Impact of Harmonic Power Terms on the Energy Measurement in AC Railways

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***Abstract*— In electric ac railways, a nonnegligible amount of active power and reactive power can be associated with harmonics. Electric railways are characterized by a mix of moving loads in variable operating conditions with a substantial superposition of different distortion patterns. The EN 50463-2 standard for the measurement of energy and of active power and reactive power does not include harmonic power terms, leading to possible inaccuracy. This article reports the estimate of the harmonic power for ac railways in real scenarios and its variability due to the operating conditions and moving loads, together with the uncertainty in the energy consumption estimate.**

***Index Terms*— Electric transportation systems, energy consumption, power quality (PQ), power system harmonics, uncertainty.**

I. Introduction

REACTIVE power and harmonic distortion are deemed responsible for increased loss and disturbance in distribution systems [1], [2], from which the many power quality (PQ) standards, especially for low-voltage and medium-voltage public and industrial networks. Similarly, in electrified traction systems, losses may occur in the traction line and at substations. However, the study of power terms at fundamental and harmonics is also relevant for suitable and accurate estimate of power and energy consumption and fair billing. The attention is focused on ac railways being much more relevant than dc systems for distortion power, as demonstrated in [3]–[5]. Railways have been always considered a special "private" network with relatively immune loads as for harmonic distortion, so that harmonic limits were rarely stipulated for PQ purposes but rather for the purpose of protecting signaling systems from interference [6], [7] and in general to limit induced noise on nearby systems [8]. There has been an increasing interest for energy consumption and fair billing, considering the efforts to improve energy efficiency, in general for electronic loads [9], electric drives [10], [11], and modern smart transportation systems [12]–[14], and the complexity of the introduced normative for energy metering onboard [15]. Metering is achieved by measuring the electrical quantities at the train pantograph (voltage and current) [16]–[18].

The widespread approach to energy metering [15], [19] focuses on fundamental quantities, assuming that distortion components can be neglected, possibly on the grounds of a small amount of active power and nonactive power associated with them. This is not completely correct if electric drives and power converters are considered [10], [11] and similarly for a distribution network, such as ac railways, where a significant amount of active and nonactive harmonic power flow can take place [3], [4]. Rolling stock is characterized by variable operating conditions and interaction with the network (variable feeding impedance, resonances, and antiresonances) and with other rolling stock items in the same supply section. The inclusion of nonactive power in the energy billing should be accurately evaluated [20] not only for the necessary physical interpretation and a comprehensive accounting of the power flow but also for the implications of responsibility of harmonic producers and the impact on consumers and industry, including meter manufacturers. On the other hand, identifying a "saving" in a reverse active power flow at some harmonics other than the fundamental should be sided by clarifying how the exploitation is carried out by the rest of the system, in other words clarifying if it is either a "nonutilized" or a regenerated power.

The relevance of the harmonic power terms is evaluated not only in an absolute perspective (weighting the harmonic power with respect to the same quantities at the fundamental) but also taking into consideration the train-operating conditions (acceleration, cruising, coasting, braking, and standstill) and the rate of occurrence, determining in this way the influence on the overall exchanged energy (consumed energy and regenerated energy, to use the EN 50463-2 terminology [15]). The exchanged energy is estimated by means of an energy measurement function (EMF) implemented onboard that includes data acquisition system and voltage and current sensors [voltage measurement function (VMF) and current measurement function (CMF)] and the energy calculation function (ECF). Fundamental active and reactive power terms are straightforwardly calculated by the ECF from pantograph voltage and current and then integrated to get the corresponding energy.

The EN 50463-2 [15], to specify limits of accuracy, clearly thinks in terms of nearly sinusoidal waveforms, with power and energy calculated using only the fundamental component (see the indication of "maximum phase displacement at rated

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frequency"). Harmonics are then considered as a disturbance, for which immunity requirements are specified, similar to the EN 50470-1 standard [19]. It is the objective of this article to demonstrate that neglecting the harmonic power terms may lead to errors in the total energy estimate of the same order of the EMF accuracy specification.

The definition of realistic conditions for the test of energy meters under nonsinusoidal conditions has attracted a lot of interest [20]–[23]. The EN 50463-2 similarly does not clarify better the EMF and ECF for nonsinusoidal conditions, reflecting what was pointed out in [24] 10 years ago: "The traditional quantities used for electrical energy pricing do not take into account the presence of harmonic distortion at the metering section. In fact, they are based upon the traditional concepts of active, reactive, and apparent power (and energy) and related power factor that are only well defined for sinusoidal voltages and currents."

The uncertainty in the ECF and EMF is, thus, influenced not only by the metrological performance of VMF and CMF but also by the adequate and all-comprehensive definition of the objective quantities (power and energy) in relationship with the pantograph quantities and their spectral content. As an input to standardization activities, the second objective is the definition of adequate measurement conditions with respect to the uncertainty due to operating conditions.

