Characterization of Active Power Flow at Harmonics for AC and DC Railway Vehicles

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***Abstract*—Highly dynamic and distorting loads like electrified trains have complex power flow schemes, with active power not exclusively assigned to the fundamental (either dc or ac). The estimate of energy consumption shall thus cover the most relevant power spectral terms, in order to adequately track and quantify the active power flow. This work investigates the dynamic behaviour of two distortion power indexes calculated with the pantograph quantities, voltage and current, using experimental recordings performed over some European railway networks (3 kV dc, 2x25 kV 50 Hz and 15 kV 16.7 Hz). The results show the relevance of a reduced set of components and the strong correlation with train operating conditions. The relevance is significant for ac systems, and in particular 16.7 Hz systems.**

***Keywords*—Energy consumption, Power Quality, Power system harmonics, Rail transportation**

I. INTRODUCTION

It is generally recognized that reactive power and harmonic distortion are responsible for increased losses in the feeding system, from which the many regulatory standards, especially for public and industrial networks. The focus of this work is on AC and DC railways and in particular the line-pantograph interface, where power and energy are measured for billing purposes in a single-train perspective [1].

It may be said that distortion components carry in general little active power. However, direct exclusion of such active power terms is too an oversimplifying approach, that biases negatively the power estimate, resulting in diminished power consumption readouts. These distorted active power terms are quite variable depending on the rolling stock operating conditions and the supply network characteristics. So, in addition, their variability must be considered to quantify the uncertainty of the so-obtained power estimates. It is remarkable that the required uncertainty of the energy measurement function implemented on-board (and including the data acquisition system and the voltage and current sensors) is about a fraction of percent [1]; it is thus close to the expected worst-case active power distortion terms and their variability, that turn out to be a relevant factor for the uncertainty budget [2].

The pantograph current harmonic spectrum (loosely speaking for all current distortion components) varies depending on its operating conditions (acceleration, cruising, coasting, braking), on the auxiliary power (drawn for ventilation, air conditioning, Low Voltage loads, etc.), and on the electrical characteristics of the feeding point (distance from substation, type of line, presence of other trains).

From a wider perspective, it is not only the measurement uncertainty of the energy measurement system to consider, but also the uncertainty accompanying statements of assessment of energy and money savings, and the comparison of different solutions with the objective of the optimization of network-wide energy consumption. Although it is true that rolling stock input distortion is at all affected by the system timetable, when the optimization changes the intervals of tractioning, coasting, cruising and braking, correspondingly the harmonic patterns and the amount of harmonic power will change. In addition, from an overall system perspective the situation might be more complex, if in extreme cases trains are close enough to “see” each other from an electrical viewpoint, with superposition of the respective harmonic patterns conducted along the traction circuit, as well as mutual influence on the respective line impedances at the pantographs.

A complete and comprehensive analysis would be quite complex and not able to give a definitive answer, being many and variable the involved quantities. Although active power of a specific component may be entering the train as a result of its commutation process, for some other components the train may be only a passive load for network voltage distortion components or active power may result from a variable phase relationship of V and I components during the journey (the phase relationship of components between different trains changes with their relative position [3]; the line impedance at the pantograph is also variable with frequency and train position, with a resistive behaviour at line resonances [3]-[5][4]).

Data of several train runs are shown to discuss the relevance of specific frequency intervals and operating conditions.

II. POWER RELATED QUANTITIES

With the IEEE Std. 1459 [6] approach the total apparent power in non-sinusoidal conditions is expressed in terms of active power (both at the fundamental and harmonics) and a series of reactive (or distortion) power terms, resulting from cross-combinations of harmonic components of voltage and current [7]. Voltage and current vectors are decomposed into a fundamental term and an additional distortion term, composed of a dc component and the remaining harmonic terms. The term

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"harmonic" is used for convenience, identifying in reality any distortion component, including those not harmonically related to the network fundamental: this occurs for inter-harmonics, time-varying components (e.g. due to distortion components leaking from traction inverters), and the general case of dc traction supply systems (where the fundamental for the substation ripple is that of the feeding high-voltage network).

$$V_H^2 = V_0^2 + \sum_{h \neq 1} V_h^2 \qquad I_H^2 = I_0^2 + \sum_{h \neq 1} I_h^2 \tag{1}$$

For dc railways the terms with index 0 have no meaning as distortion terms, corresponding conversely with what should be called the fundamental, i.e. the dc component. Eq. (1) however is preserved in this form for generality.

