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Issues of low frequency electromagnetic disturbances measurements in traction vehicles equipped with power electronics drive systems

Streszczenie: *Przedstawiono analizę zmiany szerokości pasma pomiarowego przy rejestracji składowej magnetycznej zaburzeń elektromagnetycznych emitowanych w trakcji elektrycznej dla niskich częstotliwości. W artykule zawarto różne podejścia do zmiany szerokości pasma zalecanego przez normy, a analizy teoretyczne zostały porównane z pomiarami laboratoryjnymi. (**Zmiany szerokości pasma pomiarowego przy rejestracji składowej magnetycznej zaburzeń elektromagnetycznych emitowanych w trakcji elektrycznej dla niskich częstotliwości)***

Abstract*. The article consists of bandwidth changes analysis during measurements of a magnetic component of electromagnetic disturbances emitted in electric traction for low frequencies. Apart from different theoretical research, measurements under real conditions were also carried out and an accurate comparison was performed.*

Słowa kluczowe: trakcja elektryczna, kompatybilność elektromagnetyczna, emisja zaburzeń.
Keywords: electric traction, electromagnetic compatibility, electromagnetic disturbances.

Introduction

Modern traction vehicles with electric drives are equipped with power electronics control systems of electric drives. Applied in main circuits of vehicles, power electronics systems enable smooth determination of traction characteristics depending on a set duty-cycle of motion. Constructions of modern power electronics converters consist of semiconductors, such as transistors IGBT or GTO thyristors. Apart from many advantages, such devices have a range of drawbacks-there are sources of conducted electromagnetic disturbances [1,10] and radiated disturbances [2,4,6,8,9]. It causes the necessity of the assessment of vehicle's operation and its equipment in terms of provision of electromagnetic compatibility in the electric traction system. It is regulated by the appropriate standards, which state emission limits from the electric traction vehicles [2, 4].

Description of traction vehicles research

Traction rolling stock should be examined, in compliance with the standard [2]. Apart from a slow moving test, a stationary test has to be done as well. During a ride at low speed, an urban vehicle should move with speed between 15-25 km/h, while a main line vehicle with speed 40-60 km/h. Close to a position of a measurement, a vehicle should accelerate or decelerate using 1/3 of a maximum tractive force in a given speed range [2]. Speed cannot be too high so as to enable proper pantograph-network cooperation (it pertains to network vehicles), also not too low, so as to enable electric braking. Distance of a measurement antenna from a track axis should be 10 m, and the height above a rail head should be in the range of 1-2 m (for a loop antenna: band A, B (9 kHz-30 MHz)) [6].

Generation of disturbances

Due to the operation character of systems and means of the electrified transport, especially network transport (vehicles supplied from electric traction) it is recommended by standards to conduct studies, both when vehicles are in motion and while they are in a stop position. Used during a ride with energy collection, power electronics systems (DC converters and inverters) shape output voltage (or current-in the current inverters). Principle of operation of both AC and DC drive systems relies on fast switching devices, which involves generation of disturbances. Fast-variable current and voltage in the impulse systems (fig.1, 3) are the sources of disturbances generated by vehicles. Thus, it is advised [2] to perform a test of prototypes of traction vehicles, defining the limits and requirements in the range of frequency 9kHz - 1GHz. Measurements of emission of electromagnetic disturbances should be accomplished with accordance to the regulations CISPR-standard [3]. Due to the character of measurements (during motion) the requirements of [2] standard slightly diverse from the parameters stated by standards [3] [4]. In the standard [2] measurements bands are divided into sub-ranges, also strict settings of a spectrum analyser or emi receiver are established.

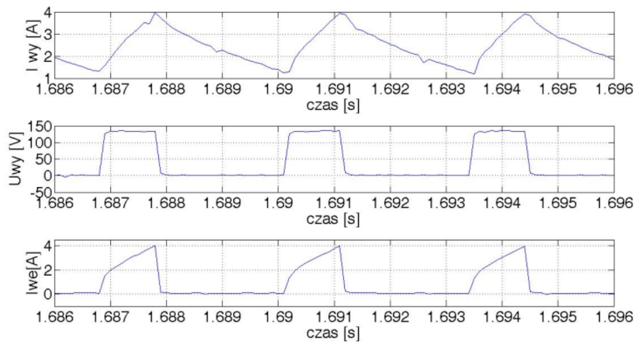

Fig.1 Exemplary curves registered in a drive system with a chopper (from the top: chopper output current-motor current, chopper output voltage- motor voltage; chopper input current).

