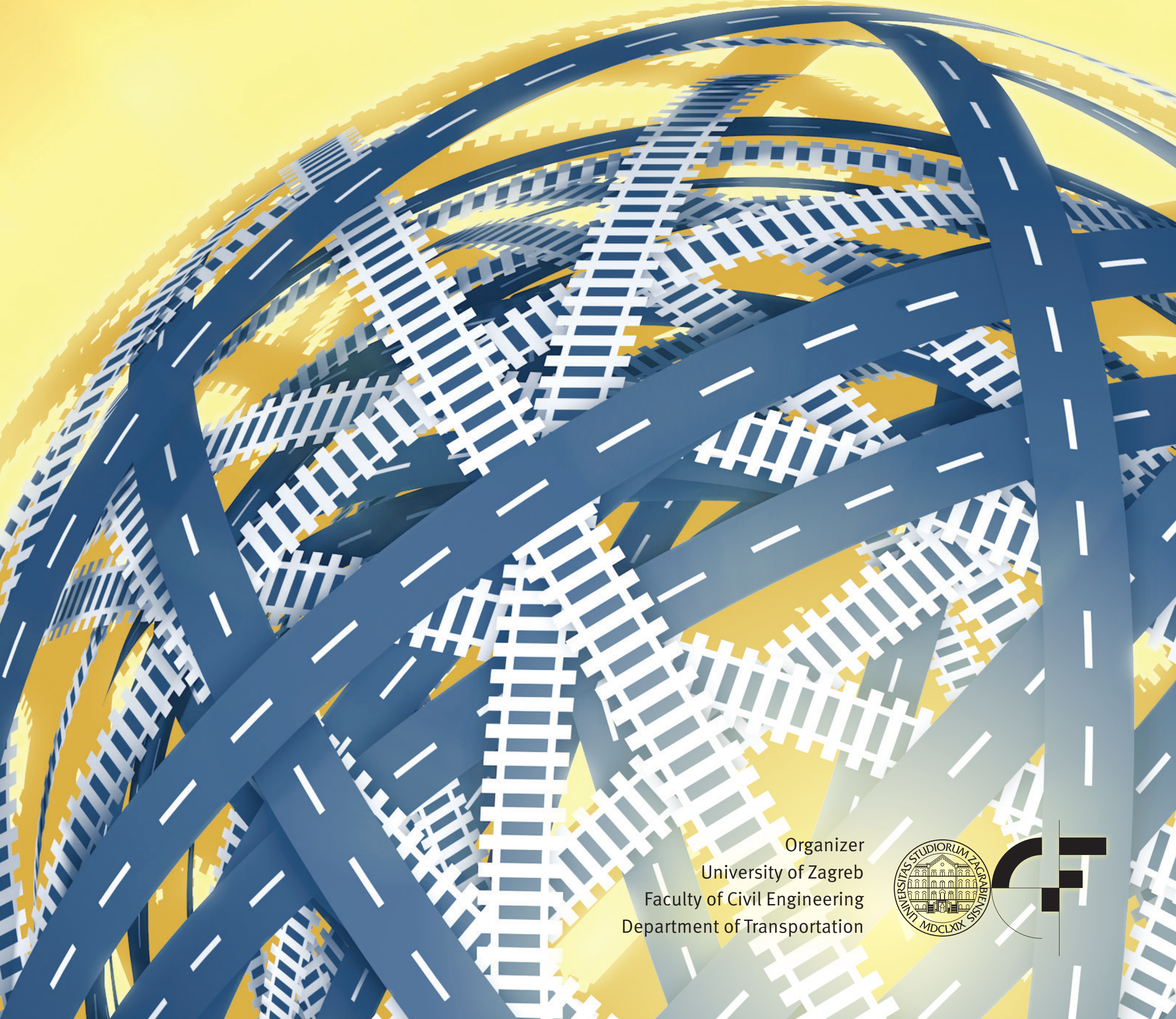
CETRA 2016

4^{th} International Conference on Road and Rail Infrastructure

23–25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



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Road and Rail Infrastructure IV

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PROBLEMS OF IDENTIFYING CONDUCTED DISTURBANCES IN A CURRENT DRAWN FROM A 3 kV DC CATENARY BY VEHICLES EQUIPPED WITH POWER CONVERTERS

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Abstract

Prediction, identification and elimination of conducted disturbances in DC supplied traction systems still remain a vital and urgent issue. Modern electric vehicles equipped with power electronic converters are the most important source of conducted disturbances due to generation of high order current harmonics, which can cause malfunction of signalling, command and control infrastructure of a railway line. Although the problem is well reported in the literature and experienced by the manufacturers of new rolling stock which are to be put in service, previously unforeseen disturbances may appear in some cases. The authors present an idea of elimination of that kind of disturbances by applying a monitor of disturbances combined with a control system of power electronic converters of a drive system. Such a solution reduces the level of disturbances and enables the vehicle to maintain the required power and traction force.