Active power terms are defined as: the total active power P, the fundamental active power P_1 and the harmonic active power P_H. P_H is in reality indirectly quantified as P-P_1 and is composed of the individual active power terms for each spectrum component, for brevity indicated by a single index h.

The generalized apparent power is given by

$$\begin{aligned} S^2 &= (VI)^2 = (V_1 I_1)^2 + (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 \\ &= S_1^2 + S_N^2 \end{aligned} \tag{2}$$

with S_N indicating the non-fundamental apparent power, corresponding to the apparent power of harmonic and inter-harmonic terms above the fundamental (applicable to both ac and dc railways with a uniform approach).

The terms composing S_N are:

- current distortion power $D_I = V_1 I_H$;
- voltage distortion power $D_V = V_H I_1$;
- harmonic apparent power $S_H = V_H I_H$;
- harmonic active power $P_h = V_h I_h \cos(\varphi_h)$;
- harmonic distortion power $D_H = \sqrt{S_H^2 - P_H^2}$.

The objective is the characterization of the distribution and variability of active power carried by spectral components in a vehicle or locomotive perspective, thus using the pantograph (or shoegear, of course) voltage and current spectra. Three points must be considered:

- the identification of suitable indexes that allow to track the active power flow and its distribution versus a certain number of quantities, such as time, absorbed fundamental current (or power), speed;
- spectrum components are derived by means of a Discrete Fourier Transform (DFT) calculation implemented as Short Time Fourier Transform (STFT), resulting in a sequence of power vectors P_i and S_i , after calculation of the voltage V_i and current I_i spectra, centered around time instants T_i ; it shall be verified the impact of STFT parameters (such as frequency resolution, tapering to reduce frequency leakage, overlap) on desirable characteristics of the calculated spectra, such as separation of two close-by components, stability during transients, and in general amplitude accuracy;
- benefit of local averaging of spectra not so much to improve the signal-to-noise ratio or equivalently reduce incoherent noise floor [9], as for to reduce components variability, improve the regularity of derived indexes and ease their interpretation; similarly, pruning of spectra by removing components with amplitude below a given threshold is also helpful to reduce variability.

A. Basic power indexes

The task of quantifying the active power carried by spectral components is split into the quantification of the fraction with respect to the fundamental active power P_1 and the effectiveness of a single component to carry active power P_h in relation to the exchanged apparent power S_h. So, to this aim two basic indexes are defined:

$$k_h = \frac{P_h}{P_1} \qquad c_h = \frac{P_h}{S_h} \tag{3}$$

The index k_h weights the amount of active power of a component with respect to the fundamental (so quantifying its contribution). The index c_h weights the amount of active power with respect to the apparent power for each component (what we may call the "harmonic displacement factor").

B. Secondary indicators

The basic primary power indexes are calculated for each component (i.e. for each frequency bin) of the STFT vectors P_i and S_i, and are then post-processed using various methods, achieving a better and more compact description of displayed results, improving intelligibility and easing their interpretation. We may call the output quantities as "indicators"; the applicable methods can be preliminarily classified as follows.

a) Spectral grouping

The primary power indexes are calculated for each component. A more compact representation can be obtained by combining adjacent frequency bins, starting from the assumption that they should have similar behavior. In general, to identify valid grouping schemes, some a priori knowledge on typical emission and power absorption mechanisms, as well as some trial and error, are necessary. The harmonic groups are written in capital, i.e. C_H and K_H.

$$K_{Hi} = \sum_{h \in H_i} k_h \qquad C_{Hi} = \frac{1}{N(H_i)} \sum_{h \in H_i} c_h \tag{4}$$

where H_i indicated the i-th group with $N(H_i)$ terms.

It is remarked that it is always possible, at least for some time intervals, that terms of the power indexes with opposite sign compensate each other and attenuate in the respective plot: this may occur when mixing distortion components sourced by the network and by the train under test, resulting in two opposite flows of current; it is similarly possible during regenerative braking that some components still absorb power, with the rolling stock as a passive load at those frequencies.

b) Statistics

Mean and dispersion, percentiles and histograms are statistical tools of increasing accuracy and completeness to describe the distribution of a set of values; the collected samples shall be representative of the various operating conditions with a balanced mix not to bias the statistics.

