate to the territory of a Member State require the agreement of that State.

Directive 2008/57/EC on the interoperability of the rail system within the Community introduces the Technical Specifications for Interoperability dedicated to the different railway subsystems.

The implementation of directives within the EU territory is dealt with by the European Commission which, through regulations and decisions, implements the Technical Specifications for Interoperability – the TSIs, the development of which is entrusted to the European Railway Agency ERA. The TSIs implement technical standardisation and enable the interoperability of the rail system in Europe to be achieved.

In accordance with Article 17(2) of Directive 2008/57/EC, verification of the interoperability, in accordance with the essential requirements, for a structural subsystem constituting the rail system shall be carried out by reference to TSIs. National rules setting out the conditions to be complied with for the verification of the interoperability, as well as the assessment and verification procedures necessary for the application of these national rules, shall be communicated to the other Member States and to the European Commission.

2.2. National legislation

The national railway legislation in Poland results from the following legal regulations:

- Railway Transport Act dated 28 March 2003 (as amended) [18];
- Infrastructure and Development Minister Regulation 720 of 13 May 2014 on the approval for putting in service of certain types of structures, equipment and railway vehicles [11];
- The List of the President of the Office of Rail Transport of relevant national technical specifications and standardisation documents, the application of which enables the essential requirements for the interoperability of the rail system, dated 19 January 2017, to be met [8].

Railway Transport Act [18] implements the directives of the European Communities. This act obliges the minister in charge of transport to issue a regulation concerning the development of a list of appropriate national technical specifications and standardisation documents, the application of which enables the fulfilment of essential requirements for the interoperability of the rail system.

The Minister in charge of transport, in Regulation 720 [11] on the approval for putting in service of certain types of structures, equipment and railway vehicles, has specified the scope of technical tests necessary to issue authorisation for putting type into service and to declare compliance with type in paragraph § 14.1. concerning the scope of technical tests for all types of railway vehicles, within which in sub-point 8 the regulation directly indicates the necessity to carry out a test of a railway vehicle regarding emitted electrical, electromagnetic and radio-electrical interferences.

The open points regarding national verification in Poland are included in the List of the President of the

Office of Rail Transport (UTK). In the scope of national EMC requirements, the open points are, among others, the issues of vehicle cooperation with signalling systems utilized in Poland, especially in terms of functions dedicated to train detection based on track circuits.

2.3. Obligatory technical specifications regarding testing the compatibility of vehicles with track occupancy checking systems

The List of the UTK President [8] contains national requirements, technical specifications and standardisation documents, the fulfilment of which enables the fulfilment of essential requirements for the interoperability of the rail system.

Regarding issues related to testing and evaluation of the electromagnetic interference generated by the vehicle onto the overhead contact line and compatibility with train detection systems by means of track circuits, the UTK President's list [8] recommends the application of the specifications:

- from PN-EN 50238:2003: "Railway applications – Compatibility between rolling stock and train detection systems" [9];
- from CLC/TS 50238-2:2015: "Railway applications – Compatibility between rolling stock and train detection systems. Part 2: Compatibility with track circuits" [4];
- and PN-EN 50617-1: "Railway applications – Technical parameters of train detection systems for the interoperability of the Trans-European railway system, Part 1: track circuits" [10]. Specific national parametric requirements in this range are included in Annex S-02 to the List of the UTK President [8] in the form of permissible interference parameters for signalling equipment.

The EN 50238:2003 specification [9] covers all adequate essential requirements set out in Annex III of Directive 2008/57/EC. Demonstration of compliance with this standard provides one of the possible means to confirm compliance with the essential requirements of that Directive. Such demonstration of conformity also requires application of the other requirements and other EC directives.

2.4. Permissible interference parameters for signalling equipment

Annex S-02 to the List of the UTK President [8] contains requirements concerning permissible values of currents or permissible interference voltages in the range of operating frequencies of the occupancy checking track circuits utilized in Poland, presented in the form of tables and diagrams. Requirements regarding permissible currents apply for classic track circuits (50 Hz), SOT-type jointless track circuits and EOC type train pass-by sensors. Requirements regarding permissible voltages apply for EON-3 electronic superimposed track circuits and EON-6 train pass-by sensors.