Keywords: electric traction, harmonics, EMC, vehicles, converters, signalling, command and control

1 Introduction

In order to ensure compatible operation of rolling stock and signalling and control systems [1, 2], railway operators apply protective measures – technical and functional solutions to reduce probability of disturbances. Typically, the methods can be divided into three categories, according to the place of application:

- reduction of the level of disturbances at their source (a supply system [3, 4] or rolling stock [5, 6, 7]);
- reduction of transmission disturbances from a source to an object;
- immunization of an object.

The above could be applied at a different stage of the life cycle of the railway system infrastructure and rolling stock (design stage, construction, exploitation), which influences effectiveness and costs of the possible solution. Examples may include:

- reduction of harmonics in a DC voltage supplying catenary (increasing number of pulses of rectifiers, application of DC side filters [3, 4]);
- imposing limits of specific harmonics in current taken by rolling stock [2, 5, 6, 7] by applying bulky on-board input filters, or by using special algorithms to control traction drives [8-16];
- application of installations immune to disturbances present in railway systems [1, 2].

2 Description of a problem

Typically, AC low frequency track circuits (50 or 60 Hz) or similar ones, in the range of 1.5÷3 kHz or higher are used in a DC traction system. The possibility of higher harmonics currents causing malfunction of a track circuit in a range close to the operating frequency of a track circuit is a perfect example of the imminent danger from higher harmonics, which are present in return traction currents flowing in the tracks [5]. Disturbances in track circuits derive from various sources; apart from a dominant one – electric traction, these include: train heating equipment, power lines and other electrical equipment.This is the reason why so many railway management boards have introduced limits for harmonics components with defined frequency of a vehicle's current. Observance of the limits shall eliminate danger of disturbances in the track circuits. Limits for rolling stock that have been stated by Centrum Naukowo-Techniczne Kolejnictwa (Instytut Kolejnictwa-Railway Institute) in paper [7] are applicable to PKP lines. Analysis of compliance with the above-stated requirements by means of appropriate methods should be performed as early as at a design stage. Commissioning and acceptance tests of the rolling stock, which are to be performed before the rolling stock is placed into service, should confirm compliance of the above-mentioned criteria.
In case railway lines electrified in different systems – DC and AC with 50 Hz frequency are adjacent to each other, the AC system may cause significant disturbances in operation of network frequency circuits. Such phenomena have been observed in several countries, in which the lines electrified in a DC voltage system (1.5/3 kV) and 25 kV 50 Hz system [2] run in parallel.
The amount of harmonics in a traction current increases with the increase of a traction substation load, as besides characteristic traction substation voltage harmonics, other harmonics caused by asymmetry of substation devices are observed. Upon introducing vehicle's converters, new harmonics appear in traction current, and their frequency results from operation of power electronic devices [3].
The paper focuses, in particular, on the issues of disturbances from traction currents and proposes to apply active on-line methods for monitoring and control of the level of disturbances generated by a vehicle, while providing traction force necessary to maintain required traction and operating parameters (acceleration, speed).

3 Requirements and criteria

In DC electric traction systems the most common solutions include the passive systems eliminating harmonics of current and voltage supplying a traction vehicle [2, 3]. It means that in most cases active monitoring of disturbances generated both by substations and traction vehicles is not applied. The methods used to eliminate conducted disturbances are based on passive filters selected to fit characteristics of the devices in such a manner that compatibility requirements defined by appropriate standards and guidelines [6, 7] are fulfilled at a test stage. In order to reduce possible dangers and ensure proper operation of track circuits, one normally uses a method of decreasing disturbances at their source:

- in a traction substation (psophometric voltage limits on a DC side of a substation (on Polish railway lines: 0.5%, that is 16.5 V)) by use of multi-pulse rectifiers and a higher harmonics filter [3];
- in vehicles equipped with power electronic converters, in order to decrease disturbances one introduces the limits for: conducted emission – vehicle's current harmonics [4, 7] and radiated emission [1, 2]. It is recommended to apply solutions for reducing emission from energy converters: multi-level inverters, internal filters, appropriate structure of devices [2, 11], and assuring a high level of a vehicle's input impedance, which requires installation of large input filters [6, 9, 10, 12, 13, 14, 15, 16].