The following analysis is carried out in a single-train perspective, based on the pantograph voltage and current, as required for power and energy consumption assessment [3], [4], [15]. The measurement setup and instrumentation are as described in [17]: for uncertainty, the 16-bit digitizer has a negligible impact, whereas the Rogowski1 coil and capacitive voltage divider have 3% and 1.4% (coverage factor $k = 2$), respectively, accounting for all influencing factors, including noise and eccentricity, as shown in [25] for Rogowski. Repeatability is an order of magnitude better.

II. Power-Related Quantities

Power quantities are defined using the IEEE Std. 1459 [26]. These definitions are well known and were already reported in the conference paper [3], in which this is an extension, so that they will be only briefly summarized for ease of reference.

The total apparent power in nonsinusoidal conditions S is subdivided into active and nonactive power terms. Finding suitable terms to decompose the nonactive term may be tricky as shown in [27]: what is relevant is separating the terms with nonnull average from those with null average. To this aim, it is sufficient to calculate the total active power $P = P_1 + P_h$ and then subtract it in a quadratic way from the total apparent power S, which can be conveniently calculated as the product of the rms values of voltage and current. The total nonactive power corresponds to Fryze's fictitious power: $Q_{hF} = (S^2 - P^2)^{1/2}$. The quantities at the fundamental P_1 and Q_1 are anyway calculated for exigency of comparison and normalization. The EN 50463-2 for ac railways, in fact, requires the measurement of active power and reactive power in traction and braking conditions, and these quantities are defined for the fundamental only. We indicate them with obvious meaning as P_T, P_B, Q_T, and Q_B. In compliance with the EN 50463-2, they are calculated when voltage and current satisfy some conditions, as detailed in Section II-B.

This solves the problem of quantifying the overall contribution of harmonics to the active power and reactive power but not that of the relevance of the single harmonic power terms. For this reason, the nonactive power terms must be separated, using (5) of the time-referred nonactive power p_q in [27], and reported as (1).

1) The first term is the harmonic reactive power Q_h.
2) The second term defines the distortion power as mixed product of terms both at fundamental and at harmonics (further decomposition does not bring any added value and reopen the discussion on the interpretation and the physical meaning of the terms).
3) The last two terms are the contributions in the presence of dc components, which in ac railways may be assumed zero, except during transients:

$$\begin{aligned} p_q = &-\sum_h V_h I_h \cos\vartheta_h[1-\cos(2h\omega t - 2\alpha_h)] \\ &+2\sum_m \sum_{m\neq n} V_m I_n \sin(m\omega t - \alpha_m)\sin(n\omega t - \beta_n) \\ &+V_0 \sum_h I_h \sin(h\omega t - \beta_h) + I_0 \sum_h V_h \sin(h\omega t - \alpha_h). \end{aligned} \quad (1)$$

The harmonic power terms are then expressed by means of convenient fractional indexes related to the fundamental.

1) The index k_h weights the active power carried by the hth component $P_h(t) = \mathrm{Re}\{S_h(t)\}$ with respect to the active power at the fundamental $P_1(t)$: $k_h = P_h/P_1$.
2) The index d_h measures instead the amount of active power with respect to the apparent power for the hth component neglecting distortion power; a complex quantity of unitary modulus $d_h = P_h/S_h + jQ_h/S_h$ may be defined, positive when absorbed by the train, that can be conveniently displayed in polar coordinates.

These two quantities (k_h and d_h) may be expressed as a function of time (tracking during a train run) or as a function of the fundamental power terms themselves. They may be also grouped for a more compact representation, but this requires knowledge of the harmonic patterns and the characteristics of the onboard converters to be effective. Grouping based on frequency adjacency was used in [4] with the objective of identifying the frequency distribution of harmonic power and the necessary frequency extension to capture the relevant contributions. Other techniques may be used [3] to relate to the operating conditions and to separate network distortion.

A. Spectrum and Harmonic Power Terms

The spectra of V_p and I_p are calculated using the short-time Fourier transform (STFT) algorithm using two window lengths for the two different fundamental frequencies, T_{16} and T_{50}. Frequency resolution is chosen so that even and odd harmonics are clearly detectable: $T_{16} = 180$ ms and

$T_{50} = 60$ ms correspond to 1/3 of the fundamental frequency. A Hann window is used for tapering. Usual time resolution to report power measurements is 1 s; the EN 50463-2 requests energy consumption values every 5 min.