Requirements for permissible values regarding interference currents and voltages from locomotives and electric multiple units as well as from static hauled stock converters [2] have been created for the operating frequency ranges of the track circuits and EOC sensors, taking into account the assumed number and structure of railway vehicles, which in the case of Poland may affect the value of the interference current as well as the geometric way of summing up the interferences. The requirements included in the List of the UTK President concern interferences with a duration longer than 200 ms.

3. Testing interferences generated onto the overhead contact line – methodology

Testing interferences generated onto the overhead contact line by traction vehicle for speeds up to 160 km/h is carried out at the Żmigród Test Track, in accordance with a special test procedure and the recommendations included in the PN-EN 50238 standard [9], CLC/TS 50238-2 technical specification [4], PN-EN 50617-1 standard [10] and Annex S-02 to the UTK President's list [8].

The 3 kV DC 12-pulse traction substation on the test ground has two rectifier units. It is equipped with a smoothing filters system whose task is to suppress the basic harmonics of the traction current. The tests take into account different configurations of the traction substation power supply and different vehicle operating conditions: standstill and running, normal state without simulated malfunctions, simulated malfunctions, start-up, recuperative braking, and running at different speeds. The tests are conducted on the basis of an adopted schedule. An example of a schedule for a traction vehicle equipped with 6 traction engines with a maximum speed of 120 km/h is shown in Table 1.

Depending on the needs, measurements can be carried out on a mobile stand on the traction vehicle, on a stationary stand on the return-current conductor to the traction substation or in the traction substation or at several locations at once. Examples of test stands for measuring harmonics in traction current are shown in Figure 1.

Table 1

Schedule for testing the interference generated by he traction unit

Traction vehicle in normal operation					
State of the vehicle/ substation	starting up to V_{MAX}	V_{const} = 40 km/h	V_{const} = 80 km/h	V_{const} = 120 km/h	regenerative braking
Filters off	+	+	+	+	+
Filters on	+	+	+	+	+
switching off traction engines (simulating malfunctioning) starting up of the traction vehicle					
State of the vehicle/ substation	1 engine on	2 engines on	3 engines on	4 engines on	5 engines on
Filters off	+	+	+	+	+
Filters on	+	+	+	+	+
at standstill					
State of the vehicle/ substation	all on-board equipment switched on (full load)	on-board equipment off; minimum load			background
Filters off	+	+			+
Filters on	+	+			+

[Own elaboration].

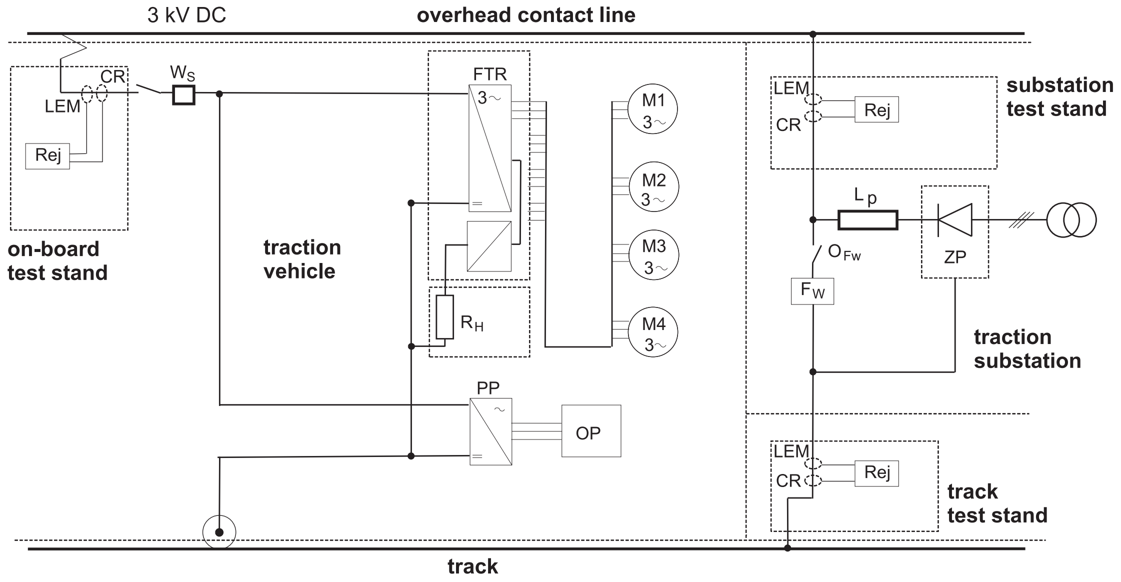

Fig. 1. Examples of measuring stands for measuring harmonics in traction current [authors' own work]

