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Relevance of Harmonic Active Power Terms for Energy Consumption in Some Railway Systems

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***Abstract* – Active power is not carried solely by the fundamental component (either dc or ac) especially for highly distorted systems, as electrified railways. The paper proposes two indexes and a preliminary assessment of the relevance of harmonic active power terms. Results are shown for three major railway systems architectures (3 kV dc, 2x25 kV 50 Hz and 15 kV 16.7 Hz) using experimental pantograph voltage and current. Harmonic power terms are relevant for the estimate of energy consumption especially for ac systems rather than dc, with some significant situations especially for 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 generally distortion components carry little active power. However, the required uncertainty of the energy measurement function implemented on-board (and including the data acquisition system and the voltage and current sensors) is in the range of a fraction of percent [1] close to the expected worst-cases harmonic active power, that may be a relevant term of the uncertainty budget.

The rolling stock harmonic pattern [2] (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, LV loads, etc.), and on the electrical characteristics of the feeding point (distance from substation, type of line, presence of other trains). A complete and comprehensive analysis would be quite complex and not able to give a definitive answer, being many and variable the involved quantities. The phase relationship between distortion components of different trains changes with their relative position [3]; similarly, the line impedance at the pantograph is also variable with frequency and train position, resulting in a variable phase angle between the voltage and current components [4][5]. Typical behaviour based on recorded train runs is presented and discussed to identify the most relevance frequency interval 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 distortion power terms resulting from cross-combinations of voltage or current harmonics [7]. Voltage and current vectors are decomposed into a fundamental and an additional term, with a dc component and the remaining harmonic terms:

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

The generalized apparent power is given by

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

S_N indicates the non-fundamental apparent power, i.e. the apparent power of harmonic and inter-harmonic terms above the fundamental (applicable to both AC and DC railways with a uniform approach):

- 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 evaluation of the active power carried by harmonics and its distribution with frequency. So, to this aim two indexes are defined:

$c_h = P_h/S_h$ that weights the amount of active power with respect to the apparent power for each component (so the harmonic displacement factor); it is observed that a value near zero implies a small amount of active power and a mostly reactive power flow takes place; a positive sign means that V_h and I_h

lie in the same quadrant, not that the active power is absorbed by the train;

$k_h = P_h/P_1$ that weights the amount of active power with respect to the fundamental active power (so quantifying the contribution of the h-th component).

These two indexes can be defined for each component and then be combined in groups of components, in order to keep the representation compact. Components of a group should have similar behavior not to create confusion and weird behavior. In general care shall thus be taken for the selection of components to group, with some a priori knowledge on typical emission and power absorption mechanisms and some trial and error. The harmonic groups are written in capital, i.e. C_H and K_H.

$$K_{Hi} = \sum_{h \in H_i} k_h \qquad C_{Hi} = \frac{1}{N(H_i)} \sum_{h \in H_i} c_h \tag{3}$$

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

It is always possible, at least for some time intervals, that power terms with opposite sign compensate each other and attenuate in the respective plot (and this shall be verified in case of doubt): the meaning of such opposite sign may indicate that the equivalent generators for two components of the same group are on opposite sides, that is the network and the rolling stock, 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.

III. RAILWAY SYSTEMS DESCRIPTION

The description of the railway systems is limited to the characteristics necessary to understand the discussed phenomena in relation to the propagation of harmonic terms, the pantograph impedance and in general the equivalent short-circuit power at harmonic frequencies.

We may in general observe that, thanks to the large amount of shunt capacitance at substations and on-board rolling stock, DC systems have the smallest harmonic power terms. AC systems in general have a larger distortion [10] with a more favorable situation for the 2x25 kV 50 Hz, featuring a larger installed power per train per km and a supply scheme with electrically separated sections of some tens of km maximum. The 15 kV 16.7 Hz system conversely is highly interconnected with wider supply sections, enhancing network resonances, possibly increasing harmonics in the range of some hundreds Hz to a few kHz [8]. It is not the current harmonics pulled by the rolling stock alone, but the product with the corresponding voltage harmonic that matters for determination of power; voltage distortion is more or less large depending on the equivalent feeding impedance of the network at that frequency, increased by network resonances.

A. DC 3 kV system

DC systems are fed by substations equipped with simple 6-pulse, or enhanced 12-pulse, rectifiers. Characteristic harmonics have order h=6n, n integer; 12-pulse reaction reduces (not to say suppresses) odd components.

Substations are generally equipped with LC filters with the purpose of reducing substation ripple, providing also very low impedance at harmonic frequencies watching from the traction line. 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 between substations, there are insulating points along the network, for maintenance exigencies and to avoid the unnecessary risk of network instability.