B. Harmonic Power Terms' Significance and Selection

With focus on both active harmonic power and nonactive harmonic power, harmonics are selected with the largest apparent power S_h. As known, in ac railways, low-order harmonics are prevalent: to avoid such biasing, the selection is uniformly done in each frequency subinterval, covering network, traction converter, and auxiliaries' harmonics. The frequency range up to 5 kHz is subdivided into three intervals: intv1, up to 500 Hz; intv2, between 500 and 1000 Hz; and intv3, between 1 and 5 kHz, and for each interval, the largest six S_h are selected and processed, calculating k_h and d_h indexes.

Since the objective is providing information to the EN 50463-2, its criteria for power calculation are considered.

1) *Area 1:* Full accuracy is required when $I_p \geq 10\% I_n$; this accuracy is specified as the maximum error of the calculated energy and depends on the EMF class, variable between 0.2% and 1%; and for $V_p < U_{\min 1}$ ($U_{\min 1}$ as in EN 50163 [28]), the required accuracy is as in Area 2.
2) *Area 2:* For I_p between 1% and $10\% I_n$, the required accuracy is relaxed by a factor of two.
3) *Area 3:* For I_p between 0.4% and $1\% I_n$, the energy measurement is required but with unspecified accuracy.
4) *Area 4:* $I_p < 0.4\% I_n$, no energy measurement is really required (in Table 16 of the EN 50463-2, we read "if energy is measured, no accuracy requirements"); as a consequence, no accuracy requirement is specified.

Similarly, the EN 50470-1 [19] specifies a transitional current I_{tr}, above which the "full accuracy requirements" apply up to the $I_{\max}$ threshold (above the nominal current I_n with some margin), whereas between $I_{\min}$ and I_{tr}, "relaxed accuracy requirements" apply.

The calculation of harmonic power terms, thus, will not be performed when the overall exchanged active power (absorbed or regenerated) is less than 0.1% P_{1n}, i.e., nominal fundamental power. When processing very small quantities, much dispersed index values may be observed, losing sometimes physical meaning (see K_H at standstill in [3]).

C. Uncertainty

As known, operating conditions are quite variable and changes to the internal operation of the onboard converters may occur at any time, with significant influence on the resulting spectrum. The variability of the pantograph network impedance influences the way emissions are coupled into the network and the amount of distortion at the pantograph, as detailed in Section III-C. The infrastructure variability represents the first source of uncertainty.

In addition, the train position and the presence of other trains nearby exert some influence by changing the way internal and external components propagate and overlap [29]: although unlikely, it is also possible that components at the same frequency from different trains of the same model partially compensate, resulting in a lower amount of harmonic power at some frequencies. A source of systematic error is, thus, the identification and separation of own and external spectral components (i.e., harmonic producer identification [24], [30]). So, inaccuracy of assignment of harmonics to the producer is another source of uncertainty, heavily dependent on the amount and type of traffic: e.g., a high-speed line with well-separated trains and a line with mixed commuter and medium/long-distance traffic, as considered in Sections III and IV.

Infrastructure variability, train position, and the presence of other trains have been preliminarily evaluated for the Swiss network in [31], including all harmonic components regardless of the harmonic producer. Uncertainty in EMF is evaluated with a Monte Carlo approach based on these experimental data: the average values well correspond to the values reported later in Section IV-C, with dispersion of the same order of magnitude.

The basic uncertainty requirements of the instrumentation for VMF, CMF, and ECF range from 0.2% to 1% (EN 50463-2 [15]). To this aim, the significance threshold for inclusion of the harmonic components should be selected with margin (0.01% P_1 in our case, compatible with the repeatability of sensors). A new measurement setup has been devised, assembled, and installed as part of the MyRailS project [18], but the uncertainty assessment is not yet complete.

The uncertainty of data processing is that of fast Fourier transform (FFT)-based methods, with an impact that is orders of magnitude smaller. Spectral leakage is controlled as described in Section II-A.

D. Tracking of Harmonic Power Terms

The most relevant harmonics are tracked over a train run, correlating these with the operating conditions and in particular with the amount of exchanged power, assessing not only their variability and significance in relative terms but also their contribution to the overall exchanged energy and their relevance as a systematic error of the EMF. In addition to the weighting of the k_h and d_h coefficients with respect to the overall power, time may be introduced to identify the cumulative effect of a single harmonic power term on the exchanged energy, telling what is the fractional change on average when that term is ignored.

III. Railway Systems' Description

An electrified railway is a distribution network with moving loads with significant dynamics and distortion [32]–[36]. The traction line undergoes severe mechanical constraints with a far from ideal electric behavior [37], [38]: voltage drops, resonances, induction, etc.

