Uncertainty of the energy measurement function deriving from distortion power terms for a 16.7 Hz railway

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ABSTRACT
In electrified railways, harmonic active power terms can be significant in the order of the uncertainty required by the EN 50463-2 standard for power and energy measurements in railways. Nonactive power terms (encompassing reactive and distortion harmonic terms) are much more significant than the sole fundamental reactive power. This work considers the implementation of the EN 50463-2 energy measurement function, including the criteria for the significance of the measured and calculated terms, and it carries out a Monte Carlo analysis to assess the impact of harmonic power terms on the measured energy and its uncertainty.

1. INTRODUCTION

It is generally recognized that reactive power and harmonic distortion are responsible for increased losses and disturbance in distribution systems [1]-[4], from which the many Power Quality (PQ) standards, especially for low- and medium-voltage public and industrial networks. Similarly, in electrified traction systems, reactive and distortion losses may occur in the traction line and at substations, possibly also impacting the feeding high-voltage network upstream. Single-phase AC networks are known to have problems with unbalance, load fluctuation, and reactive power demand for the utility, a popular research subject in recent years [4]-[7]. Harmonics and power transients may be sources of disturbance for many systems and equipment operating in a railway context next to a traction line [8]-[10] or connected to it, such as sensing and metering equipment [11]. In particular, susceptibility to harmonics has been considered in the recent years for power and energy metering equipment and in industrial and railway applications [12][13]. Likewise, it is important to note that harmonics also contribute to active and distortion power terms relevant to an accurate estimate of power and energy consumption [14]-[20]. Energy consumption and fair billing aspects have become increasingly relevant, considering the

efforts to improve energy efficiency, especially for modern smart transportation systems [19][20] and the introduction of a complex normative for on-board energy metering [13]. Metering is achieved by measuring the electrical quantities at the interface between the load and the network: the measured voltage and current at the sliding contact supported by the train pantograph, v_p and i_p, can be used for both PQ [21]-[25] and energy metering [14]-[18] purposes.

It is generally assumed that distortion components carry little active power and they are negligible compared to the active and reactive power carried by the fundamental component. However, it was demonstrated that for ac railways harmonic terms can carry a significant amount of active and reactive (or distortion) power and need suitable characterization [14]-[16].

The relevance of the pantograph harmonic power terms should be evaluated not only in an absolute perspective (comparing to the respective quantities calculated at the fundamental only in the EN 50463-2 [13]), but also by taking into account the influence of the train operating conditions (acceleration, cruising, coasting, braking and standstill) and their rate of occurrence. In this way, the influence of the harmonic power terms on the overall exchanged energy ('consumed' and 'regenerated' energy, to use the terminology of the EN 50463-2 [13]) can be estimated. The exchanged energy is estimated with

an Energy Measurement Function (EMF) implemented on board, whichh includes the data acquisition system and the voltage and current sensors (Voltage Measurement Function [VMF] and Current Measurement Function [CMF]) and the consequential Energy Calculation Function (ECF), using v_p and i_p as an input.

The EN 50463-2 [13], when specifying the limits of accuracy, is clearly written in terms of nearly sinusoidal waveforms, with power and energy calculated only taking into account terms at the fundamental (see e.g. the indication of 'maximum phase displacement at rated frequency'). Harmonics are considered as a disturbance from which the immunity requirements, common to the EN 50470-1 standard [12], are defined and subject to a considerable amount of research [26]-[28].

The economic impact of fractional energy saving with a magnitude commensurate to the observed variability caused by harmonic power terms is definitely worth better comprehension of the problem. As pointed out in [14]-[16], using waveforms measured during tests in some European railways [22], the magnitude of the identified harmonic power terms is indeed relevant for the uncertainty budget.

It is the objective of this work 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. It is evident that the ECF and EMF uncertainty is influenced not only by the metrological characteristics of the VMF and CMF chains, where sensors and acquisition systems are located, but also by the adequate and comprehensive definition of the objective quantities (power and energy) and their relationship with the basic quantities (pantograph voltage and current and their spectra).

2. HARMONIC POWER QUANTITIES

The quantities of the problem are briefly introduced and clarified here. IEEE Std. 1459 [29] has been selected as the most useful source of the definition of power terms. The total apparent power in nonsinusoidal conditions is obtained by the multiplication of the two voltage and current vectors, expressed as a Fourier series in the time domain or, equivalently, as a vector of harmonic components in the frequency domain of order h referring to the fundamental pulsation ω, both with the information on amplitude V_h and I_h and phase α_h and β_h (for the sake of compact notation, the pedix 'p' for 'pantograph' is dropped from the harmonic components, transformed vectors, and power terms).

$$v_p = V_0 + \sqrt{2}\sum_h V_h \sin(h\omega t - \alpha_h) \qquad (1)$$

$$i_p = I_0 + \sqrt{2}\sum_h I_h \sin(h\omega t - \beta_h) \qquad (2)$$

Active and nonactive power terms may be conveniently separated using Equations (4) and (5) of the time-referred nonactive power p_q in [30]. In Equation (3), the active power terms appear for the fundamental P_1 and each harmonic P_h. In Equation (4), the expression for the nonactive power terms is more complex, including products with harmonics of different orders and with the fundamental:

- The first term is the harmonic reactive power Q_h.
- The second term is a set of mixed products that define distortion power D_h and involve both fundamental and harmonics (decomposing the term further does not provide

any useful information and reopens the discussion on the interpretation and the physical meaning of the terms).