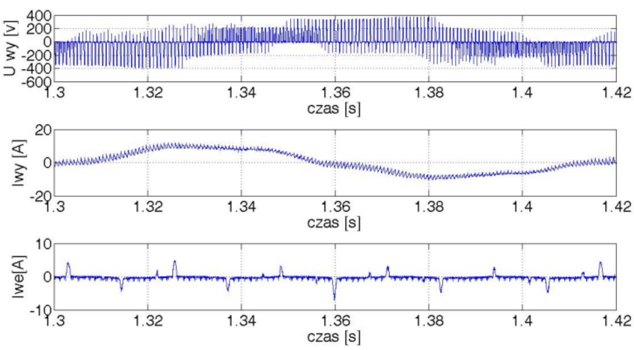

Fig.2 Exemplary curves registered in a drive system with an inverter and an asynchronous motor (from the top: output voltage (phase) of inverter-motor, output current (phase) of inverter-motor; input current (phase) of an inverter)

According to the standards [3,4], a bandwidth (BW) used in measurements in the range of frequencies 9 kHz –

150 kHz should reach the level of 200 Hz, while according to the standard [2] 1 kHz. If during tests BW, which is used differs from BW imposed by standard [3], then the results of measurements should be properly transformed. It is recommended by standard [4], in case of a transformation resulting from application of a BW other than the reference BW, assuming disturbances of narrowband character, while in standard [2] - broadband character of disturbances. Lack of clarification regarding the character of a run to be assumed while transforming the measured values and lack of possibility of measuring a signal in a time domain, cause a considerable problem. If a signal is narrowband, its frequency spectrum will not depend on the selection of a BW, when a signal is broadband, it depends on the signal character, the so called coherence, peak values depend on a bandwidth. In the two extreme cases, while the measured signal is broadband coherent or incoherent, the appropriate correction factor from the following may be introduced:

$$CF1 = 20\log\frac{\mathrm{BW}_{6\mathrm{ref}}}{\mathrm{BW}_{\mathrm{actual}}} \tag{1}$$

or

$$CF2 = 10\log\frac{\mathrm{BW}_{6\mathrm{ref}}}{\mathrm{BW}_{\mathrm{actual}}} \tag{2}$$

where: CF-correction factor, BW_{6ref} -bandwidth approved for the specific measurement band [3], BW_{actual} - the applied bandwidth [5].

It was shown in the measurements described in [9], that both narrowband and broadband character occur in the systems of electric traction disturbances. At the measurements of compliance with the standards, when a vehicle passes an antenna, signals generated by vehicle's drive systems are of broadband character for each $BW_{actual.}$ It results from the fact that during this time a vehicle accelerates or decelerates. Power electronics drive systems operate in a transient state. Their disturbances have a continuous frequency spectrum. Other power electronics systems, not related with a drive (converter for battery charge and supply of auxiliary needs), irrespective of dynamics of vehicle motion are in a steady state. Spectrum of their disturbances is discrete, thus depending on the measurement bandwidth, disturbances can be narrow-or broadband. In the measurements described in [9], during measurements narrow-band signals were registered, when a vehicle was in a considerable distance from a test point, and their maxima did not occur near a measuring position. However, it does not have to be like that. Specific approaches of using a specific CF lead to the subsequent doubts, due to the fact that recalculation of peak values registered at certain BW into values corresponding to other BW depends on the level of coherence of a measured signal. Additionally, it might occur that during a measurement at 1000Hz BW, disturbances at certain frequency bands will be broadband, and for the same bands at 200 Hz would be narrowband. The best method for determining the sources of disturbances would be checking the nature of each frequency from the measured band by measurements during a stationary test for two BWs and dividing the area of frequencies into parts, in which disturbance has both narrow- and broadband nature, and then introducing such correction factors that ensue from this measurement. Unfortunately, character of drive systems operation (during starting and braking modes) causes a completely different spectrum of disturbances than during a stop mode. During a stop, drive converters are under voltage, but are not operating, while auxiliary converters, which normally operate at a specified frequency, are the main sources of disturbances. Hence, this methodology of processing would lead to misinterpretation.

For the coherent signals (such as impulse signals from devices generating repetitious signals, such as switchable feeders (impulse), commutators, ignition systems operating at steady states, fluorescent lamps (glow discharge tubes) factor CF1 is used. Factor CF2 [5] is used for incoherent signals generated by power electronics systems in dynamic (transient) states, DC gas lamps, corona discharges. It means that depending on the applied correction factor (CF1 or CF2), performance of the appropriate correction of measured emission values consists in difference between the obtained values and value 13, 97 dB (conversion of the values of magnetic field measured with BW 1000 Hz into BW 200 Hz using factor (1)) or 6, 98 dB (conversion of the values of magnetic field measured with BW 1000Hz into BW 200Hz using factor (2)). Difference in values, about 7dB, is large enough so that might be decisive as far as the issues of fulfilment, by the rolling stock, of emission limits stated in the standard [2] are concerned. Thus, while making corrections, it is important to be aware of the nature of emission source. It will allow for classification of measured disturbance as totally or partially coherent or incoherent [6], due to the fact that under real conditions the nature of a source does not have to be unambiguous.