A. 2 × 25-kV 50-Hz System

The traction line is fed with double-secondary transformers with their primary connected to high-voltage three-phase

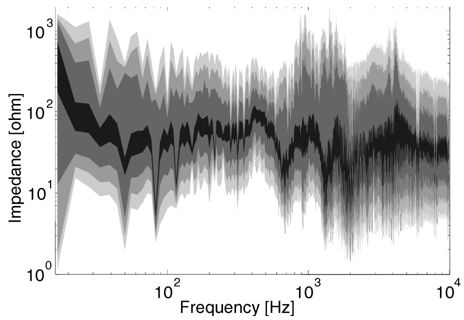

Fig. 1. Example of pantograph line impedance variability using histogram curve (5%–20%–40%–60%–80%–95%) [17].

feeder lines, and load is balanced by phase rotation, tapping cyclically different pairs of phases. This arrangement requires the electrical isolation by phase separation sections of adjacent line sections, each fed by one substation. For the considered Italian high-speed line, the installed power is quite large (substations are rated 60 MVA, autotransformers 15 MVA) and the length of supply sections is in the order of 25–30 km.

B. 15-kV 16.7-Hz System

The 15-kV 16.7-Hz system is highly interconnected with supply sections longer than those of 2 × 25-kV 50-Hz systems. This increases the chance of network resonances at low frequency, causing abnormal amplification of voltage distortion in some cases [17]. The 16.7-Hz network is used for mixed traffic (long/medium distance and commuter traffic).

C. Line Resonances and Antiresonances

The pantograph line impedance is subject to a significant variability versus frequency and longitudinal position of the train [17], [37], [38], as shown in Fig. 1. The influence on current and voltage distortion and on harmonic power terms can be explained with an example. A loco pulls some traction current I_p characterized by a few harmonics under quite large pantograph impedance near a resonance, so that voltage distortion is increased. Symmetrically, at antiresonances with particularly low values of pantograph impedance, the I_p current components are "amplified" in a situation of nearly short-circuit condition at those frequencies. For both, there will be an apparent increase in specific harmonic power terms. In addition, at resonances and antiresonances, the pantograph impedance becomes almost resistive [37], significantly increasing the fraction of active power.

IV. Results for the 15-kV 16.7-Hz and 2 × 25-kV 50-Hz Systems

The results are reported for one 16.7-Hz system and one 50-Hz system. An instrumented train ran in normal commercial service for several kilometers and data have been extracted for both the identification of typical significant events and phenomena, and to derive statistical figures based on the entire ensemble [39]. The amount of data is reported by continuous recording for 2 days for each railway system. The results are as follows.

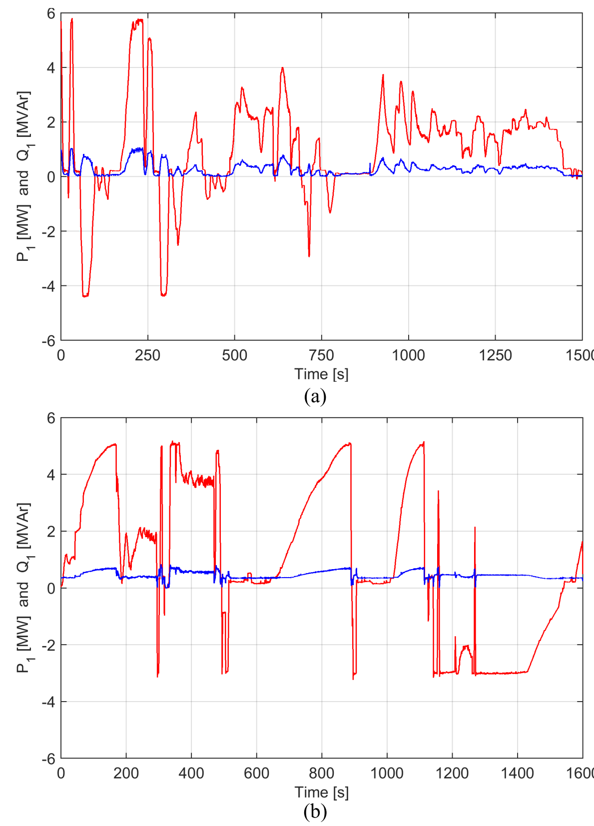

Fig. 2. Fundamental active P_1 (red) power and reactive Q_1 (blue) power for (a) 15 kV 16.7 Hz and (b) 2 × 25 kV 50 Hz.

1) Typical run showing power absorption and regeneration profiles (train dynamics) and the calculated output quantities as per EN 50463-2 for both the fundamental and harmonic terms up to 5 kHz.
2) Identification of the most relevant harmonic power terms setting and tracking the intv1–intv3 groups of Section II-B; the stability of components membership is also checked.
3) For the selected components belonging to a group, indexes k_h and d_h are calculated and displayed for a test run, as well as their statistics are given for the entire set of data.
4) The impact on the energy measurement uncertainty is evaluated considering the output quantities at step 1) and the statistics at step 3).

A. Run Profiles, Spectra, and EN 50463-2 Quantities

Two typical profiles are shown in Fig. 2, where a sequence of traction, cruising/coasting, and braking phases may be seen, including time intervals with stops at stations.