Percentiles are particularly meaningful for this study since they describe directly the combination of value (or threshold) and relative frequency. Such threshold may be defined to correspond to intensity relevant to the accuracy requested for the evaluation of the absorbed power and energy consumption. Selected thresholds may be in the range 0.01-1%.

c) Correlation

To support a first visual interpretation of trends and curve shapes, correlation coefficients may be calculated with respect to the most representative quantities of operating conditions (namely the fundamental active power P_1 and train speed v). Specific k_h or K_H indexes will then be accompanied by a correlation coefficient value for a time interval selected to adequately encompass a sequence of train operations, such as standstill, acceleration, coasting/cruising, and braking to stop.

d) Repeatability

The evaluation is extended to different data sets, all taken in similar (ideally identical) conditions, such as the same train route and timetable in different days, or in time intervals with similar absorbed (or regenerated) power or speed, so to claim similar operating conditions. Repeatability is evaluated as Type A uncertainty [2], i.e. sample standard deviation.

e) Reproducibility

To assess reproducibility, repeatability should be tested with different setups and trains, so to verify the goodness of the conclusions drawn on the significance and characteristics of some spectral components and related power indexes. Since the rolling stock will change between data sets, there will be little chance to find the same spectral components and this will have a negative impact: a direct calculation as a Type A uncertainty will result almost surely in poor reproducibility, although an approach based on qualitative reasoning would say that there are similarities between the different data sets and between the resulting power indexes. This judgment would be based on the observation that: network distortion components are almost identical for trains running on the same network portion; rolling stock that is architecturally similar with respect to power drives and converters will exhibit similar spectral behavior, adjusted for the specific switching frequencies.

It is however true that systems with lower installed power per km per train, featuring widely different traffic load and connected to high-voltage networks with different pre-existing harmonic distortion will be characterized by different harmonic patterns and Total Harmonic Distortion values [10]. For this reason reproducibility should be evaluated with care, after that dispersion of power index values and repeatability have been assessed. The used term “similarity” to assess reproducibility does not imply that the evaluation will be subjective and qualitative only. There are suitable performance indexes for model validation [11][12], already applied e.g. to the evaluation of models of electric traction networks [13].

III. RAILWAY SYSTEMS DESCRIPTION

The considered dc and ac railway systems are briefly described for the characteristics related to the discussed phenomena and quantities, in relation e.g. to the harmonic propagation, pantograph impedance and in general the equivalent short-circuit power at harmonic frequencies.

Some considerations can be anticipated: it may in general be said that, thanks to the large amount of shunt capacitance at substations and on-board rolling stock, dc systems have the smallest harmonic distortion and harmonic power terms. AC systems have a larger harmonic distortion [10], better for the 2x25 kV 50 Hz, thanks to the larger installed power per train per km and to the supply scheme, using electrically separated supply sections of some tens of km maximum. The 15 kV 16.7 Hz system conversely has a highly interconnected network enhancing network resonances, possibly increasing harmonics between some hundreds Hz to few kHz [14].

It is in fact the product of current distortion components pulled by rolling stock with the corresponding voltage harmonic that matters for determination of power terms, and voltage distortion is more or less intense depending on the amount of installed power and on the equivalent network feeding impedance at that frequency (possibly increased by network resonances).

A. 3 kV dc system

DC systems are fed by substations equipped with 6- or 12-pulse rectifiers. Characteristic harmonics have order h=6n, n integer; 12-pulse reaction reduces odd components.

Many substations are equipped with filters, mostly LC, with the purpose of reducing substation ripple on the traction line [15], and as a matter of fact providing also very low harmonic impedance. Symmetrically rolling stock installs large on-board filters mainly for the exigency of signalling protection (power frequency track circuits), further reducing line distortion.

Although in principle a dc line can be electrically continuous with no need of electrical separation of substations, there are insulating points along the network, dividing it in shorter supply sections, for maintenance exigencies and to avoid unnecessary network instability.

B. 2x25 kV 50 Hz system

The traction line is fed with double-secondary transformers with primary connected to high voltage 3-phase lines; load is balanced by phase rotation, tapping cyclically different pairs of phases. This arrangement requires the electrical insulation of adjacent line sections, each fed by one substation. For the considered Italian high-speed line case, the installed power is quite large (each electric substation rated 60 MVA, autotransformers 15 MVA), much larger than that of dc lines.