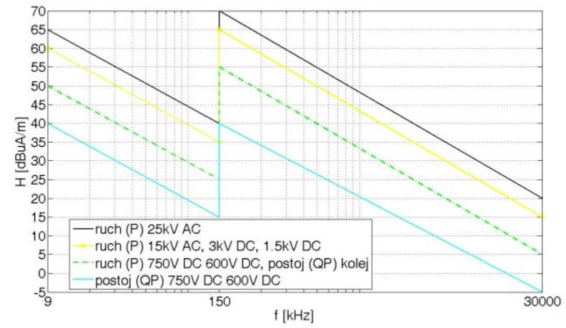

Fig 3. Limits of admissible disturbances for a magnetic component in the frequency range 9kHz- 30 MHz specified in the standard [2] during a slow moving test (P- peak detector)) and a during stop (QP- quasi peak detector)).

Theoretical analysis of the nature of electromagnetic disturbances generated from impulse systems

Limits presented in the standards [2,4] (fig.4) can be described in terms of discontinuity caused by the change of a BW at 150 kHz [4]. Therefore, it can be understood, that if one uses one BW in a measurement band in the whole spectrum of frequency, the limits will be continuous.

While analysing the assumption about discontinuity of the limits [4] one can conclude that the value of a magnetic field measured below and above the border frequency of 150 kHz is the same, but presented in a different manner. It provides different values, as a result of a BW changing.

Fig. 5 presents forecasted differences in values registered while using two different BWs (9 kHz - above 150 kHz and 200 Hz below 150 kHz). These differences (30dB - marking for the purposes of this article, "X" as a correction factor) are defined by the standard [2] determining the admissible limits, and while analysing their values one can conclude which correction factor- (1) or (2) should be used. Applying an appropriate formula one obtains:

$$CF1_{150kHz} = 20\log\frac{\mathrm{BW}_{6\mathrm{ref}}}{\mathrm{BW}_{\mathrm{actual}}} = 20\log\frac{\mathrm{BW}_{200\mathrm{Hz}}}{\mathrm{BW}_{9\mathrm{kHz}}} = -33dB \tag{3}$$

or when a generated signal has a coherent character or

(4) $$CF2_{150kHz} = 10\log\frac{BW_{6ref}}{BW_{actual}} = 10\log\frac{BW_{200Hz}}{BW_{9kHz}} = -16{,}5dB$$

when a generated signal has an incoherent character

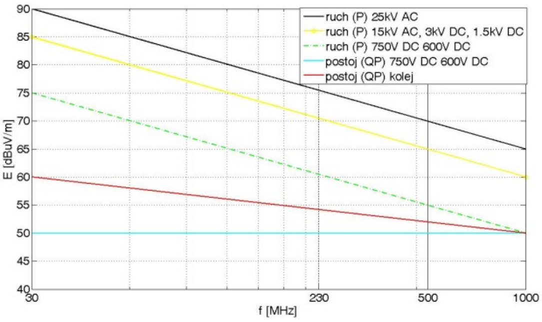

Fig.4 Limits of admissible levels of disturbances for the electric component in the frequency range 30 MHz-1 GHz defined in the standard [2] during a slow moving test.(P-peak detector) and during a stationary test (QP-quasi-peak detector) [apart from measurements of magnetic component disturbances, one performs measurements of vertical and horizontal electric component disturbances].

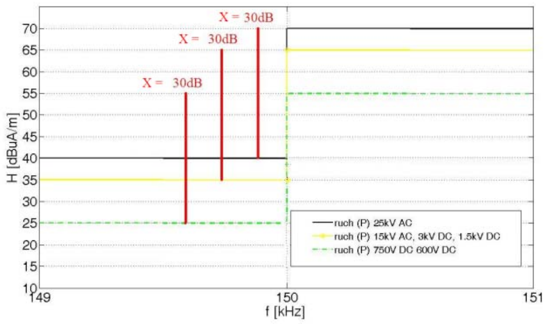

Fig. 5 Presentation of forecasted differences in values of the same magnetic field measured below (BW = 200Hz) and above (BW = 9000 Hz) border frequency 150 kHz with usage of different BWs (peak detector).