Furthermore, one aims at decreasing the sensibility of receivers to disturbances by: separating operating frequency of low-current devices (signalling, command and control) from frequency of disturbances generated by traction devices [2, 5], shielding and earthing, changing operating principles and modes of the receivers [17], and eliminating the conditions for disturbances transmission [2] by: separating high-current circuits (traction) from low-power ones – signalling and control circuits (other transmission paths of various signals, appropriate distances or shielding of common areas).

4 Methods for identifying and eliminating possible dangers

4.1 Traction substation equipment

For many years now, on Polish railway lines, in 3 kV DC traction substations, which are fed with medium voltage (15, 20 or 30 kV), one has been using resonant filters (contours: for 300, 600,900 and 1200 Hz harmonics with an additional capacitor 50 μF) and a choke of 4 mH in substations with 6-pulse rectifiers and contours for 600 and 1200 Hz harmonics with an additional capacitor of 100 μF and a 1.8 mH choke (in substations with 12-pulse units). LC type filters (gamma type filter– with capacitance up to 0.8 mF and inductance 4-6 mH) are used in new or modernised traction substations, especially in those supplied with 110 kV voltage. These filters are more efficient than the resonant filters [3, 4] applied so far.

4.2 Traction substation equipment

Modern traction vehicles that are quipped with converter drive systems constitute a significant source of current harmonics that interfere with traction return current flowing in rails to a traction substation. The most common solutions for the main circuits of modern traction vehicles supplied from a 3 kV DC system include choppers supplying DC motors and voltage source inverters feeding asynchronous motors.
Vehicles equipped with choppers are usually the sources of current harmonics with constant frequency, which equals the converter operation frequency. In turn, the traction voltage source inverters operate with fluent frequency change, which causes them to generate a harmonics spectrum in an extremely wide frequency range, which, on the other hand, makes this type of a vehicle the one posing biggest threat to proper operation of a rail traffic management system [2, 6, 9, 16]. When applying a voltage source inverter with sine PWM modulation, voltage harmonics with the following frequencies appear in a motor's phase voltage:

$$f_{h1} = i \cdot f_{tr} \pm j \cdot f_{sin} \quad \text{for } i = \text{odd};\ j = \text{even}; \tag{1}$$

$$f_{h2} = i \cdot f_{tr} \pm j \cdot f_{sin} \quad \text{for } i = \text{even};\ j = \text{odd}; \tag{2}$$

where:
f_{tr} – carrier wave frequency;
f_{sin} – basic voltage component frequency.

Thus, what appear in a DC link current are two groups of harmonics. The first one includes the so-called changeable harmonics that depend on the basic frequency f_{sin}, and their most significant frequencies may be defined by a formula:

$$f_{DC1} = i \cdot f_{tr} \pm 3 \cdot f_{sin} \quad \text{for } i = \text{odd}; \tag{3}$$

Frequency of the so-called stationary harmonics depend only on even multiplicity of frequency – carrier wave f_{tr}, which can be described by the formula:

$$f_{DC2} = i \cdot f_{tr} \quad \text{for } i = \text{even}; \tag{4}$$

Example of the harmonics spectrum of traction current generated by a traction vehicle without the method of harmonics elimination with sine-triangle PWM (f_{sin}= 0-60 Hz, f_{tr} = 500 Hz) is shown in Fig. 1 (results of computer simulation). One can observe several instances of limit overrun [7] (red solid – limits), especially in a frequency range of 1500-1800 Hz. Therefore, it is necessary to use the methods for spectrum shaping. Methods for reducing current harmonics generated by a traction vehicle drive system can be divided by an operation mode and off-line and on-line methods. Due to the highest operating reliability, the off-line methods can be widely used on-board the traction vehicles. These methods include application of passive low-pass filters of gamma type and tuning a traction converter to the limits applicable on the routes, in which a given vehicle is to be operated. The main advantage of the solutions used within the off-line method is their reliability.
Failure of an input filter usually results in cut of power supply to a drive system, and automatic change in drive inverter modulation is not possible. The disadvantage of these types of systems is that there is a lack of possibility to adapt to the conditions that have not be foreseen by a designer at the test stage.