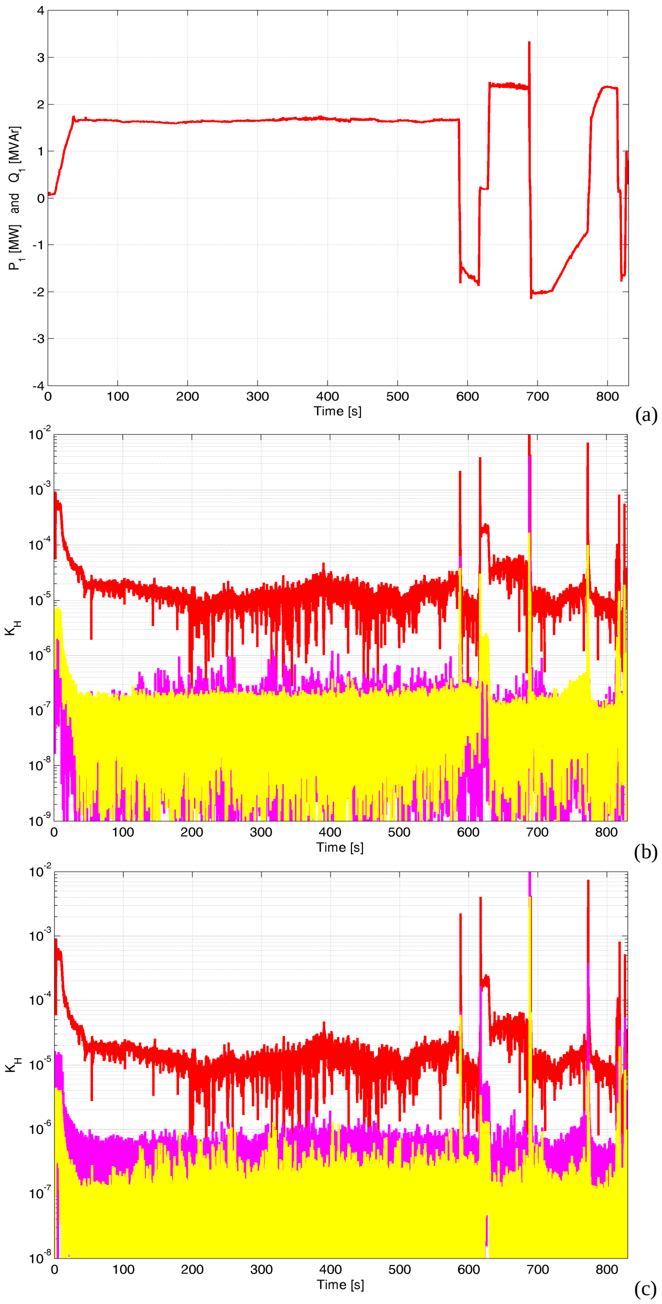
C. 15 kV 16.7 Hz system

The 16.7 Hz system is an almost fully interconnected railway with rare insulating points with a dedicated high voltage transmission and distribution network, as well as generation stations, all operated at 16.7 Hz. Catenary voltage drops are lower thanks to the lower supply frequency. The 16.7 Hz network is more similar to a 1x25 kV network and is used for mixed traffic (long/medium distance and commuter traffic).

IV. RESULTS

Results for each of the three railway systems show grouped C_H and K_H coefficients for two choices of the frequency intervals: up to 500 Hz (red, C_{HA}, K_{HA}), 0.5-2 kHz (purple, C_{HB}, K_{HB}) and 2-10 kHz (yellow, C_{HC}, K_{HC}) for set1; then attention is focused on the low order components (set2), reducing the intervals so to have up to 150 Hz (red, C_{HA}, K_{HA}), 150-500 Hz (purple, C_{HB}, K_{HB}) and 0.5-2.5 kHz (yellow, C_{HC}, K_{HC}).

The active/reactive power at fundamental and the KH and CH values for set1 and set2 are shown for the three systems in the following figures: Fig. 1 for the 3 kV dc, Fig. 2 for the 2x25 kV 50 Hz and Fig. 3 for the 15 kV 16.7 Hz system.