Symbols:

Traction vehicle

W_S – high-speed circuit-breaker
Odb – current collector
FTR – traction inverter
R_H – set of braking resistors
M1, …, M4 – traction engines
PP – auxiliary circuit converter
OP – auxiliary circuits

Traction substation

ZP – rectifier unit
L_p – inductor
O_{Fw} – smoothing filter disconnector
F_W – smoothing filter
TR – power grid transformer

Test stands

LEM – transducer for measuring the direct component of the traction current
CR – transducer for measuring the alternating component of the traction current
Rej – recorder

The choice of the location for measuring the interference current at a mobile site depends on the type of rolling stock:

1. In the case of electric locomotives and electric multiple units, measurements are made as close to the current collector as possible. Exceptionally, measurements may be taken elsewhere on the main cable, provided that it can be shown, theoretically or practically, that there will be no significant difference in the results.
2. In the case of diesel locomotives, the measurements shall be made on an auxiliary high voltage cable.
3. In the case of hauled stock equipment (e.g. static converter or battery charger), measurements are also made on the auxiliary high voltage cable in the case of different components connected in parallel, or on the cable supplying the device if a single component is involved.

The transducers for current measurement are the LEM transducer for the measurement of the direct component and the Rogowski coil for the measurement of the variable component in the frequency range of track circuits utilized in Poland. The LEM transducer measures signals in the band from 0 Hz to 10 kHz, while the Rogowski coil measures signals in the band from 25 Hz to 1 MHz.

On the basis of the recorded measurements, the harmonics of the signal generated onto the overhead contact line by the traction unit are analysed for four frequency ranges: 0 - 1 kHz, 1–3 kHz, 3–20 kHz and 20–40 kHz, with filters on and off in the traction substation. Permissible values of interference are included in Annex S-02 of the UTK President's list. Harmonic analysis is performed with a time window of 200 ms. The overlapping of adjacent samples subjected to harmonic analysis is 80%.

4. Influence of commutational disturbances on the results of harmonic analysis of the traction current

The traction energy is converted in the traction vehicle for traction and auxiliary purposes by means of traction converters and auxiliary converters. Modern traction vehicle designs are individual ones prepared by manufacturers. Therefore, a variety of technical solutions for traction engine control are encountered. The use of inductive elements or LC filters that slow down the rate of input current build-up is an important part of the system design at the vehicle's power input. Another common feature is the use of traction converters, whose task is to adjust the power taken or returned by the traction engines. The converters installed in traction vehicles, due to the non-linear nature of the circuits, cause distortions of the current in the overhead contact line.

The electric circuit of the direct current traction vehicle may be considered as a series-parallel one in which a power supply with a defined impedance is connected in series (traction substation or energy-regenerative traction vehicle) through the resistance and inductance of the power supply network, the resistance and input inductance of the vehicle and a set of parallel connected vehicle filter capacities to the load with variable impedance.

The engines of the traction vehicle in the generator mode during electromagnetic braking produce energy which is either received by other vehicles or is lost on its own resistors as heat. Fig. 2 shows a simplified diagram of a vehicle's traction power supply circuit for vehicles equipped with an LC input filter, in which a commutational disturbance can be generated.

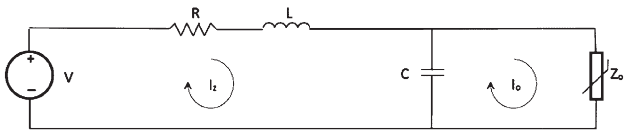

Fig. 2. Simplified diagram of an electrical circuit in which a commutational disturbance is generated [authors' own work]

where:

R, L, C – vehicle filter parameters,

V – the voltage of the overhead contact line (traction substation voltage or the voltage between the current collector and the wheels of a vehicle being in energy-regenerative mode – with a specific impedance of its own, connected in series with the resistance and inductance of the power supply network),

Z_o – receiver impedance,

I_o – receiver current,

I_z – power supply current.