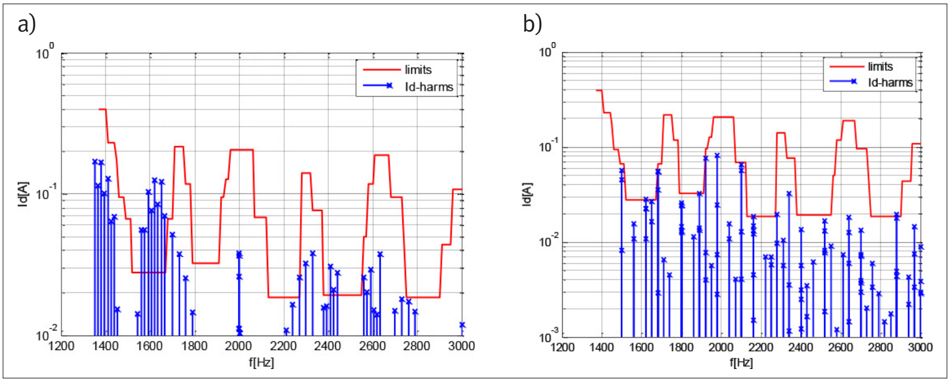

Figure 1 Traction current harmonics spectrum of a) 2 MW vehicle with a sine-triangle PWM, without harmonics elimination, b) 0.5 MW drive system with application of SHE and SHR methods.

Operating conditions of a traction drive system are perceived as extremely difficult ones due to a large number of variables: change of voltage, load and a drive operating point. The large number of variables that are random in their nature, makes it difficult to adjust passive methods, which would fulfil their role under all conditions. Therefore, it is reasonable to design and develop methods based on an on-line operating principle. Such systems must rely on devices that monitor the condition of a drive system with a view to generated disturbances. When a measuring system detects that the set limits have been exceeded, it shall act so as to stop a disturbing influence of a drive system. For this type of a system to be developed, it is essential to solve two basic technical issues. At the stage of an on-line system design, one should develop a method for effective and fast detection of traction current harmonics. Fig. 2 shows selected elements of an exemplary system designed for measurement and acquisition of traction current waveforms [17]. Use of a LEM converter ensures the appropriate level of separation from a vehicle's main circuit, but at the same time it requires an output signal to be conditioned (integrating circuit). Further signal processing has been performed using application developed in a LABVIEW environment, and it allows taking into account measuring system frequency characteristics, and comparing the harmonics spectrum with the applicable limits. In real systems, the examined current waveforms very often present features characteristic for high-frequency distorted waveforms. In addition, there is a problem of signals variable frequency (start-up and braking) when the speed of a vehicle changes. All these factors can cause the methods based on the Fourier's analysis to be ineffective [18]. Another issue consists in developing a system's response to detected disturbances. The simplest solution is to disconnect (power reduction) a drive system from a power supply system. However, this solution may pose several problems related to traffic disruptions. Such an option solves the problem of disturbance generation, but it causes a new one, namely, a traction vehicle that is on the route, but is not supplied from any source. Another solution consists in using systems generating a signal having frequency and value the same as the interfering signal, but an opposite phase, in order to enable signal compensation.

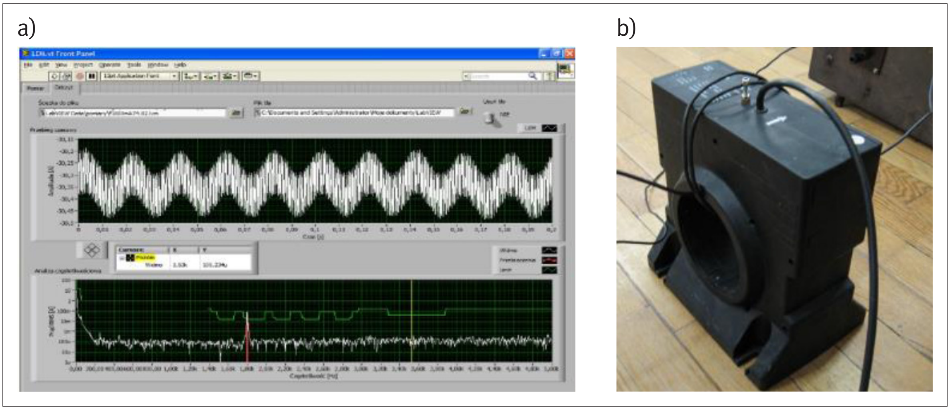

Figure 2 The elements of a laboratory model of the system used for on-line monitoring of the harmonics in current consumed by a converter from a DC network: a) a screenshot of an application developed in the LABVIEW environment; b) LEM RA 2000-S/SP1 converter.

