

Considerations on measurement of low frequency emissions generated by traction vehicles

Marek Patoka¹, Adam Szela¹, Tadeusz Maciołek¹

¹ *Warsaw University of Technology, Pl. Politechniki 1, 00-661 Warsaw – Poland,
marek.patoka@ee.pw.edu.pl; adam.szela@ee.pw.edu.pl; tadeusz.maciolek@ee.pw.edu.pl*

Abstract - The article presents the analysis of resolution bandwidth changes while registering a magnetic component of low frequency electromagnetic disturbances emitted by the electric traction vehicles equipped with power electronic drive systems. The analysis was undertaken for comparison between laboratory tests and those implemented in real conditions. Conclusions are presented regarding the validity of the correction coefficients use for the disturbances results measured with other than the recommended resolution bandwidth.

I. INTRODUCTION

State-of-the-art traction vehicles with electric drives are equipped with power electronics control systems with electric motors. Power electronics systems, used in the main circuits of vehicles, enable smooth formation of traction characteristics depending on the set motion cycle. Structures of today's converter systems include semi-conducting elements, such as: IGBT transistors or GTO thyristors. Systems of this type, apart from many advantages, also have a number of side effects - they are sources of radiated [1, 2, 3, 4, 5] and conducted electromagnetic disturbances [4, 5, 6, 7, 8]. It is thus necessary to ensure vehicle operation by verifying such emissions against limits suitable for railway traction applications. It is governed by the relevant standards, which define the emission limits for electric traction vehicles [9, 10].

II. ASPECTS OF EMC MEASUREMENT IN ELECTRIC TRACTION

Due to the nature of electrified railway operation the EMC - compliance tests of traction vehicles cover "slow moving and stationary tests" [9, 10]. While running at low speed, an urban vehicle should ride with speed of 15-25 km/h, while a long-distance vehicle with speed of 40-60 km/h. In front of the measurement position,

a vehicle should speed up or slow down using 1/3 of its maximum tractive effort in the given range of speed [9]. The speed cannot be too high, so as to enable the correct pantograph-catenary cooperation (it concerns to network vehicles), or too low, in order to enable electric braking. Distance between a measuring antenna and a vehicle under test (DUT) should be 10 m. During the measurement of magnetic component of electromagnetic field (CISPR A, B, 9 kHz - 30 MHz) the loop antenna should be placed at a height above the rail level in the range of 1 - 2 m.

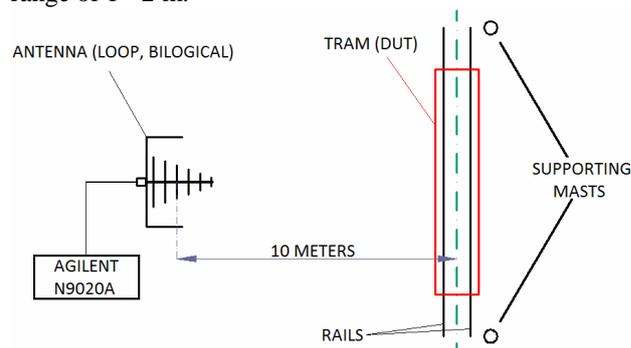


Fig. 1. Measurement stand during EMC research.

While running, the applied power electronics systems (DC/DC converters and inverters) shape the output voltage (or current - in current inverters). The principle of operation of both AC and DC drive systems involves fast switching of semiconductors, which entails generation of disturbances. Fast-changing waveforms of current and voltage in impulse systems are the sources of disturbances generated by traction vehicles. Thus, it is recommended [9] to conduct a study of prototype traction vehicles, stating the limits and requirements for the measurement in the frequency ranges of 9 kHz – 1 GHz [9, 10]. Study of electromagnetic disturbances emission should be based on the CISPR recommendations - standard [11]. **Due to the character of the measurement (examination of a moving source of noise emission - a vehicle in motion), requirements imposed by standard**

[9] differ from the parameters defined by standards [10, 11]. In standard [9], measurement bands are divided into sub-ranges, defining also the set-up of a spectrum analyser or EMI receiver [12].