The voltage equation in an electrical circuit, the diagram of which is shown in Fig. 2, can be described by a system of two differential equations:

$$L\frac{dI_z}{dt}RI_z+\frac{1}{C}\int_0^t\left(I_z-I_0\right)\mathrm{d}t=V \tag{1}$$

$$\frac{1}{C}\int_0^t\left(I_z-I_0\right)\mathrm{d}t=Z_0I_0 \tag{2}$$

From the system of equations (1) and (2) it follows that a change of load current I_o forces a change of voltage on the vehicle filter capacitor and thus a change of current value in the vehicle supply circuit. The vehicle filter elements *L* and *C*, together with the serially connected inductance of the power supply circuit, determine the frequency of oscillation of the filter response to the commutational disturbances. Their role is also to limit the intensity of current and voltage variations in electrical circuits and to reduce the harmonics generated in the traction current, and indirectly contribute to reducing interference and failure of vehicle components and trackside infrastructure.

The commutational disturbance has the character of a unit stroke, which in signal theory is described by fading oscillations. As a result of a jump change in the load current value in the vehicle power supply system, a wide signal spectrum with decreasing harmonics above the resonance frequency of the vehicle filter should be expected [3].

Under laboratory conditions, in the measuring system for recording interferences, four electrical waveforms of a simulated unit stroke with an amplitude of 1 A were recorded. One with a very short rise time of 9 ns (Fig. 3a) and three with an extension to, respectively, 48 ms (Fig. 3b), 140 ms (Fig. 3c), and 200 ms (Fig. 3d). The corresponding harmonic analysis is shown in Fig. 4. The rise time is defined as the time that elapses between the change of signal value from 0.1 to 0.9 of the maximum value.

In order to assess changes in the harmonic content depending on the length of the rise time, the analysis was performed in a time window increased to 800 ms. The results of the analyses are shown in Fig. 4.

In a unit stroke current, the harmonic values decrease as the signal build-up time increases. At the same time, the distribution of the frequencies contained in the signal changes in a manner correlated with the signal rise time.

5. Influence of commutational events on the results of the analysis of harmonics contained in the traction current based on the example of conducted tests

The problem of the influence of commutational events on the results of the analysis of harmonics contained in the traction current is described below on the basis of the example test recorded during tests of one of the traction vehicles.

Fig. 5a shows the course of the direct current component and Fig. 5b of the variable current component registered at the test site during the recuperative braking tests associated with power input to the vehicle's traction engines (positive current values in Fig. 5a) and the power absorbed by another traction vehicle from the traction engines (negative current values in Fig. 5a). In the recorded signals at the moment of the end of recuperative current generation by the traction vehicle to the overhead contact line (approx. 42.5 sec. in Fig. 5a), a short increase in the level of the variable component was identified (Fig. 5b).

Commutational disturbance, for which the electrical waveforms of the direct and current components are shown in Fig. 6, is short-lived (the time from 0.1 to 0.9 of the signal change value is about 47 ms and the total duration of the transient state is about 75 ms) and has dynamics reaching about 7.5 kA/s.