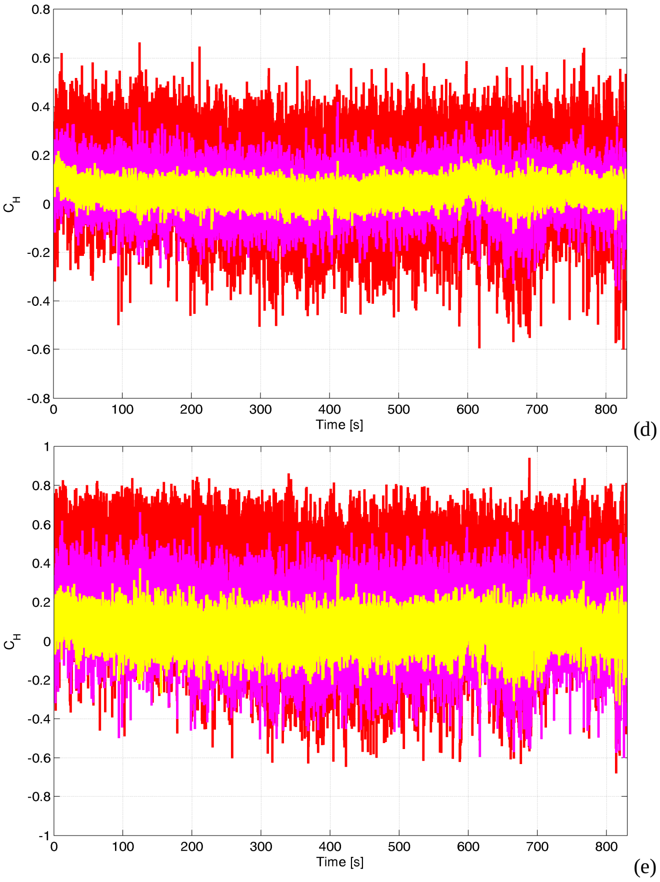
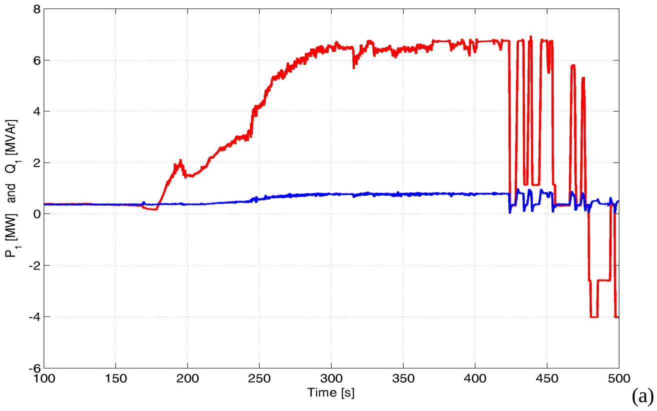


Fig. 1. Italy 3 kV dc: (a) active and reactive power at DC; (b,d) K_{HA}, K_{HB}, K_{HC} for set1 and set2; (c,e) C_{HA}, C_{HB}, C_{HC} for set1 and set2.

As expected, we may say that dc electric transportation systems in general are characterized by a significantly reduced distortion with recognizable active power components in the first 150 Hz only. Confirmation shall be however sought in a more extended analysis using data from different systems and different positions along the supply network.