It seems reasonable to actively and directly influence the control strategy that is implemented by a drive voltage source inverter. One possibility is to reduce power of a drive system. Figures 3 a and b show influence of the decreased power of a vehicle on DC-link current harmonics for a selected operating point of an inverter drive system (results of computer simulation). This method allows both for reducing harmonics and maintaining supply of a drive system; however it also forces to reduce a torque, which with higher loads may influence vehicle's movement, especially dynamics at higher speeds. Its disadvantage lies in lack of control over values of particular harmonics, due to the fact that power decrease does not equally influence all current harmonics (Fig. 3).

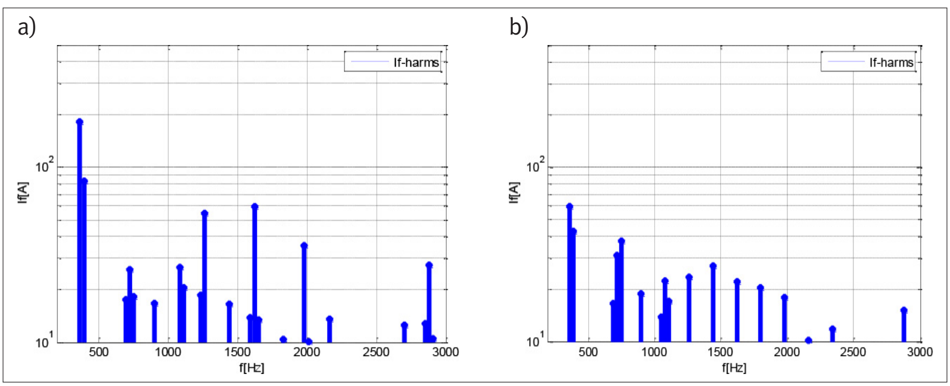

Figure 3 Results of simulation calculations of DC-link current harmonics generated by a 0.5 MW drive system: a) full power; b) reduced power

In this case a more favourable solution is to tune a drive system in such a manner to maintain the set torque T of traction motors for the desired speed ω. For this purpose, the authors propose to use a SHE method (selective harmonic elimination) and its modification – SHR (selective harmonic reduction) [16] . The method allows for maintaining the value and frequency of a basic component of inverter's output voltage at a set level in conjunction with a simultaneous regulation of voltage harmonics, and hence shaping the harmonics spectrum of traction current. Fig. 1b shows a harmonics spectrum that has been determined based on a computer simulation of a 0.5 MW traction drive system using a combination of the SHE and SHR methods.

5 Conclusion

Application of the described methods for traction current spectrum shaping enables reaching a set speed, and thus a driving torque of vehicle's traction motors, while reducing amplitudes of DC catenary current harmonics generated by the electric traction vehicle. Such solution enables maintaining required traction parameters – tractive force developed on the wheels provide appropriate movement dynamics and the compatibility requirements are fulfilled within the set limits.

Taking into account efficiency of modern measuring signals processing systems and effectiveness (confirmed during laboratory tests and simulation) of the methods for inverter control that have been proposed by the authors to eliminate current harmonics, it seems promising to apply the described concept of a system for on-line mode operation. Operating principle of this type of a system should be based on monitoring of current consumed by a vehicle. In case one detects overrun, the system implements a control strategy that allows reducing amplitudes in a range in which the overrun was discovered. Depending on the assumption, a new control strategy may be determined in real time or loaded from the previously prepared 'map' of controllers (lookup table).

The primary advantage of this type of a system is the on-line monitoring of emission of conducted disturbances generated by a traction vehicle during operation. It significantly increases the security level on a railway line by eliminating the possibility that vehicles disturb the operation of the rail traffic management systems. However, it is required to autotest the on-board system on an ongoing basis, so to ensure reliability and its proper operation performance, and to prevent disturbances of vehicle's operation – as a result of incorrect indications and the malfunction of the system.

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