Assuming the nature of the generated signals, one obtains the following absolute difference resulting from the comparison of the values obtained by (3), (4) and X values (fig.5):

(5) $$\delta_{kr} = CF1 - X = -33 - (-30) = -3dB$$

(6) $$\delta_{nr} = CF2 - X = -16{,}5 - (-30) = 14{,}5dB$$

where: δ_{kr} - an absolute error with the assumption that a signal is coherent (difference between factor (3) and X value (fig. 5)) is obtained from the analysis of discontinuity of limits with a registration based on the another bandwidth.

Comparing differences (5), (6) it can be stated that signals with set limits were of a rather coherent than incoherent character. It is also visible that the proper selection of BW during the measurements of electromagnetic disturbances plays a significant role regarding their proper registration, while a choice` of an incorrect BW might cause huge differences in an assessment, if compared to the limits of generated disturbances values.

Analysis of a BW selection at laboratory measurements of disturbances emitted by a voltage source inverter and a chopper.

The measurements were conducted under laboratory conditions, where the laboratory drive systems: a series DC motor with a chopper and a cage motor with voltage source inverter, including dynamic states served as a source of electromagnetic disturbances emission. Loop receiving antenna was set 1m away from the source of disturbances. This distance was a result of the limitations of measurements conditions since they were conducted in the closed laboratory environment and not in the open measurement polygon and as a result of considerably lower powers of laboratory systems in comparison to real systems. Agilent MXA N9020A spectrum analyser was used as a measurement receiver. Exemplary time domain curves registered by the LEM converters on both sides of measurement system have been presented in fig. 1 and 2. Measurements have been accomplished in 3 sub-ranges of frequencies, and each had 5000 test points. Such number of points is sufficient [7] for the used measurement sub-ranges width and BWs of analyser. In total, measurement range covered by the research (9kHz-150kHz) recorded 10000 measurement points. Measurements were accomplished with usage of a peak ~~values~~ detector. Sweeping time was set automatically by the analyser, so as in the specific settings of BW and, span (f_{max}-f_{min}) was sufficient for the registration of not distorted values of disturbances. Number of the performed measurements cycles at a given sweeping time was conditioned by attainment of a set, unchangeable character of the envelope.

Results of the registration are presented in fig 6-13.

Various values of a background noise in a measurement of a system with a chopper and an inverter are caused by a different place of a measurement. (fig.6, fig. 11)

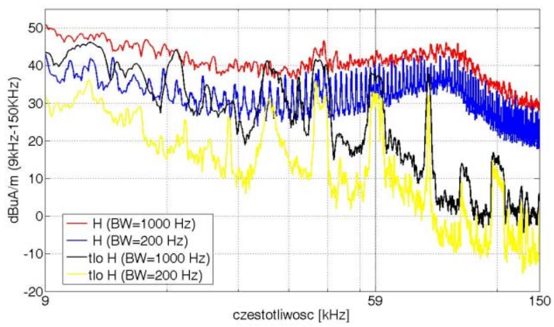

Fig.6 Results of registration of disturbances generated by an inverter-motor system and a background noise in a band 9 kHz-150 kHz at two BWs.

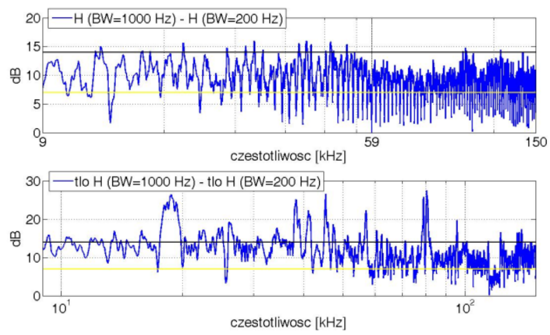

Fig.7 Comparison of differences between the values of disturbances of an inverter and a background noise measured at two BWs of a receiver (correction factors were marked for signals that are completely coherent, around 14 dB and incoherent around 7 dB).

As it can be seen in figures 6 and 7 differences between values registered with BWs of 1000Hz and 200Hz in a function of frequency are changeable. Hence, after a summary of results in a form of histograms, made at individual ranges (fig. 7, fig. 8) differences can be noticed, depending on the range of a measurement frequency spectrum. In the range 9kHz-59kHz, differences in the measured values in the largest number of cases (about 1200/5000 test points 'k') are about 12 dB in the range 59 kHz-150 kHz -10 dB (about 1400/5000 measurement points 'k').