III. PROBLEMS OF RESOLUTION BANDWIDTH RECALCULATION

Resolution bandwidth of the receiver (BW) used in the measurements in the frequency range 9 – 150 kHz, according to standards [10, 11] should be 200 Hz, while according to standard [9] - 1 kHz. **This divergence derives from measurement conditions: the vehicle is moving and a measurement at 200 Hz bandwidth would not be sufficiently fast, and would also be time-consuming.** Standard [9] recommends splitting CISPR A [11] frequency range into two sub-ranges: 9 - 59 kHz and 59-150 kHz (BW 1000 Hz, sweeping time 300 ms for each sub-range - this would be sufficient for the moving sources). If a BW, different than recommended by standard [11], is used during measurements, the results should be properly corrected. Whilst BW recalculation, according to standard [10], correction should be carried out *on the basis that the noise is impulsive in nature* (Annex B, B.5), while according to standard [9] - on the basis *that the noise is a broad band white noise* (Annex B, B.2). Lack of straight clarification regarding the character of a waveform to be assumed while recalculating the measured values and lack of possibility of measuring the signal in time domain poses a problem. If the signal is narrowband, its magnitude will not practically depend on the BW selection, when a signal is broadband, depending on the character of a signal, the peak values depend on the BW (the so-called coherence). With two extreme cases the broadband signal may be coherent (fundamental frequency plus harmonics) and incoherent (random frequency spectral components), an appropriate BW correction coefficient can be introduced [13]:

$$CF1 = 20 \log \frac{BW_{\text{ref}}}{BW_{\text{actual}}} \quad (1)$$

or

$$CF2 = 10 \log \frac{BW_{\text{ref}}}{BW_{\text{actual}}} \quad (2)$$

where: CF - correction factor for broadband signals (CF1 coherent, CF2 incoherent), BW_{ref} - reference BW approved for a specific frequency range [3], BW_{actual} - applied BW [13].

CF1 is applied for coherent signals including impulse signals from devices generating repetitive signals, generated by switchable chargers, commutators, ignition systems operating in steady states and fluorescent lamps

[13]. Whereas CF2 is used for incoherent signals generated by the power electronics systems in dynamic states (transient), e.g. gas lamps DC and corona discharge [13].

The measurement described in [2], confirms that both broadband and narrowband disturbances occur in the electric traction systems. During the compliance measurements, when a vehicle passes the antenna, the signals generated by vehicle's drive systems are of broadband character for each BW. It emerges from the fact that during a moving test, a vehicle accelerates or decelerates. Power electronic drive systems operate in a transient state. Their disturbances have continuous spectrum of frequency. Other power electronic systems, not related to the drive (e.g. converters for battery charging and supply of auxiliary devices), regardless of vehicle's motion dynamics are in the steady state of operation. The frequency spectrum of the disturbances is discrete, thus, depending on the BW, disturbances can be narrowband or broadband.

In the measurement described in [2] narrowband signals were recorded, *for sometime before and after the train passes the measurement point*, however the broadband were seen *only when the train was passing through the antenna position (chapter 4.3.2.1.4 General Comments 9 kHz to 150 kHz)*. During measurements of an electric vehicle both cases appear - the train has to accelerate to the required speed, before it reaches the antenna position. Specific approaches regarding rescaling of the results (with CF1, CF2 or no CF application), lead to further doubts. It is due to the fact that recalculation of the peak values registered at certain BW into values corresponding to another BW depends on the level of coherence of the measured signal. Additionally, it may occur that during the measurement with BW 1000 Hz, disturbances in specific frequency ranges would be seen as a narrowband and for the same ranges with BW 200 Hz - as a broadband.