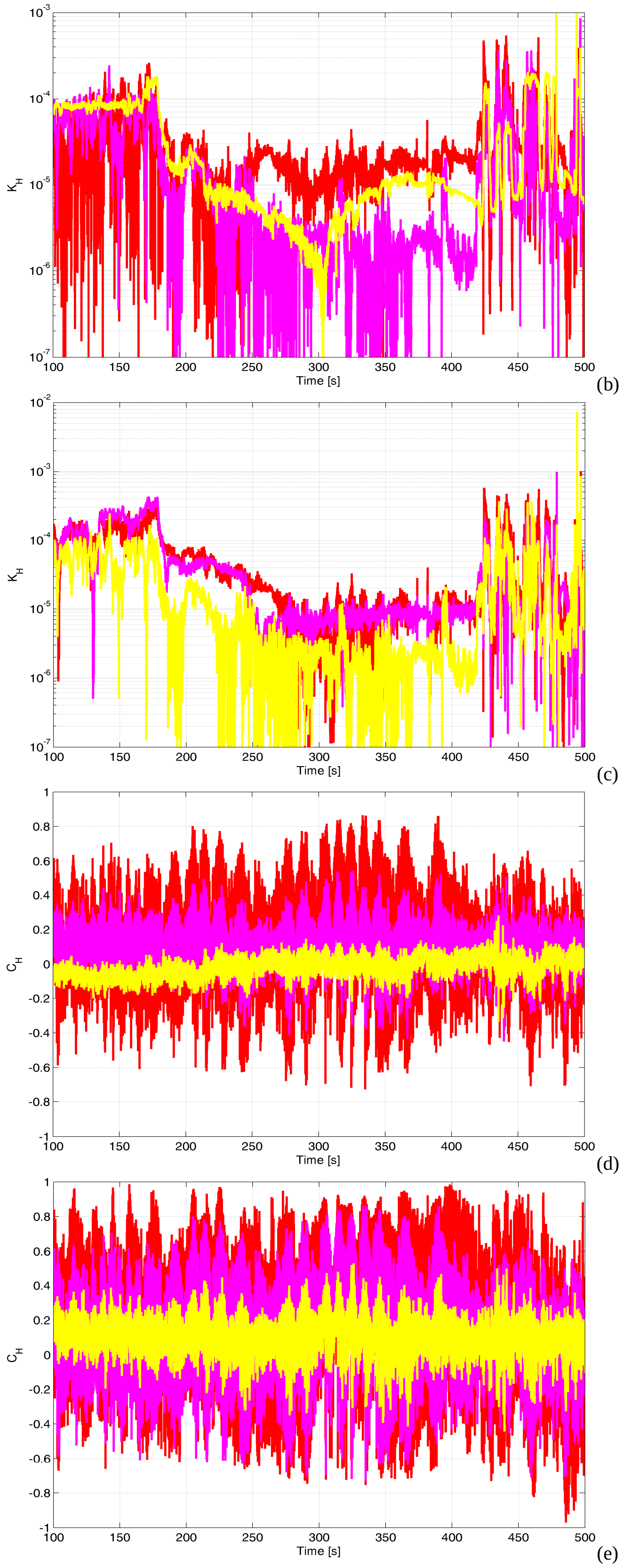
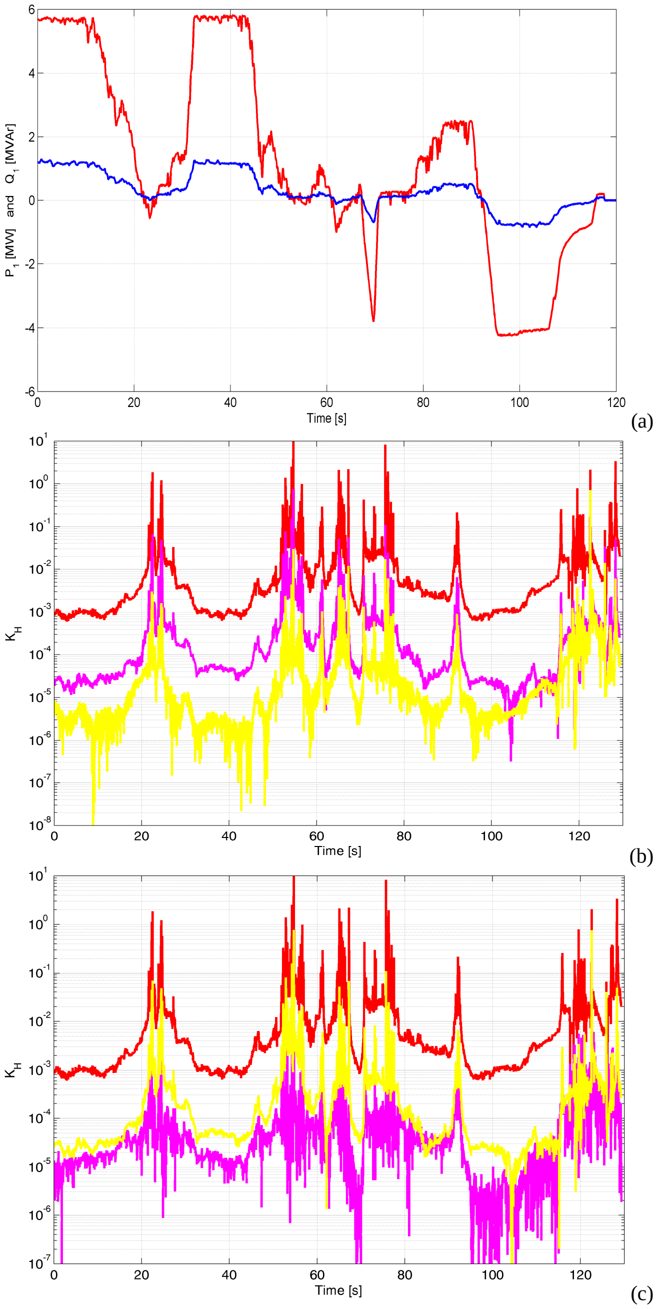
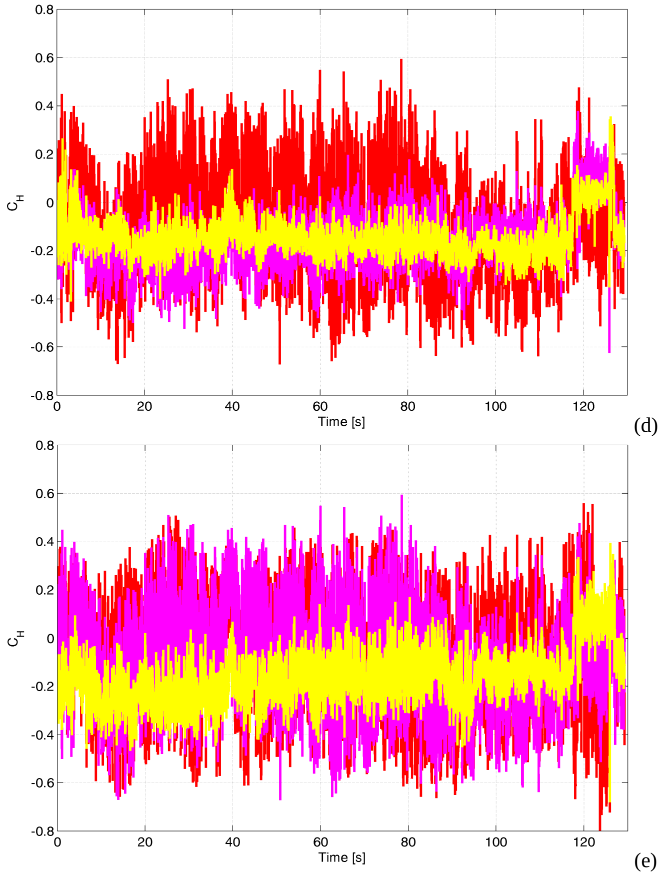