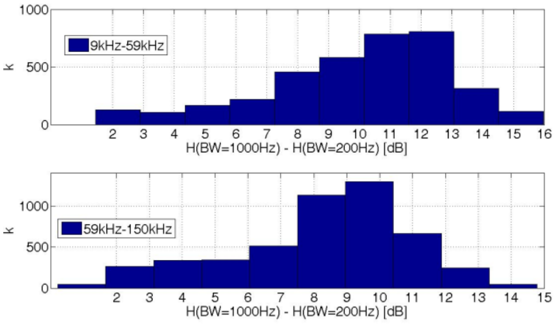

Fig.8 Histograms showing a difference in the values of disturbances from an inverter-motor system, registered for various bandwidths in the range of frequencies 9kHz-59 kHz and 59 kHz-150 kHz (k-number of test points). [Test points for frequencies, in which measurement background noise values were close to the values of device disturbances of a value smaller than 4dB were omitted in the assessment of the results in the above picture. Number of test points in the first sub-range has been reduced to 3676, while in the second one to 4888].

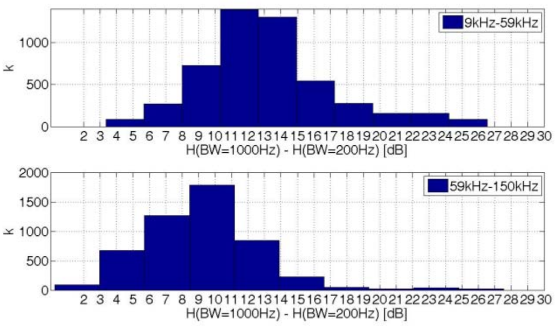

Fig.8a Histograms showing a difference in values of background noise at the measuring place of an inverter-motor system registered for the frequency ranges 9 kHz-59 kHz and 59 kHZ-150 kHZ (k-number of test points).

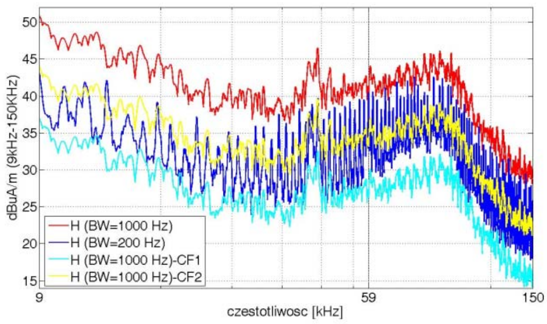

Fig. 9 Results of registration of disturbances from an inverter-motor system in a range of frequencies 9 kHz- 150 kHz at two BWs with application of CF1, CF2 corrections for the values measured by 1000 Hz bandwidth.

In fig. 9, it can be noticed that application of correction factors that enable recalculation of values measured by various bandwidths, leads to differences in obtained results. Due to the nature of a run, which is not always of broadband character, application of correction factors is approximated.

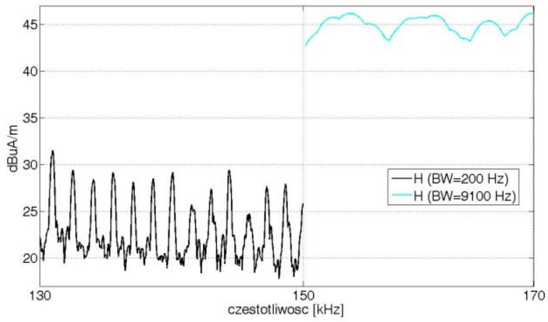

Fig.10 Results of registration of disturbances from an inverter-motor system in the range of 150 kHz frequency at two BWs.

Difference of disturbances values in the range of 150 kHz frequency, thus in a place in which standards [3, 4] suggest a change of a BW (from 200 Hz to 9 Hz) is 14 dB. Application of correction factor X with the calculation of a magnetic field value registered with bandwidth 9 kHz to the band 200 Hz generates difference around 16 dB and in relation to the factors (3), (4) 19 dB and 2,5 dB respectively. Application of the previously discussed methods of recalculations leads to differences of the obtained results, what decreases values transformed theoretically in comparison to the intended values.

The closest to the appropriate value is the application of the correction factor (4). Results of measurements for the emission of disturbances of a system with a chopper are presented in fig. 11-14.

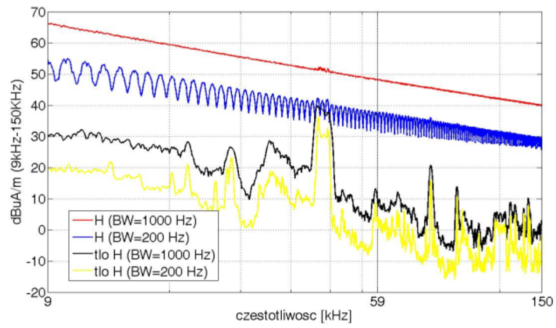

Fig.11 Results of registration of disturbances generated by a chopper-motor system and a background noise in the band 9 kHz-150 kHz at two BWs.