Standard [9] allows conducting the equivalent "slow moving test", by measuring the emission at the "stationary test" in which the vehicle operates with a proper tractive effort but against mechanical brakes. Unfortunately not always this kind of operation can be applied [9] (i. e. if some additional electrical circuits operate during electrodynamic braking). If this test is possible there is no problem of a moving source of the noise and BW 1000 Hz does not have to be applied in CISPR A frequency range. In practice, the equivalent "slow moving tests" are not undertaken; therefore proper recalculations have to be applied. It means that appropriate correction of the measured noise values consists in deducting from the obtained noise components an appropriate value calculated using formulas (1, 2) i. e. for $BW_{\text{ref}} = 200$ Hz, $BW_{\text{actual}} = 1000$ Hz, $CF1 = -13.97$ dB, $CF2 = -6.98$ dB. The difference

between these values is around 7 dB, and is considerable enough to determine whether rolling stock fulfils limits [9]. Thus, it is important to be aware of the source of emission while the correction of BW has to be applied. It will allow for classification of the examined disturbance as completely or partially coherent or incoherent, since in real conditions the character of a source does not have to be unequivocal.

IV. LABORATORY RESEARCH

The measurements were implemented in laboratory conditions, where the sources of electromagnetic disturbances were the laboratory drive systems (dynamic states were included):

- series motor with a chopper,
- squirrel cage motor with a voltage source inverter.

A loop receiving antenna was placed in a 1 m distance from the EUT (equipment under test). This distance depended on:

- the room limitations, since the measurements took place in a closed laboratory, instead of the outdoor measurement site,
- considerably smaller power of laboratory systems in comparison to the real systems.

Agilent MXA N9020A spectrum analyser was used as a measurement receiver. The measurements were implemented by a peak detector (max hold) in the CISPR A frequency range. Sweeping time was set automatically by the analyser, so as at specific settings, i.a. BW and span, it was sufficient for registration of reliable values of disturbances. Number of performed measurement cycles at a set sweeping time was conditioned by the steady, unchangeable character of a waveform envelope obtainment. All the data were measured with the same conditions; therefore the applied method does not provide inaccuracy. The results of the registration are shown in fig. 2 ÷ 5. Different values of ambient noise while measuring a system with a chopper and an inverter are caused by a different place of measurements fig. 2, 3).

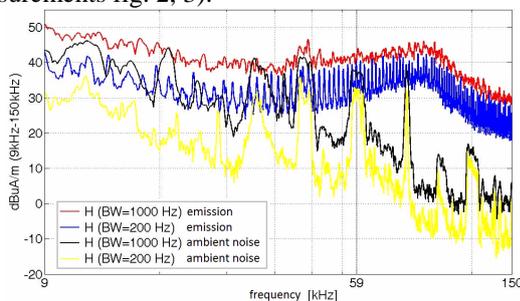


Fig. 2. Voltage source inverter - induction motor. CISPR A frequency range. Emission and ambient noise measured with different BWs (no correction factors applied).

Fig. 2, 4 show the specific ambient and drive noises measured with different BWs. The noise values for the frequency ranges, where the ambient is almost on the same level that the drive's noise, were excluded from the study. Fig. 3, 5 indicate that the usage of correction factors does not lead to the proper results. Due to the nature of a waveform which is not always broadband, application of correction coefficients is a very rough estimate. Therefore, one should introduce a correction factor of a value between -13.97 dB and -6.98 dB, which has to be added to the values measured with the 1000 Hz BW to obtain reference values measured with the 200 Hz BW.

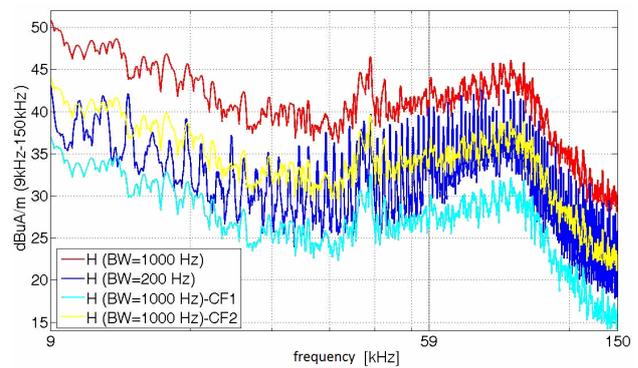


Fig. 3. Voltage source inverter - induction motor. CISPR A frequency range. Emission measured with different BWs with correction factors application (yellow - BW 1000 Hz with CF2 application, cyan - BW 1000 Hz with CF1 application).