Samples of the typical line spectra with visible odd characteristic harmonics are shown in Fig. 3, where a good correspondence with the three intervals intv1–intv3 may be noted. The low-frequency components of intv1 are in general related to network distortion, and the clusters of spectral lines at higher frequency are the patterns of the onboard converters, mostly of the four-quadrant type. The particularly intense third

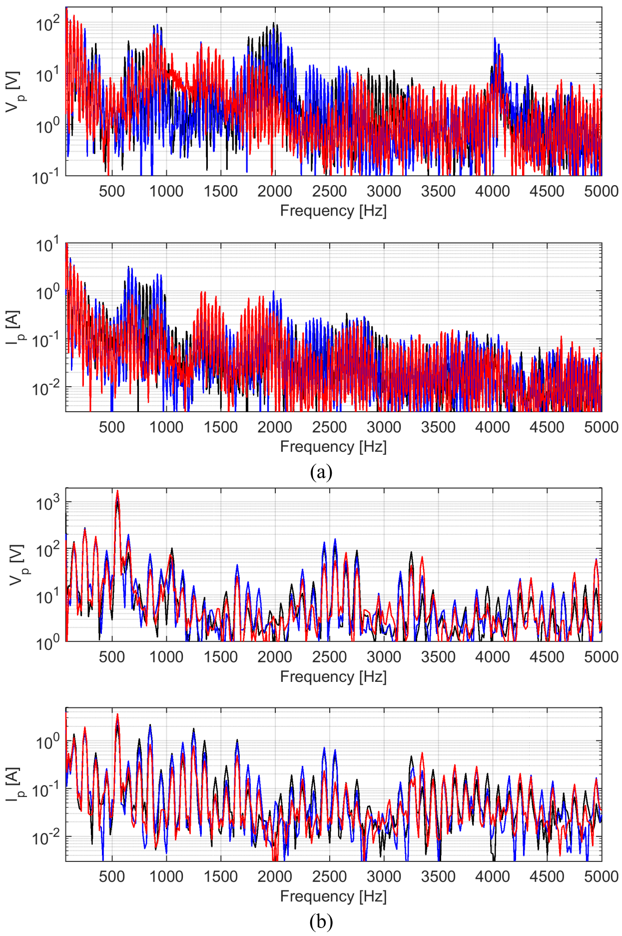

Fig. 3. Harmonic spectra of pantograph voltage and current for traction (black), braking (blue), and coasting (red). (a) 15 kV·16.7 Hz. (b) 2 × 25 kV·50 Hz.

harmonic (50 Hz) in the 16.7-Hz system is due to not only the typical 4QCoperation [35] but also the onboard auxiliaries working at 50 Hz, overlapping to the third harmonic of the fundamental [3].

During the data visual inspection, an excessive distortion was observed, not justified by the interaction of the train with a line resonance for two reasons: it lasted for a very long time and it was located at 550 Hz (11th harmonic), so well below the first line resonance of a 2 × 25-kV system. The harmonic is well visible in Fig. 3 and is caused by distortion on a high-voltage feeder, occurring in correspondence with a neutral section. The energy parameters in Section IV-C are, thus, calculated for the 2 × 25-kV system using both the whole test run and excluding the first 327 s up to the neutral section is located. As shown later in Table III, there is no dramatic impact on energy values.

In Fig. 3, the variability of harmonics among the operating conditions of traction, braking, and coasting is clearly visible: harmonics around 800 Hz (traction converter switching frequency) are missing during coasting (see Fig. 3(a)-I_p) and similarly, harmonics between 1250 and 2500 Hz in Fig. 3(b)-I_p are consistently lower. The hump of voltage harmonics in Fig. 3(a)-V_p is caused by a line resonance, amplifying the negligible harmonic content of the current I_p.