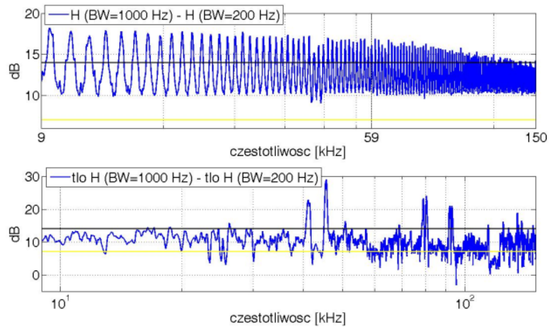

Fig.12 Comparison of differences of chopper and background noise values of disturbances at two BWs of a receiver (correction factors for totally coherent signals of about 14 dB and incoherent of about 7 dB were marked).

In case of a system with a chopper, calculation on the basis of correction factors seems to be much easier than in case of an inverter. It results from fig. 13 that correct values (i.e. obtained by lowering a signal registered at 1000Hz BW to envelope of maximum values of a signal registered at 200 Hz) can be obtained using a factor of 9 dB value).

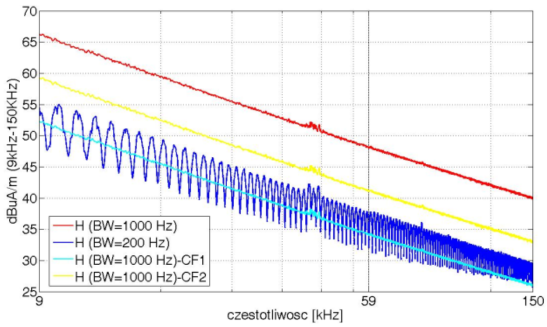

Fig. 13 Results of registration of disturbances from a chopper-motor system in the frequency range 9 kHz-150 kHz at two BWs and with application of corrections CF1, CF2 for values measured by 1000 Hz BW.

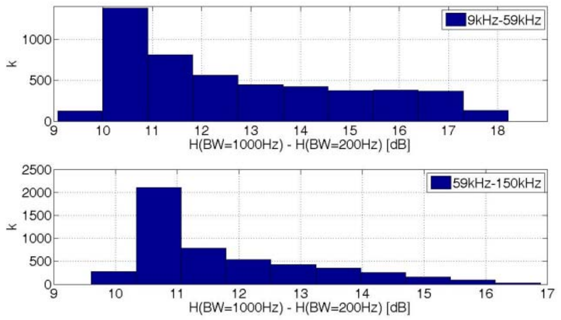

Fig. 14 Histograms showing a difference in values of disturbances from a chopper-motor system registered for various BWs in the range of frequencies 9 kHz-59 kHz and 59kHz-150 kHz [Lack of test points removed from the assessment of results due to the close value of background and device disturbances-values that are always higher than 4 dB]

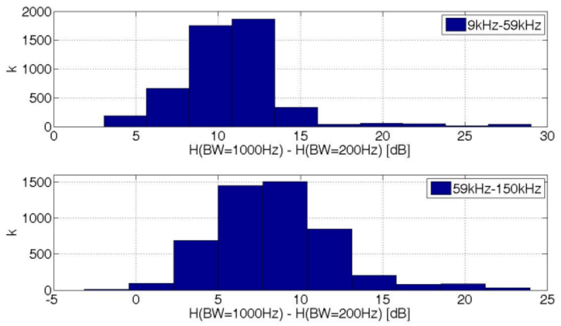

Fig. 14a Histograms showing a difference in values of a background noise at the measuring place of a chopper-motor system registered for various bandwidths in the range of frequencies 9 kHz-59 kHz and 59 kHz-150 kHz.

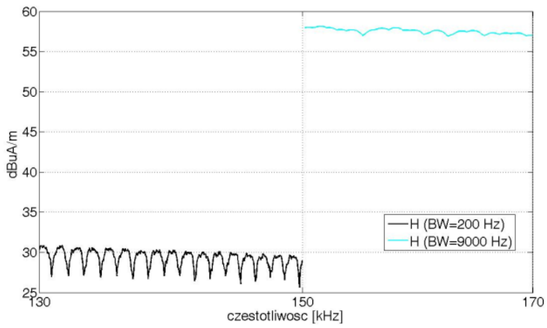

Fig.15 Results of registration of disturbances from a chopper-motor system around frequency of 150 kHz at two BWs.

Differences in the results of emission for various BWs of a system with a chopper slightly differ in comparison to a system with an inverter. In fact, in the whole analysed band, a difference is similar-typically 10-11 dB.