Fig. 2. Italy 2x25 kV 50 Hz: (a) Active and reactive power at 50 Hz; (b,d) K_{HA}, K_{HB}, K_{HC} for set1 and set2; (c,e) C_{HA}, C_{HB}, C_{HC} for set1 and set2.

This 2x25 kV network (Italian high speed line) features a large installed power per km per train, compared for example to the French network, that has higher traffic and features a larger voltage distortion [10]. A comparison between different 25 kV schemes may be useful, with a more detailed representation of the harmonics, focusing on those that feature a correlation typical of rolling stock harmonics compared to the network generated ones [14].

It is possible to observe that the yellow curve for the group at highest frequency is always the lowest one, indicating a relevance of harmonics below 2 kHz and, in particular, up to 500 Hz, as confirmed by the red curve in Fig. 2(b).





(d)

(e)

Fig. 3. Switzerland 15 kV 16.7 Hz: (a) active and reactive power at 16.7 Hz; (b,d) K_{HA}, K_{HB}, K_{HC} for set1 and set2; (c,e) C_{HA}, C_{HB}, C_{HC} for set1 and set2.

By observing the shift of the yellow curve of the K_H index for the two frequency intervals (set1 and set2) reported in Fig. 3(b) and (c), we may conclude that both components below 150 Hz and around 2-2.5 kHz are quite relevant: the former are related to network distortion, the latter to the onboard traction converters. Values of K_H between 0.1 and 1% characterize the entire test run, indicating a significant contribution of higher order harmonics.