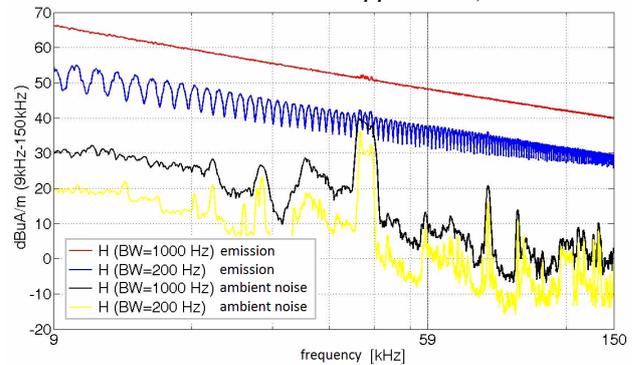


Fig. 4. Chopper - series DC motor. CISPR A frequency range. Emission and ambient noise measured with different BWs (no correction factors applied).

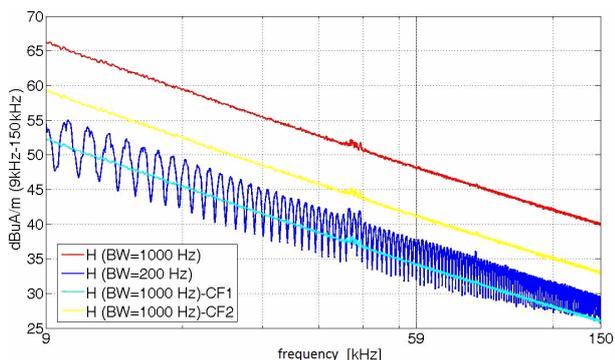


Fig. 5. Chopper - series DC motor. CISPR A frequency range. Emission measured with different BWs with correction factors application (yellow - BW 1000 Hz with CF2 application, cyan - BW 1000 Hz with CF1 application).

V. IN-SITU MEASUREMENTS

In order to compare laboratory measurements with real conditions, the measurement of two trams were conducted:

- tram equipped with 8 series DC motors of 41.5 kW supplied with an IGBT chopper ("chopper tram").
- tram equipped with 4 three phase squirrel cage motors of 104 kW supplied with an IGBT voltage source inverter ("inverter tram").

Two kinds of measurements in a CISPR A frequency range were done:

- two tram rides, according to standard [9] (9 - 59 kHz, 59 - 150 kHz, sweeping time 300 ms, BW 1000 Hz) + correction factors (CF1, CF2) application
- twelve tram rides - to be fast enough (for moving sources measurements) BW 200 Hz and sweeping time 300 ms were applied [9], the CISPR A sub range was divided into twelve sub ranges: 9 - 21 kHz, 21 - 33 kHz, 33 - 45 kHz, (...), 141 - 153 kHz. No correction factor is needed.

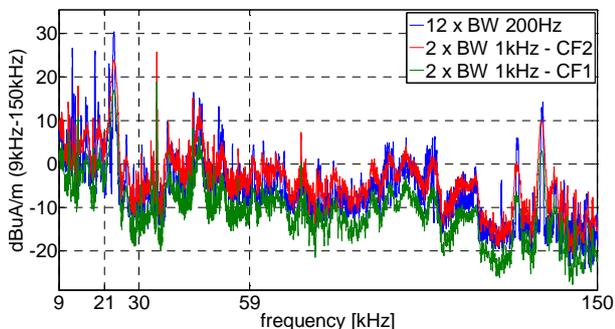


Fig. 6. Chopper tram. CISPR A frequency range. Ambient noise measured with 12 x BW 200Hz, 2 x BW 1000 Hz - CF2, 2 x BW 1000 Hz - CF1.