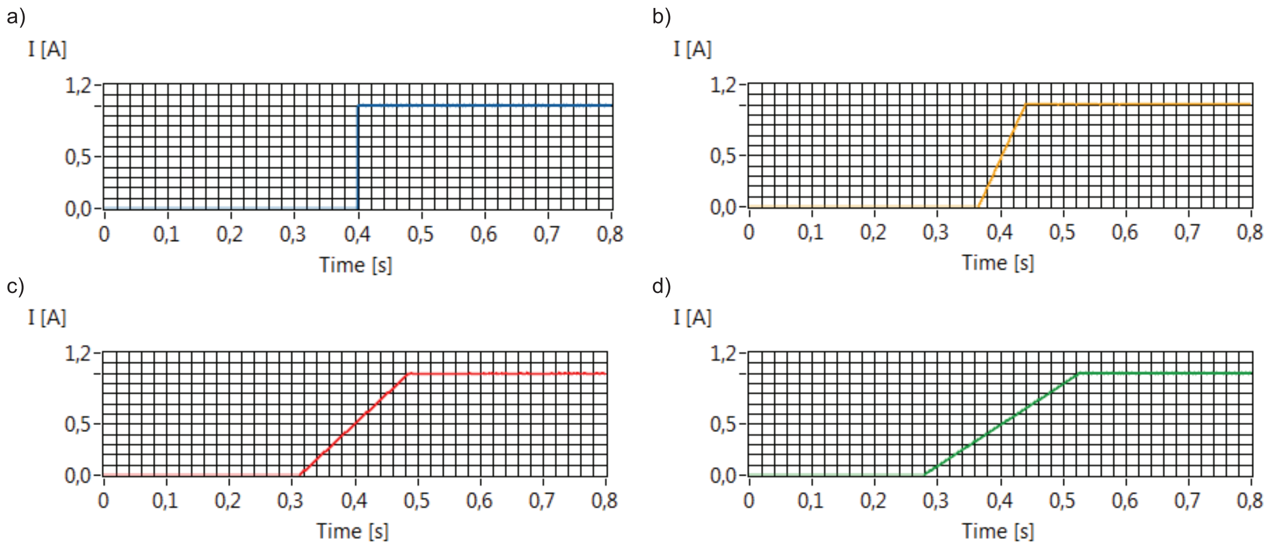

Fig. 3. Time courses of the unit stroke signal with the rise times of 9 ns (a), 48 ms (b), 140 ms (c), 200 ms (d) [authors' own work]

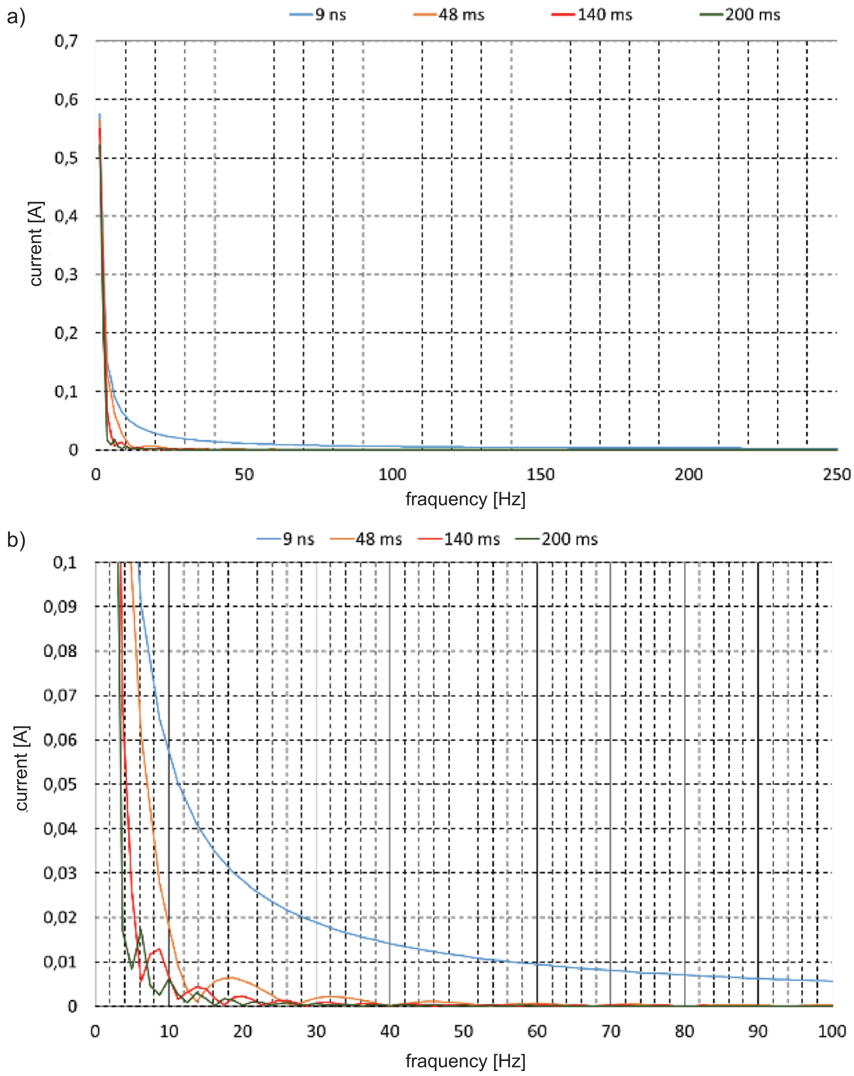

Fig. 4. Harmonics included in the unit stroke of current of amplitude 1 A with the rise times of 9 ns, 48 ms, 140 ms, and 200 ms: a) full range of current values, b) range of current limited to 0.1 A – time window of 800 ms [authors' own work]