B. AC 2x25 kV 50 Hz system

The traction line is fed with double-secondary transformers where the primary is connected to high voltage 3-phase lines; thus the load is balanced by phase rotation, tapping cyclically different pairs of phases. This arrangement of course requires the electrical isolation of adjacent line sections, each fed by one separate substation, because of the phase displacement and the unavoidable short circuit in case of accidental bridging. For this reason there are in place “phase separation sections” (also called “neutral sections”) at which the rolling stock shall reduce power absorption to zero and lower the pantograph. For the considered Italian high-speed line case, the installed power is quite large (each electric substation is rated 60 MVA and autotransformers 15 MVA), much larger than that of DC lines.

C. AC 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 and medium distance and commuter traffic).

The drawback of a highly interconnected network is that resonances and anti-resonances may be more complex and appear from hundreds Hz to several kHz.

IV. RESULTS

Results for each of the three considered railway systems are shown with grouped c and k coefficients for the following frequency intervals: up to 500 Hz (black, C_{HA}, K_{HA}), from 0.5 to 2 kHz (dark grey, C_{HB}, K_{HB}), and from 2 to 10 kHz (light grey, C_{HC}, K_{HC}). The selection of these intervals was done based on the general knowledge of the operation of on-board converters, although there are differences between systems and rolling stock, that should be analyzed with a closer look.

A. DC 3 kV system

In Fig. 1 the absorbed active power P_1 (top), the fractional active power K_H for the three harmonic groups (middle) and their average displacement factor C_H (bottom) are shown for a 500 s run on a 3 kV Italian line.

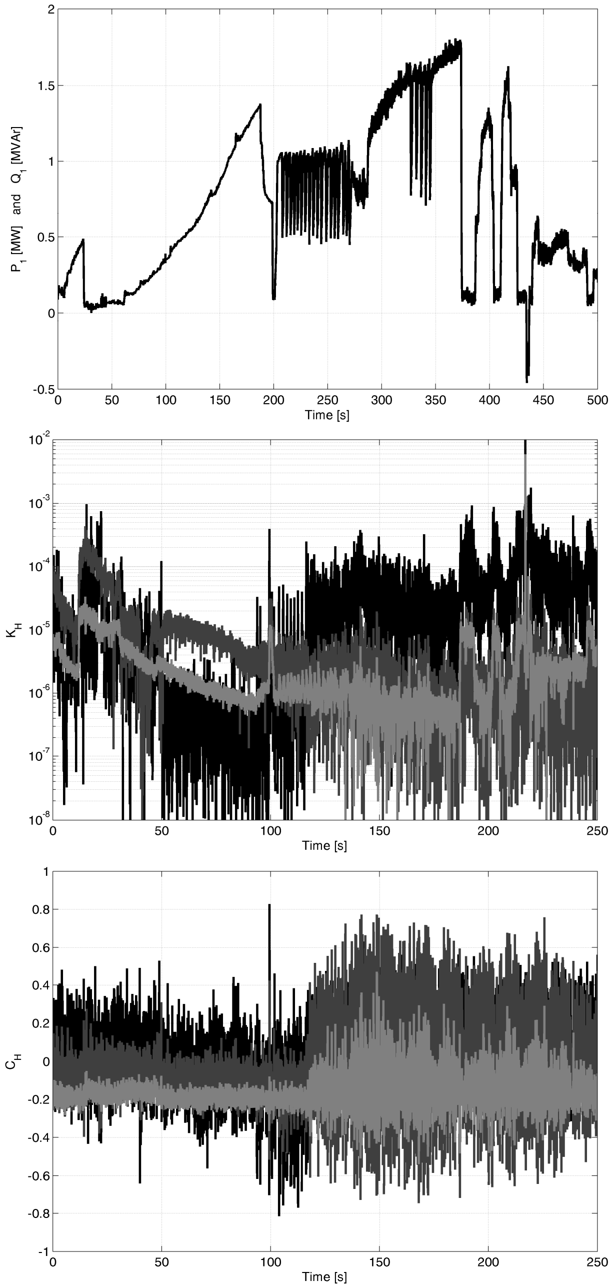

Fig. 1. Italy 3kV: (top) Active power at dc ("Q_1" appears for similarity with AC plots); (middle) K_{HA}, K_{HB}, K_{HC}; (bottom) C_{HA}, C_{HB}, C_{HC}

The low frequency components carry the largest active power, around 0.03% for about 10% of the time (black curve, Fig. 1-middle). This active power "enters" the train, as the sign of C_H is positive on average.

B. AC 2x25 kV 50 Hz system

In Fig. 2 the profile of the absorbed active power P_1 and Q_1 (top), the fractional active power K_H for the three harmonic groups (middle) and their average displacement factor C_H (bottom) are shown for a 300 s run on a 2x25 kV Italian line.