The described method is time consuming, but it leads to analyses of correction coefficient application validity during normative measurements [9]. Fig. 6 and 7 compare the values of an ambient noise and chopper tram's emissions registered with compliance to standard [9], using -6.98 dB correction factor and time consuming method sustaining BW 200 Hz. Fig. 8, 9 show the same case for inverter tram respectively.

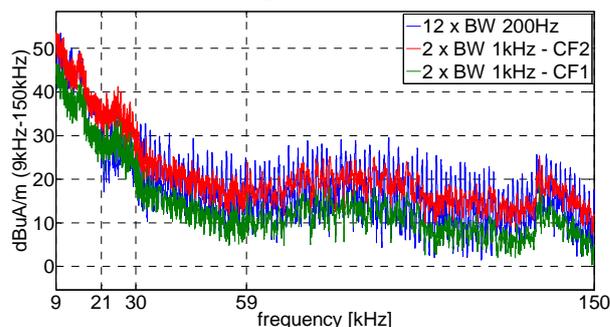


Fig. 7. Chopper tram. CISPR A frequency range. Emission measured with 12 x BW 200Hz, 2 x BW 1000 Hz - CF2, 2 x BW 1000 Hz - CF1.

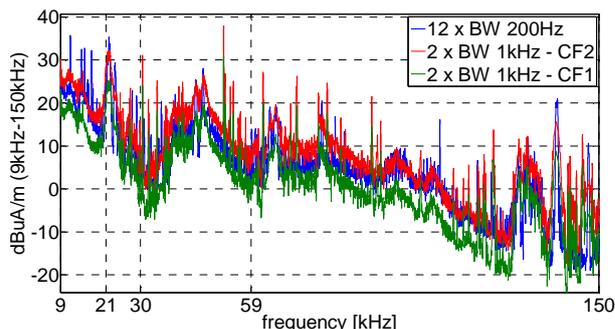


Fig. 8. Inverter tram. CISPR A frequency range. Ambient noise measured with 12 x BW 200Hz, 2 x BW 1000 Hz - CF2, 2 x BW 1000 Hz - CF1.

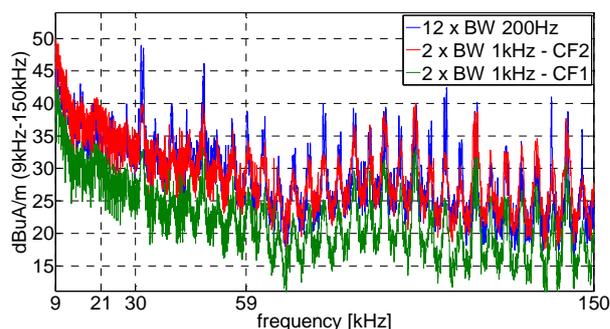


Fig. 9. Inverter tram. CISPR A frequency range. Emission measured with 12 x BW 200Hz, 2 x BW 1000 Hz - CF2, 2 x BW 1000 Hz - CF1.

Analysis of the results (fig. 6 - 9) shows disadvantages of the correction coefficients usage. The noises emitted by the trams supplied with different power electronics devices and having different motors are dissimilar.

Comparably to the laboratory research neither CF1 nor CF2 correction factor are thoroughly appropriate. After a short glance at fig. 7, 9 it seems that the application of CF2 is relevant only for an inverter tram. The further analysis exposes, that both correction factors are proper neither to the inverter nor chopper tram noises. If the chopper tram noise is considered, the application of CF2 is valid only for ranges between 9 - 21 kHz. In case of the 21 - 30 kHz interval, the best results are achieved by applying an approximate -12 dB correction. In other frequency ranges, almost no correction factor should be applied (about -1 dB, -2 dB). As far as the inverter tram is concerned, there are several frequencies in which rather narrowband emission appears and practically no corrections have to be applied. In both cases the application of CF1 (-13.97 dB) is definitely too extensive. The results of measurements conducted in conformity with recommendations of standard [9], which will undergo CF1 or CF2, will not be correct. Either the chopper or inverter tram noise is underestimated if CF1 or CF2 is used. In both cases a lower error is achieved, whether CF2 is used (so the signals are incoherent), but because of some narrowband noises presence, an exact calculation has to be forbidden. The examined vehicles might be wrongfully classified as fulfilling the criteria of the standard. It would be helpful if the standard clarifies the limits for BW 1000 Hz, without the necessity of recalculation of the measured values. It would be clear and unambiguous, and would not lead to any controversy, which can largely occur in EMC study anyway.