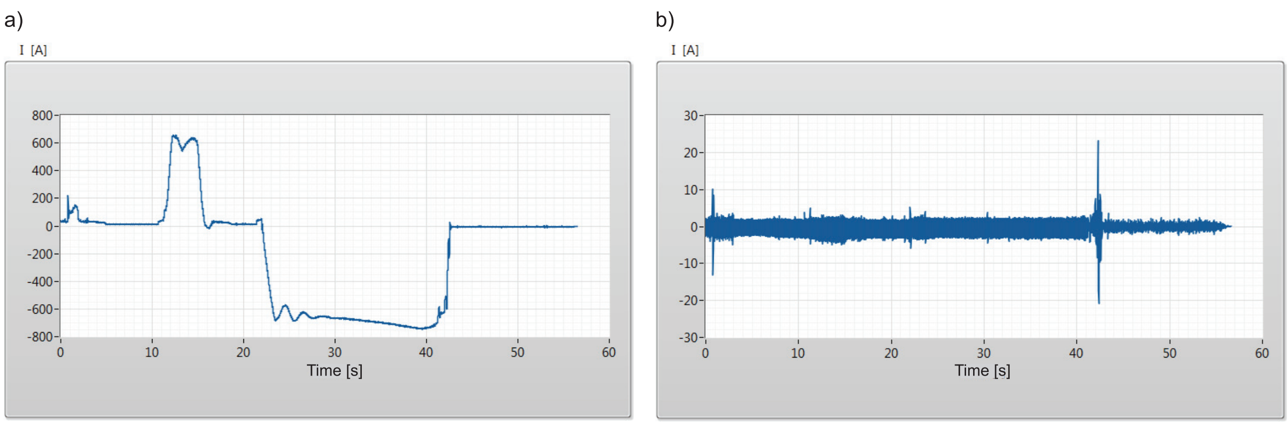

Fig. 5. Course of the direct current component a) and variable current component b) in the test in which the phenomenon of commutational interference was identified [authors' own work]

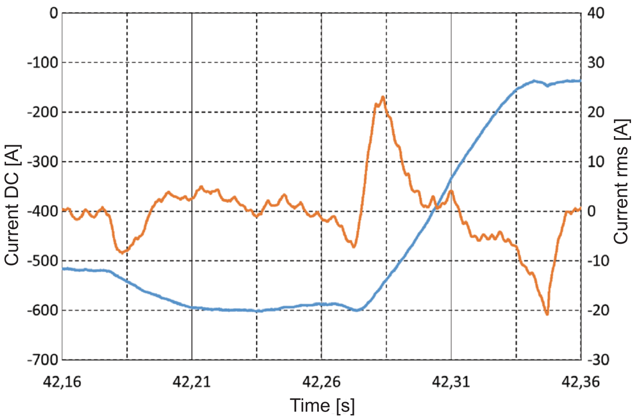

Fig. 6. Dynamics of change of the direct (blue curve) and variable component (orange curve) at the time of the commutational disturbance – sample length 200 ms [authors' own work]

Figure 7 shows the results of the harmonic analysis of the direct and variable traction current components recorded on the vehicle in the frequency band from 0 to 1 kHz. The analysis was carried out separately for the time segments from the beginning of the test to the moment of the commutational event (Fig. 7a), for the commutational event (Fig. 7b), and from the commutational event to the end of the test (Fig. 7c). The analysis was performed in the 200 ms time window. The results of the analysis confirmed that the limit value of 1.2 A for the frequency of 50 Hz was exceeded in the part of the sample with the commutational event. The calculated actual values were about 1.36 A for the variable component of current signal (RMS) and 1.33 A for the direct component of current signal (DC). In other parts of the test, the recorded levels of interference in the frequency band from 0 to 1 kHz were lower than the permissible limits.

The calculated higher frequency harmonics are shown in Fig. 8.

Exceedances in the 1 kHz – 3 kHz band are the effect of the 12-pulse rectifier unit of the traction substation powering the test track on the test ground and are not taken into account in the assessment of the level of interference generated by the traction vehicle. The commutational interference has not caused a noticeable increase in the level of interference in the frequency band above 1 kHz.

Thanks to the short-term nature of the disturbance, which is shorter than the 50 Hz track circuits response time of 200 ms, and taking into account the slight exceeding of the 1.2 A limit value, this part of the signal can be excluded from the harmonic analysis.