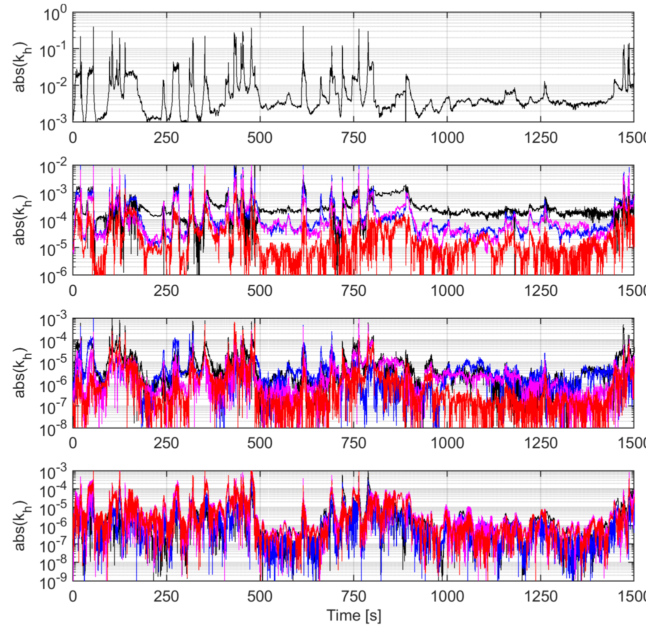

Fig. 4. Tracking of k_h in 16.7 Hz (top to bottom): 1) 3rd; 2) 5th (black), 7th (blue), 9th (magenta), and 11th (red); 3) 39th (black), 41st (blue), 43rd (magenta), and 45th (red); and 4) 115th (black), 117th (blue), 119th (magenta), and 121st (red).

B. Harmonic Power Groups and Tracking k_h and d_h

STFT spectra are processed to extract the intv1–intv3 groups, based on the magnitude of S_h. The k_h and d_h indexes for the selected harmonics are then tracked versus time. The absolute value of k_h is shown in Fig. 4 for the 16.7-Hz system using a logarithmic axis: the third harmonic is responsible for a significant fraction of the total harmonic active power, and the value of P_h, however, is quite well distributed among the various clusters around the characteristic harmonics of traction converters and auxiliaries. The evolution of the selected harmonics versus time is shown in Fig. 5: some of the 2-kHz and the few 4-kHz harmonics indicate external influence, possibly of FLIRT trains, as Re460 does not have such emissions.

The power flow and the inductive/capacitive behavior are analyzed plotting the index d_h in polar coordinates against the absolute value of P_1 (see Fig. 6).

Low-order harmonics with an external origin common to an entire supply section are usually unaltered (e.g., fifth and ninth); the seventh is in this case an exception, for which there is no convincing explanation. Some of the high-order harmonics due to converter modulation undergo sign reversal and change in distribution for both internal and external terms (see 43rd, 117th, and 121st), whereas the most intense ones (41st and 45th of the 800-Hz converter modulation) have almost constant angle and amplitude.

A similar analysis was performed in [10], where the prevailing harmonics are the fifth and the seventh caused by the front-end rectifier of the variable speed drive; the harmonic active power is much larger due to the lack of waveform shaping, and the harmonic nonactive power is larger than the fundamental reactive power, as in the present case (see Section IV-C).

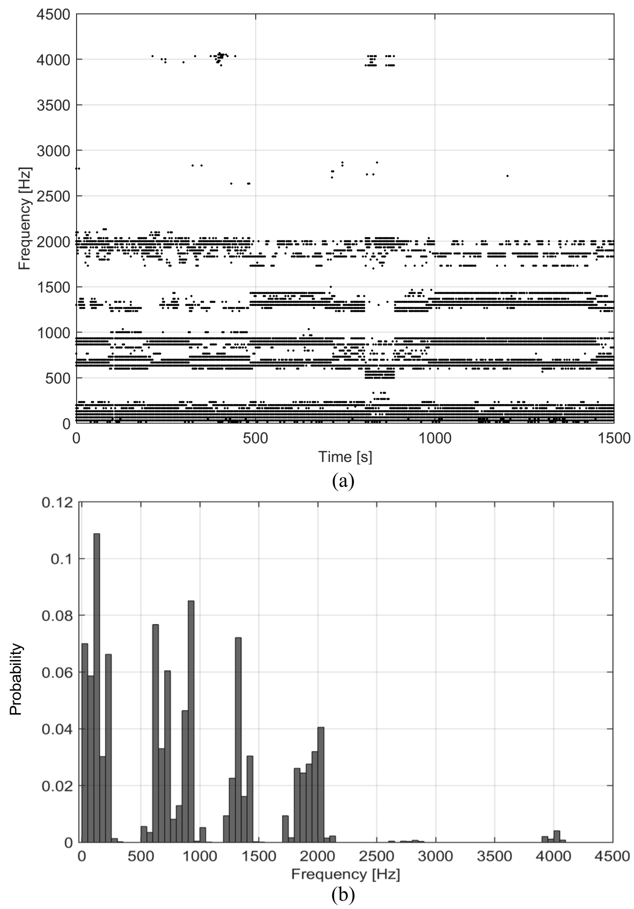

Fig. 5. Membership plot of selected harmonic power terms for the 16.7-Hz system: characteristic harmonics of converters are clearly visible. (a) Time behavior. (b) Probability distribution.