Around frequency of 150 kHz, - at the point, in which the standards [3, 4] advise a change of a BW from 200 Hz into 9kHz it is around 18dB. Application of a correction factor X while calculating a magnetic field registered at 9kHz bandwidth to 200Hz band generates a difference of 12dB, and as far as factors (3) and (4) are concerned, 15 dB and 1,5dB respectively. Applying X factor (fig.5) and (3), the obtained result is lowered, while with factor (4) overstated.
In this case application of a correction factor (4) is the closest to the correct value.

Stationary measurements under real conditions

It was a tram with an inverter drive and static converters that was a device measured under real conditions. The measurements were carried out with maintenance of the standard conditions and with usage of the same equipment that was previously used in laboratory measurements. Measurements were conducted for two BWs-200 Hz and 1000 Hz.

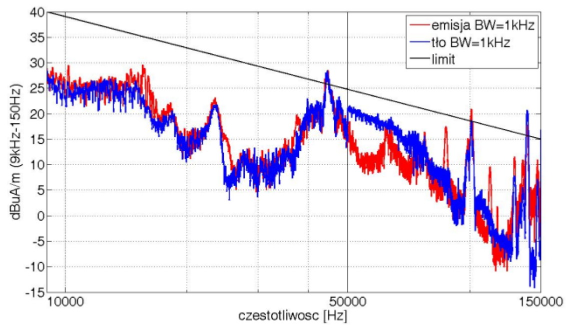

Fig.16 Results of registration of disturbances from the tram under measurements and a background noise for a BW 1kHz.

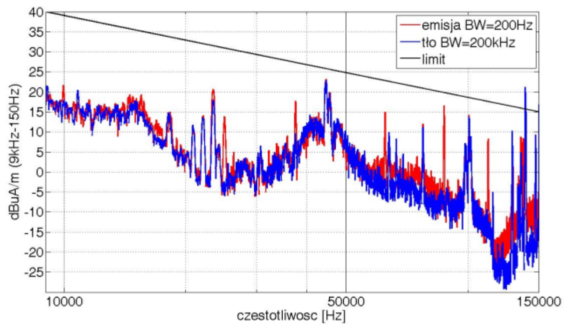

Fig.17 Results of registration of disturbances from a tram under measurements and a background noise for a BW 200 Hz.

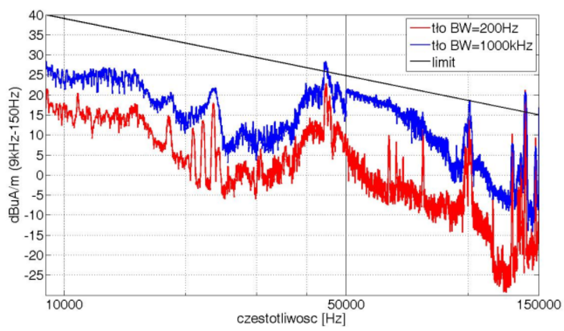

Fig.18 Comparison of a background noise at measurement site registered for two values of BW.

It can be seen in fig. 16 that background noise around 60kHz was of unstable character (most probably caused by operation of another device during background noise measurements), thus its value is higher than the value of disturbances emission from a tram during a stationary test . It is visible that values registered at two different BWs differ considerably, which confirms the necessity of conscious interpretation of the results registered in slow moving test other than at the recommended BW.

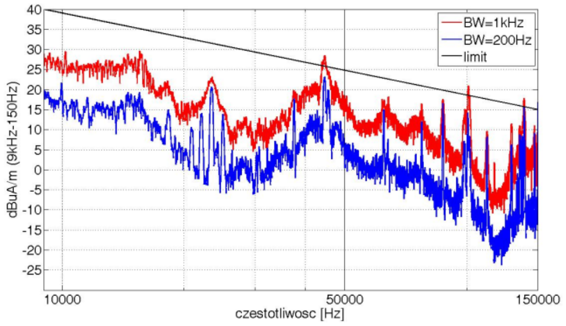

Fig.19 Comparison of disturbances generated by a tram for two values of BW.

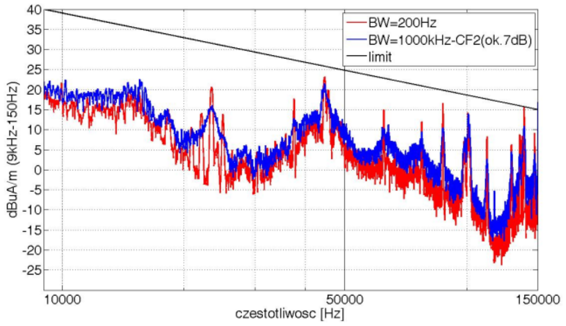

Fig.20 Comparison of disturbances generated by a tram for two values of BW, with application of a correction factor CF2 (around 7dB).