6. Conclusions

The analysis of theoretical issues and the results of measurements measured under simulated and real conditions allow the following conclusions to be drawn:

- short-term commutational phenomena increase harmonic levels in the traction current,
- power control algorithms for traction transformers shall eliminate the effects of short-term commutational phenomena in order to limit 50 Hz harmonic and sub-harmonic generation,
- in cases of incidental and short term (< 200 ms) exceeding of the limit values, it is possible to exclude fragments of the recording of a commutational event from the recording of FFT analysis on the basis of the analysis of the direct current component of the traction current in the time domain,
- in cases of doubt, detailed tests shall be carried out regarding the effect of interference generated by a vehicle on the signalling equipment in the operating band of the circuits for which such an exceedance has been identified.

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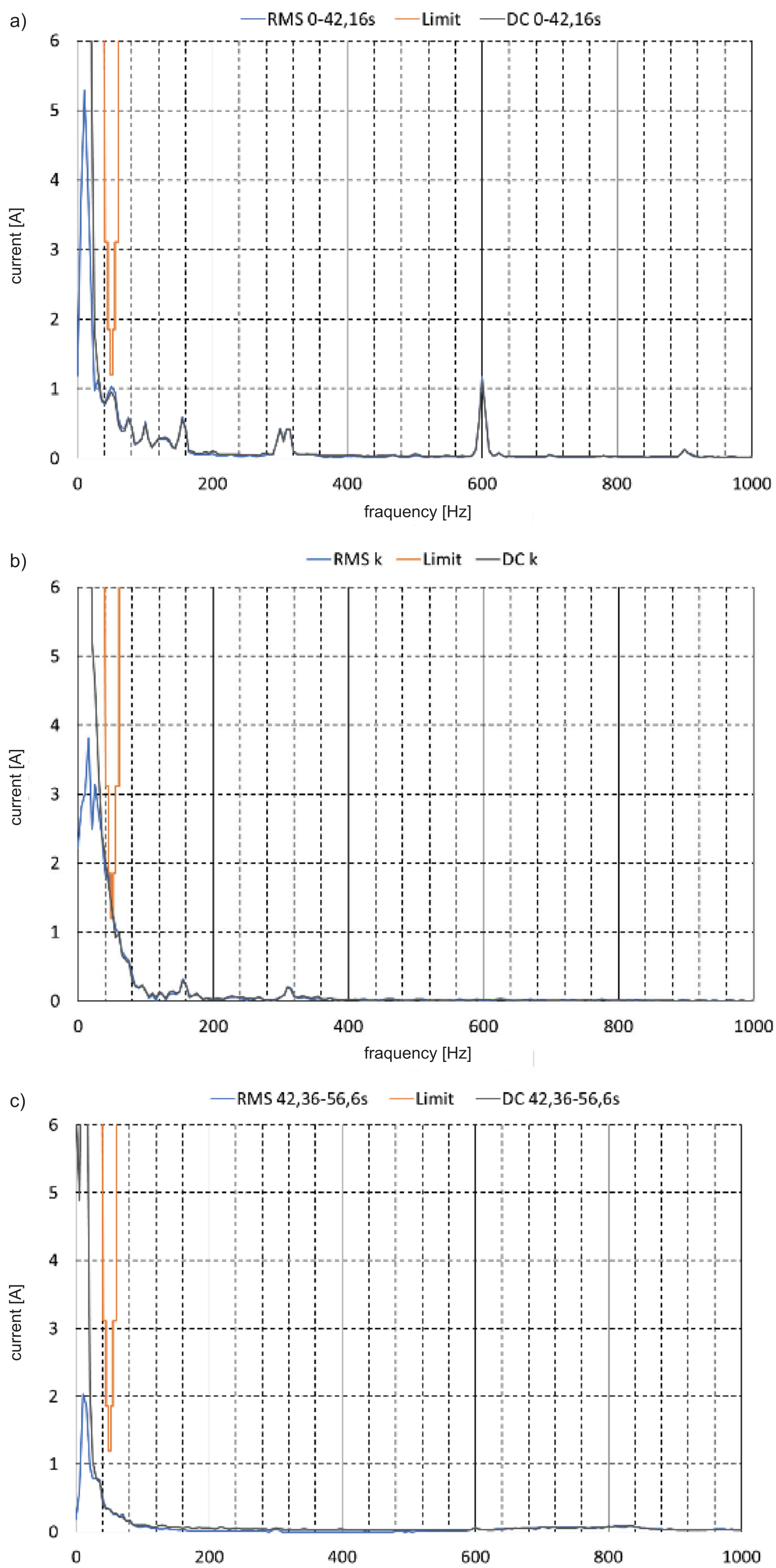