C. Impact of Harmonics on the Measured Energy

The energy values of the runs in Fig. 2 are calculated for distinguishing traction and braking phases and active power and reactive power, including in the latter the distortion terms of Section II (see Tables I–III). Energy is calculated as the sum of the power terms (active or reactive) for each phase (traction or braking) and multiplying for the power sample interval (i.e., T_{16} or T_{50}): E_{AT}, E_{AB}, E_{RT}, E_{RB} (E_{xy} with x = Active, Reactive and y = Traction, Braking). The "E" terms are based on P_1 and Q_1, and the "ΔE" terms on P and $(Q_{hF}^2 - Q_1^2)^{1/2}$. The use of the term "energy" is an abuse for reactive power but allows a uniform notation in line with the EN 50463-2: the unit of measure is Joule.

It is observed that the error percentage value is subject to slight variations depending on the type of run, the driving style, and its duration, including the distribution of the operating conditions intervals between traction, braking, etc.

A few observations may be made for the calculated energy values and the variation when all harmonic terms are included.

1) The error caused by the harmonic correction is larger for Areas 3 and 4 with lower accuracy, belonging to lower rms current values; and Area 2 accounts approximately for 5%–10% of the active power, much variable for reactive energy, and also when comparing the two systems.

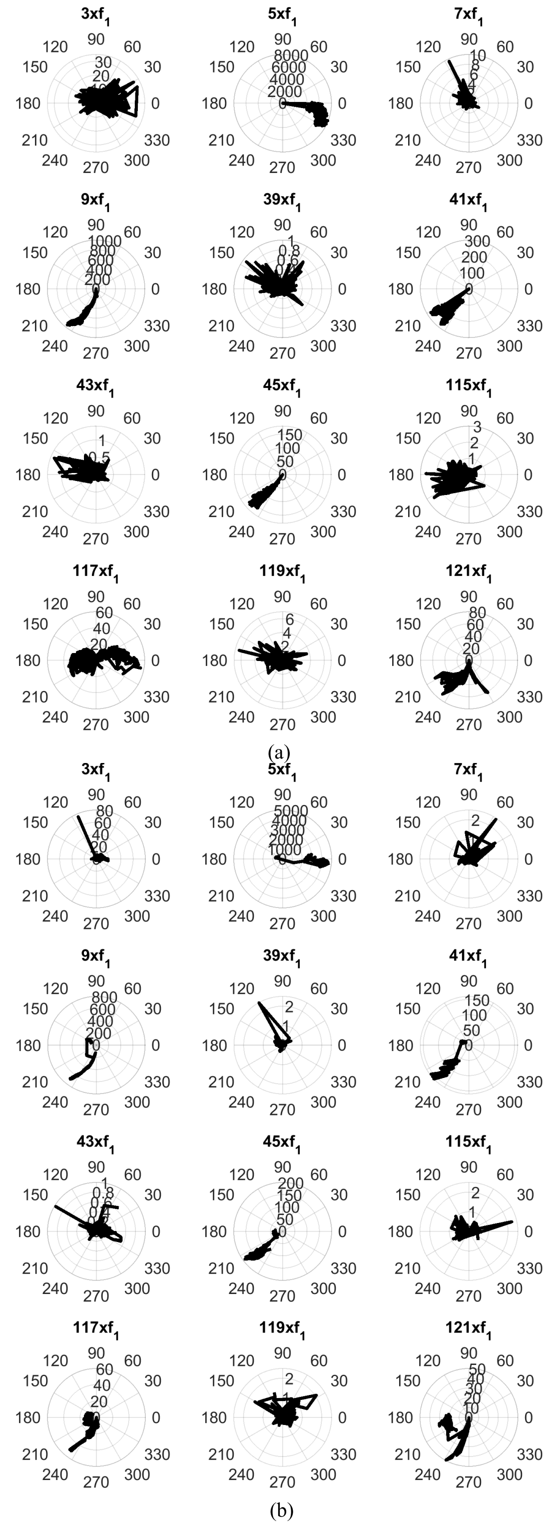

Fig. 6. Polar plot of the d_h against the absolute value of P_1 for the 16.7-Hz system. (a) Tractioning ($P_1 > 0$). (b) Braking ($P_1 < 0$).

2) The two systems behave quite differently, in that for the 16.7-Hz system, the harmonic carry more active power in Area 1, but then the 50-Hz system prevails in the other areas.

3) The error for the "active energy" is much smaller, as expected, as the harmonics carry a moderate amount of active power.