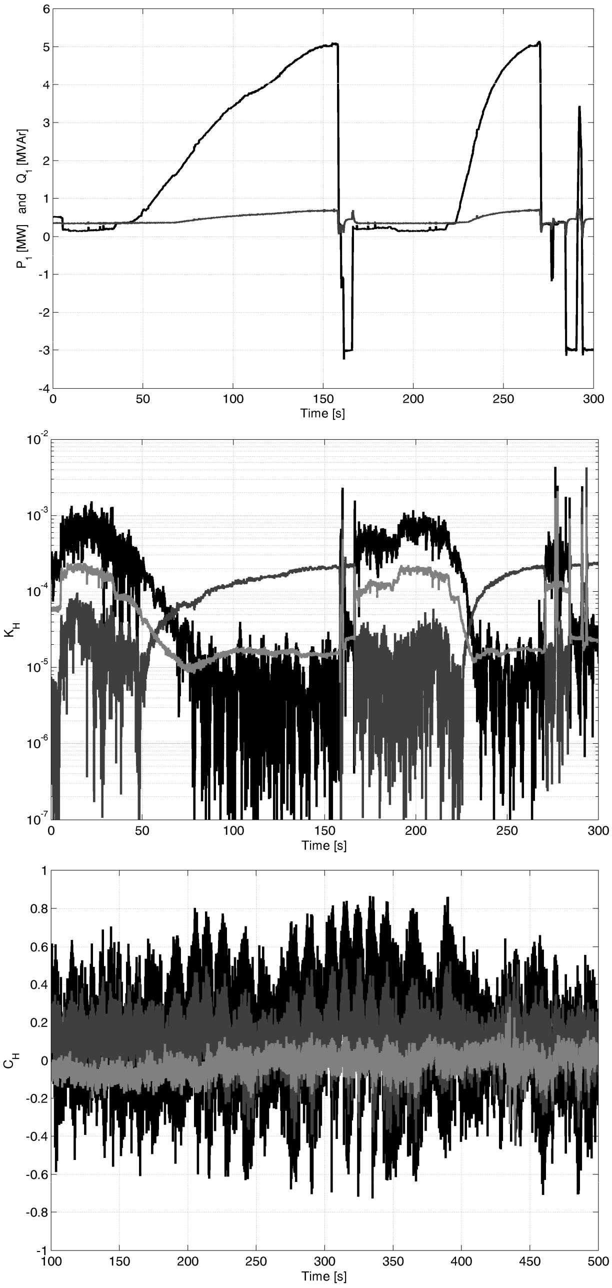

Fig. 2. Italy 25kV: (top) Active and reactive power at fundamental; (middle) K_{HA}, K_{HB}, K_{HC}; (bottom) C_{HA}, C_{HB}, C_{HC}

The active power for the low-frequency components is larger than it was for the DC system, around 0.1% for about 25% of the time when the absorbed power P_1 is small. Then, medium frequency components, including traction converter switching components, represent the largest contribution (about 0.02%).

Observing the large values of K_{HA} and K_{HC} in the two intervals with no traction, it is reasonable to assume that the train is a passive load for the low frequency components (for which also the C_{HA} values are non-null), and there is a non-negligible exchange of power for the high-frequency group, where the first harmonics of the auxiliary converters are located.

It is observed that the black C_{HA} curve goes frequently to large values up to ±0.8, indicating a prevalence of active power for the harmonics of the first group. The light grey curve is always near zero, indicating that the power exchange is almost purely reactive.

C. AC 15 kV 16.7 Hz system

In Fig. 3 the profile of the absorbed active power P_1 and Q_1 (top), the fractional active power K_H for three harmonic groups (middle) and their average displacement factor C_H (bottom) are shown for a 110 s run on a 15 kV Swiss line, characterized by a larger harmonic active power: around 3% when there is no traction power, and 0.1% during full traction (t=20 s), as well as during braking (t=60 s). Medium frequency components (dark grey curve, K_{HB}) account for less than 0.01% in the intervals of large exchanged current, followed by the lower light grey curve of the high-frequency group (K_{HC}).

Considering the sign of C_H, it is possible to see a change of sign between the dark grey (medium frequency, C_{HB}) and the light grey curve (high frequency, C_{HC}): the dark grey curve is slightly negative when auxiliaries are on at the beginning, then both turn to positive during heavy traction, and the light grey curve (C_{HC}) is negative during light traction, coasting and braking (between about 30 and 60 s).

It is worth noting also the different behavior of the two AC systems, as far as the location of the harmonics associated to traction and to auxiliary converters, reflected in the different behavior of the two grey curves, for medium and high frequency groups, often exchanging the role.