VI. CONCLUSIONS

Correcting the results obtained by the measurement by other, than the one recommended for a given frequency range, BW is not a trivial issue. Depending on the character of disturbances, one should apply the correction coefficient. Depending on the examined system, results of the measurements of electric vehicles in the CISPR A frequency range, conducted in conformity with recommendation of standard [9] should undergo further analysis. Application of simple calculations is neither unambiguous nor valid. The simplified method of CISPR A frequency range measurement is relatively faster, but the correction factor usage is practically almost impossible. The limit specified by standard [9] should be form differently - with no need of correction factor applications. To specify different limits for the CISPR A frequency range for the railway purposes, the further analysis of moving sources' electromagnetic phenomena is required.

VII. REFERENCES

- [1] Szeląg A., Patoka M. "Issues of low frequency electromagnetic disturbances measurements in traction vehicles equipped with power electronics drive systems". *Przełąd Elektrotechniczny* 9/2013.
- [2] Rowell A. J., Bozec D., Welsh D. W., "Improved methods of the measurement of radio frequency emissions from railway". www.york.emc.co.uk, 2004.
- [3] Szeląg A., Patoka M., „Pomiary i analiza przewodzonych i promieniowanych zaburzeń elektromagnetycznych w energoelektronicznych układach autonomicznych pojazdów trakcyjnych”. *Przełąd Telekomunikacyjny*, 11/2013.
- [4] Ogunsola A., Mariscotti A. "Electromagnetic Compatibility in Railways. Analysis and Management". Springer 2013.
- [5] Mariscotti A, Marrese A., Pasquino N. "Experimental investigation on radiated emissions generated by pantograph arcing and their effects on telecommunication bands". XX IMEKO World Congress Metrology for Green Growth. IX 2012, Busan, Republic of Korea.
- [6] Szeląg, A., Steczek M. "Analysis of input impedance frequency characteristic of electric vehicles with a.c. motors supplied by 3 kV DC system for reducing disturbances in signaling track circuits caused by the harmonics in the vehicle's current". *Przełąd Elektrotechniczny* 3a/ 2013.
- [7] Mariscotti A., Armanino G. "In-house test of low frequency conducted emissions of static converters for railway application". XVII IMEKO World Congress Metrology in the 3rd Millennium VI, 2003, Dubrovnik, Croatia
- [8] Zając W., Szeląg A. "Appraisal of electromagnetic compatibility of power electronic converters with traffic control system during design of the suburban railway". *Electromagnetic Compatibility Conference EMC' 94*, IX 1994 Rome.
- [9] EN 50121-3-1. *Electromagnetic Compatibility – Rolling Stock – Train and Complete Vehicle*
- [10] EN 50121-2. *Electromagnetic Compatibility – Part 2: Emission of the Whole Railway System to the Outside World*
- [11] EN 55016. *Specification for radio disturbance and immunity measuring apparatus and methods. Radio disturbance and immunity measuring apparatus.*
- [12] Svoboda M. "On site radiated emission tests of railway and automotive applications". 2013 International Symposium on Electromagnetic Compatibility (EMC Europe 2013), Brugge, Belgium, IX 2013
- [13] Bare D., Parker T. "Separate emissions by bandwidth". *Elliott Laboratories, Sunnyvale, CA – Tests & Measurements World*. 2/1/2002.