Fig. 7. Harmonics in the band from 0 to 1 kHz – time window of 200 ms: a) before commutational event, b) commutational event, c) after commutational event [authors' own work]

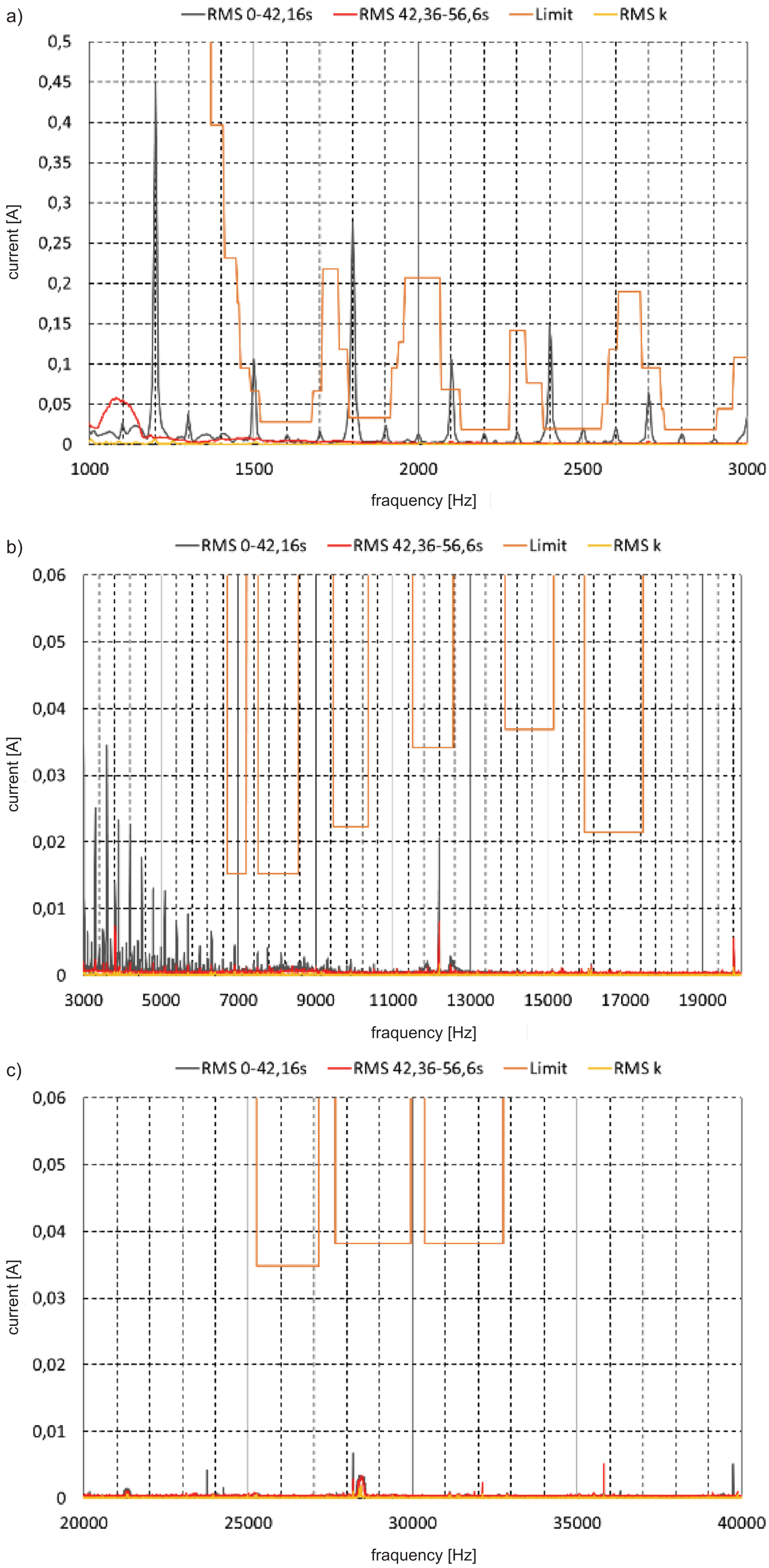

Fig. 8. Harmonics in bands: a) 1 kHz to 3 kHz, b) from 3 kHz to 20 kHz, c) from 20 kHz to 40 kHz – time window of 200 ms [authors' own work]

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