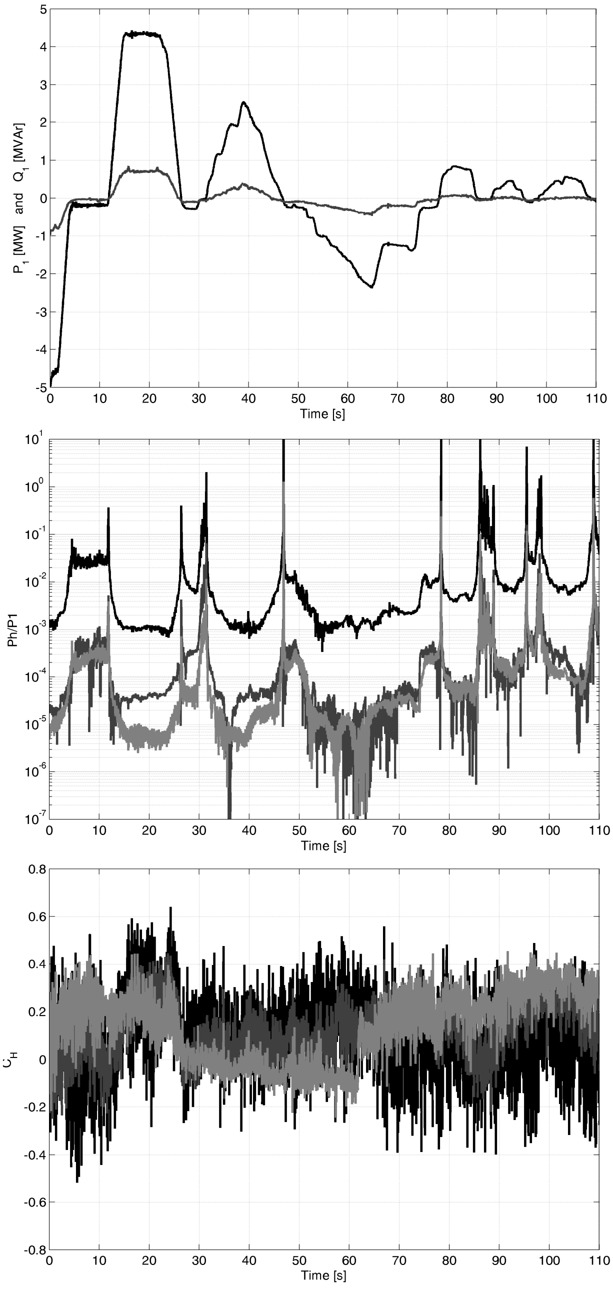

Fig. 3. Switzerland: (top) Active and reactive power at fundamental; (middle) K_{HA}, K_{HB}, K_{HC}; (bottom) C_{HA}, C_{HB}, C_{HC}

V. CONCLUSIONS

From the presented results for all the examined railway systems there are low-frequency harmonics up to 500 Hz carrying altogether about 0.01%P_1 of active power, and up to 0.1% for shorter intervals. For AC systems, depending on the type of the on-board converters, significant active power may be found up to 2 kHz (2nd harm. group). For the 16.7 Hz system the amount of harmonic active power is slightly larger, with K_H values between 0.1% at large power intervals and

0.3% when the absorbed power is less than 1 MW.

Although some deal of compensation of active power components of the same group cannot be excluded (thus resulting in an overall smaller net active power flow), it may be said that these terms account for about 0.1% of the power budget, if weighted by the time duration and the total active power in each condition.

It was demonstrated thus with sample data that harmonic active power is a non-negligible term of the consumed energy metering function [1], at least for AC railway supply systems.

Further research is foreseen to better characterize the frequency distribution of the most relevant terms, their statistical consistency over entire train runs (more extended than the presently examined data) and to correlate them to train operating conditions. In order to increase the significance and the confidence of the results, this analysis should be extended to other railway supply systems: the French 2x25 kV (featuring a higher level of harmonic distortion [10]) is a good candidate to confirm the results obtained with the newer Italian 2x25 network; the German 15 kV network is similarly a good candidate for the confirmation of the data observed for Switzerland.

VI. ACKNOWLEDGMENT

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REFERENCES

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

[2] G. W. Chang, H.-W. Lin, and S.-K. Chen, “Modeling Characteristics of Harmonic Currents Generated by High-Speed Railway Traction Drive Converters,” *IEEE Trans. on Power Delivery*, vol. 19 n. 2, April 2004, pp. 766-773.

[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] 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.

[5] 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.

[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] 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.

[9] J. Bongiorno and A. Mariscotti, “Recent results on the power quality of Italian 2x25 kV 50 Hz railways”, 20th IMEKO TC4 Symp. on Measurements of Electrical Quantities, Sept. 15-17, 2014, Benevento, IT, pp. 953-957.

[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.