V. CONCLUSIONS

This work has presented the problem of the assessment of active power terms at harmonics (and in general for spectral components other than the fundamental) and their relevance for the accuracy of the estimate of power consumption of rolling stock.

The harmonic active power terms have been analyzed for three cases, related to the Italian 3 kV dc and 2x25 kV 50 Hz and the Swiss 15 kV 6.7 Hz systems. Some conclusions have been drafted on the relevance of the harmonic active power, both in terms of relative amplitude with respect to the “fundamental” (including for generality dc) and frequency extension.

A wider analysis is of course necessary for verifying the statistical consistency and the relevance of the photographed situations for these systems, and to extend the considerations to other similar systems (e.g. French network for 2x25 kV, German network for the 15 kV, and possibly one or two systems operated at 1x25 kV).

The conclusions are that dc systems have in general a negligible harmonic active power presence, that the considered 2x25 kV system has quite a large installed power and a moderate harmonic distortion, and that the 15 kV network has quite a complex harmonic pattern, showing a significant contribution in the range of 1% for harmonics in the hundreds Hz and those around the switching frequencies of the onboard converters.

REFERENCES

[1] CENELEC EN 50463-2, *Railway applications – Energy measurement on board trains*, 2017.

[2] BIPM, *Evaluation of measurement data — Guide to the expression of uncertainty in measurement*, JCGM 100, 2008.

[3] B. Hemmer, A. Mariscotti, D. Wuergler, “Recommendations for the calculation of the total disturbing return current from electric traction vehicles,” *IEEE Trans. on Power Delivery*, vol. 19 n. 2, April 2004, pp. 1190-1197.

[4] M. Fracchia, A. Mariscotti and P. Pozzobon, “Track and traction line impedance expressions for deterministic and probabilistic voltage distortion analysis”, IEEE Intern. Conf. on Harmonics and Quality of Power ICHQP, Orlando, Florida, USA, Oct. 21-25, 2000, pp. 589-594.

[5] J. Holtz and H. J. Klein, “The propagation of harmonic currents generated by inverter fed locomotives in the distributed overhead supply systems,” *IEEE Trans. on Power Electronics*, Vol. 4, n. 2, April 1989, pp. 168-174.

[6] IEEE Std. 1459, *IEEE Standard Definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Condition*, 2010.

[7] A. E. Emanuel, “Powers in nonsinusoidal situations - A review of definitions and physical meaning,” *IEEE Trans. on Power Delivery*, July 1990, Vol. 5, n. 3, pp. 1377-1389.

[8] F. De Rosa, R. Langella, A. Sollazzo, and A. Testa, “On the Interharmonic Components Generated by Adjustable Speed Drives,” *IEEE Trans. on Power Delivery*, vol. 20, n. 4, Oct. 2005, pp. 2535-2543.

[9] R. G. Lyons, *Understanding Digital Signal Processing*, 3rd ed., Prentice Hall, 1996.

[10] A. Mariscotti, “Results on the Power Quality of French and Italian 2x25 kV 50 Hz railways”, Intern. Instrum. and Meas. Techn. Conf. I2MTC, Graz, Austria, May 13-16, 2012.

[11] A. Mariscotti, “On the validation of models of large complex electrical systems”, *Intern. Journal of Measurement Technologies and Instrumentation Engineering*, vol. 4 n. 1, Jan.-March 2014, pp. 17-42

[12] A. Duffy and A. Orlandi, “A review of statistical methods for comparing two data sets,” Appl. Comput. Electromagn. Soc. J., vol. 23, no. 1, pp. 90–97, Mar 2008.

[13] J. Bongiorno and A. Mariscotti, “Evaluation of Performances of Indexes used for Validation of Simulation Models based on Real Cases”, *Intern. Journal of Mathematical Models and Methods in Applied Sciences*, Vol. 9, 2015, pp. 29-43.

[14] A. Mariscotti, “Direct Measurement of Power Quality over Railway Networks with Results of a 16.7 Hz Network,” *IEEE Trans. on Instrumentation and Measurement*, vol. 60 n. 5, May 2011, pp. 1604-1612.

[15] A. Mariscotti and P. Pozzobon, “Synthesis of line impedance expressions for railway traction systems”, *IEEE Trans. on Vehicular Technology*, vol. 52 n. 2, March 2003, pp. 420-430.