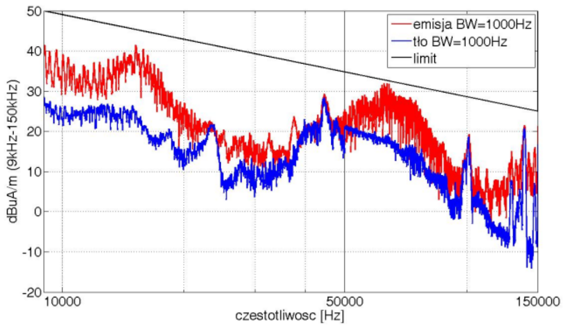

Fig. 21 Comparison of disturbances generated by a tram in motion with a background, for 1000HZ measurement bandwidth.

Fig. 20 shows that cutting CF2 correction factor from the values measured by 1000 Hz BW, gives results similar to the values obtained by 200 Hz BW. Careful analysis shows that even after performance of correction, an envelope of a blue run seems to be higher than a red run, prompting the use of a higher correction factor. Quite the opposite conclusion can be drawn adhering to the peak values-in this case; correction lowers the results for some frequencies.

These frequencies are of narrow-band character and are the frequencies of auxiliary converter operation (basic harmonic and higher harmonics), application of correction factors towards them leads to errors-maximum values, which are often generated by narrow-band signals, play significant role in assessment of emission compliance with the standards.

Described measurement was the stationary test, where a problem of a non-stationary disturbances source did not occur. However, a problem of BW change, applies to measurements during motion, thus application of variables in a function of frequency of scalers would lead to wrong interpretation caused by an incorrect assessment of disturbances nature.

It can be noticed in fig 21, that in a frequency ranges under assessment (appropriate height of a background) for 1000 Hz BW, it is narrowband nature of disturbances.

Summary and conclusions

The above presented considerations and discussions about the obtained results point to the fact that it is important, but not always possible and unequivocal enough to determine the nature of the measured emission from vehicles with power electronics converters. It is significant for performance of corrections of the values measured during certification tests, due to the applied BW. If one assumes that standard [4] by means of a change of limits continuity defines differences to be expected between the results due to applied BW (table 1), may lead to errors, because values of the results considerably depend on the nature of disturbances, i.e. whether they are narrow or broadband and analogically, by which BW are measured.

Table 1. Differences in values registered at various BWs for 150 kHz.

Driver system	X	d (CF1)	d (CF2)	d (Pom)
	[dB]			
Inverter with an asynchronous motor	30	33	16.5	14
Chopper with a series motor	30	33	16.5	18

where: X value obtained from the analysis of discontinuity of limits [2] with registration based on another BW (9 kHz and 200 Hz) (fig.5), d (CF1), d (CF2) – difference in values registered with various BWs (9 kHz and 200 Hz) obtained by theoretical calculations according to the formula (3), (4). d (Pom) – difference in the values registered with various BWs (9 kHz and 200 Hz) obtained by means of laboratory measurements (fig.9, 10).

Table 2. Differences in the registered values at various BWs for the range of frequencies 9kHz-150 kHz.

Supply system	d (CF1)	d (CF2)	d (Pom) hist	d (Pom) sr
	[dB]			
Inverter with an asynchronous motor	13.97	6.98	9	8.99
Chopper with a series motor	13.97	6.98	10,5	12.25

Where:d (CF1), d (CF2) – difference in the registered values at various BWs (1 kHz and 200 Hz) obtained by theoretical calculations according to the formula (1),(2).d (Pom) hist –the most common value of differences in the registered values at various BWs (1000 Hz and 200 Hz) obtained by means of laboratory measurements (fig.7, fig.11)d (Pom) Sr –difference in average values of disturbances registered at various BWs (1kHZ and 200Hz) obtained by means of laboratory measurements.

If one assumes that converter drive systems (choppers and inverters) used in electric vehicles, emit disturbances of the same nature as the systems analysed in laboratory conditions and partially as auxiliary converters in a vehicle, hence from the presented studies and analyses it ensues that in the measurement range of 9kHz-150kHz, in the systems with inverter and chopper drives, disturbances of narrowband nature, which values are almost independent from the used BW (fig.9, around 60 kHz difference reaches 2dB, fig. 20, frequencies around 130kHz) might appear as well. However, there is a need for calculations of the intended values, which due to various natures of disturbances might not be unequivocal (fig.21-broadband disturbances).

The standard [2] identifies other BWs with respect to the nature of the measured devices (vehicles in motion), therefore it appears to be justified to take into account differences in obtained results while applying the same BW as it is generally recommended in [3], stating the limits differently or by unambiguous identification of types of corrections to be made.

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