TABLE I
ENERGY VALUES AND ERROR (15 kV 16.7 Hz)

Quantity	Area 1	Area 2	Area 3	Area 4
E_{AT} [MJ]	1878.3	81.513	0.4925	0.02383
ΔE_{AT} [kJ]	4604.9	0.9059	0.04238	0.004189
err %	0.25%	0.0011%	0.0086%	0.0176%
E_{AB} [MJ]	-325.76	-33.664	-3.1726	-0.03311
ΔE_{AB} [kJ]	0.5644	0.3209	0.02350	0.004782
err %	-0.00017%	-0.00095%	-0.00074%	-0.0144%
E_{RT} [MJ]	330.83	26.078	0.5973	0.03075
ΔE_{RT} [MJ]	244.08	62.478	3.2326	0.4354
err %	73.8%	239.6%	541.2%	1415.9%
E_{RB} [MJ]	49.398	2.8379	0.1473	0.02735
ΔE_{RB} [MJ]	32.425	19.018	1.587	0.4207
err %	65.6%	670.1%	1077.4%	1538.2%

TABLE II
ENERGY VALUES AND ERROR (2 × 25 kV 50 Hz)

Quantity	Area 1	Area 2	Area 3	Area 4
E_{AT} [MJ]	2407.1	230.56	0.07933	0.01063
ΔE_{AT} [kJ]	-200.40	67.059	-0.0604	0
err %	-0.008%	0.029%	-0.076%	0%
E_{AB} [MJ]	-1007.7	-55.161	0	0
ΔE_{AB} [kJ]	-159.21	4.259	0	0
err %	0.016%	-0.0077%	—	—
E_{RT} [MJ]	372.59	195.82	0.2732	0.06089
ΔE_{RT} [MJ]	84.577	32.551	0.2253	0.05547
err %	22.7%	16.6%	82.5%	91.1%
E_{RB} [MJ]	156.83	23.129	0	0
ΔE_{RB} [MJ]	31.940	4.1008	0	0
err %	20.4%	17.7%	—	—

TABLE III
ENERGY VALUES AND ERROR (2 × 25 kV 50 Hz, TIME > 327 s)

Quantity	Area 1	Area 2	Area 3	Area 4
E_{AT} [MJ]	1696.1	158.81	0.01785	0.01063
ΔE_{AT} [kJ]	-201.40	31.553	0.02344	0
err %	-0.012%	0.02%	0.131%	0%
E_{AB} [MJ]	-991.46	-54.179	0	0
ΔE_{AB} [kJ]	-161.06	3.4416	0	0
err %	0.0162%	-0.064%	—	—
E_{RT} [MJ]	257.59	163.69	0.1456	0.06089
ΔE_{RT} [MJ]	49.868	24.929	0.1277	0.05547
err %	19.4%	15.2%	87.7%	91.1%
E_{RB} [MJ]	154.72	22.637	0	0
ΔE_{RB} [MJ]	31.092	3.9449	0	0
err %	20.1%	17.4%	—	—

4) The amount of reactive energy significantly increases if harmonics are included. Although there is no direct relationship with energy consumption, it implies higher system losses. Assuming a 1% harmonic dissipation loss in static machinery, the observed increase in reactive energy compared to the total active energy will account for about 0.1%–0.2%, so comparable to the most stringent class of accuracy of the EN 50463-2.
5) Regarding the higher distortion before the neutral section, it may be said that the changes in the energy consumption parameters are not dramatic, but a 10% reduction of E_{AT} in Area 2 may be observed.

In general, the deviations in the calculated reactive energy are significant and represent a significant uncertainty for the EMF in terms of definition of terms. For active power, the relevance of harmonics is variable: significant for the 16.7-Hz system (comparable to the most stringent class of accuracy in the EN 50463-2 [15]) and more than an order of magnitude smaller for the 50-Hz system. It is, however, observed that the 16.7-Hz system performance is the result of several items of rolling stock in the same supply section, whereas for the high-speed 50-Hz system, trains are almost always running well separated, and harmonic sources in the feeding supply section are very few. Harmonic power and energy should be analyzed more deeply with a much wider set of data to increase the significance of the results and to avoid biasing the judgment with local phenomena and singular cases.

V. CONCLUSION

The behavior of the harmonic active and nonactive power terms has been considered for two railway systems, a 15-kV 16.7-Hz system and a 2 × 25-kV 50-Hz system, extending the analysis presented in [3]. The objective is the analysis of the typical distortion patterns in ac railways and the verification of the relevance of such terms to the EMF of the EN 50463-2 standard. To this aim, the most relevant harmonic power terms have been identified and tracked over train runs longer than 25 min each: harmonic patterns of onboard converters are clearly visible, although they might be caused by trains nearby and by the network, as in the case of the 16.7-Hz system; these patterns disappear in case of major transients or when auxiliaries predominate (stops at stations).

The most relevant components with respect to the harmonic active power (index k_h) are the low-order ones (reaching consistently a value of 1%), whereas the largest values for converter patterns are in the range of 0.01%–0.1%. Values change with operating conditions, which should reflect the real exploitation of the rolling stock for a reliable and truthful assessment.

The target is the procedure of the EN 50463-2 and the EMF uncertainty with respect to the influence of factors (the harmonic power terms) not included in the approach indicated in the standard. It was shown that the exclusion of harmonic power terms from the computation causes errors of the estimate which in some cases may be significant, similar to the most stringent class of accuracy of 0.2%.

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