- The last two terms, beginning with V_0 and I_0, are the contributions in the presence of DOC components, which in AC railways may be assumed to be zero, except during transients.

$$p_a = \sum_h V_h I_h \cos\vartheta_h [1 - \cos(2h\omega t - 2\alpha_h)] \qquad (3)$$

$$p_q = -\sum_h V_h I_h \sin\vartheta_h \sin(2h\omega t - 2\alpha_h) +$$
$$+ 2\sum_m \sum_{m\neq n} V_m I_n \sin(m\omega t - \alpha_m)\sin(n\omega t - \beta_n) + \qquad (4)$$
$$+ V_0 \sum_h I_h \sin(h\omega t - \beta_h) + I_0 \sum_h V_h \sin(h\omega t - \alpha_h)$$

EN 50463-2 for AC railways requires the measurement of both active and reactive power in traction and braking conditions (identified in this work as the 'output quantities' of the standard). Correspondingly, four energy terms are defined. Although the definitions of such terms are given for the fundamental frequency, harmonics can be included in a straightforward manner:

- Active power terms at the fundamental P_1 and harmonics P_h can be readily summed, all contributing to the total active power P_t and then to the energy defined for it.
- Nonactive power terms are considered in terms of absolute value to indicate the amount of power (and then current) exchanged, so we may sum (by the rooted sum of squares) all these reactive and distortion power terms to get an indication of the total nonactive power Q_t and the energy defined for it.

These quantities will be calculated with a frequency domain approach, using the Discrete Fourier Transform (DFT). The DFT is calculated on each 60 ms cycle of v_p and i_p (the fundamental being 50/3 Hz). The calculation of power quantities based on time records accounting for a single cycle or less are described well in [37]. A standard tapering window may be used to limit the effects of spectral leakage, which in such applications is caused by two factors: i) v_p and i_p waveforms suffer from slow fluctuations caused by the load changes and the reaction of active loads, causing a slight low-frequency modulation effect so that a slight difference between the two ends of the record may occur and ii) the instantaneous frequency of the fundamental varies as a result of various types of instabilities [31][32]. The transformed harmonic spectra V and I (subscript 'p' has been removed to keep the notation compact) are then 'cleaned' to remove noise components from the analysis, 'pruning' the components against a threshold determined to select components with a significant harmonic active power, as clarified in Section 3.

The active and nonactive power terms and the energy quantities calculated from V and I are detailed and further discussed in the next section.

3. ENERGY MEASUREMENT FUNCTION

The EMF is simply the calculation of cumulated power terms, either active or reactive power. The EN 50463-2 requires that the terms for the traction and braking phases (with positive and negative input current i_p, respectively) are calculated separately, thus resulting in four energy terms: E_{AT}, E_{AB}, E_{RT}, E_{RB} (E_{xy} with x = active, reactive and y = traction, braking). The calculation

must comply with the EN 50463-2 standard criteria, expressed for the fundamental rms of the quantities:

- *Area* 1: Full accuracy is required for $I_p \geq 10\ \%\ I_n$, with I_n being the locomotive nominal current. This accuracy is specified as the maximum error of the calculated energy and depends on the class, variable between 0.2 % and 1 %; for $V_p < U_{min1}$ of EN 50163 [33], the required accuracy is the same for Area 2.
- *Area* 2: For I_p between $1\ \%\ I_n$ and $10\ \%\ I_n$, the required accuracy is relaxed by a factor of two.
- *Area* 3: For I_p between $0.4\ \%\ I_n$ and $1\ \%\ I_n$, the energy measurement is required but with an unspecified accuracy.
- *Area* 4: $I_p < 0.4\ \%\ I_n$ – no energy measurement is actually required (in Table 16 of EN 50463-2, it is written 'if energy is measured, no accuracy requirements'). Consequently, no accuracy requirement is specified.

Based on these four 'areas', we calculate the energy quantities separately for each area (indicating the quantities with an appended index $i = 1...4$, such as $E_{xy,i}$) in order to assess the respective uncertainty impact. The energy quantities are then aggregated by simplifying the index i in order to make an overall final energy estimate.

Going back to the definition of the power terms for the calculation of the energy, the definitions in Section 2 are followed using the harmonic vectors V and I. The sum of the fundamental and harmonic active power terms (P_1 and P_h, $h \geq 2$) gives the total active power P_t. The sum of the reactive and distortion power terms (Q_1, Q_h and D_h) gives the total reactive power Q_t.

A threshold is used to prune the harmonic vectors, avoiding the issue of noise contributing to the sum and thus negatively influencing the estimate of uncertainty. The threshold is determined using the fundamental active power as a reference, as explained in [14], Section II.B: Considering the $0.4\ \%\ I_n$ threshold of Area 4, assuming that the maximum 40 harmonic terms of equal amplitude add to the harmonic active power, the selection criterion is $P_h \geq 0.01\ \%\ P_1$.

4. UNCERTAINTY FRAMEWORK AND MONTE CARLO

A Monte Carlo analysis is performed for the calculated energy terms described in Section 4.1 using the measured spectra and the calculated active and non-active power terms described in Section 4.2. As explained in Section 4.3, the spectrum components are not independent, and their joint probability would be very difficult to determine. For this reason, replicated versions of the measured spectra are used, keeping the correlation between components typical of the real system and applying a random disturbance to the vector components similar to the one estimated based on the measured data. In other words, the available measured and selected cycles (about 2000) are augmented using the observed variability as a model.

The energy is calculated with the EMF in compliance with EN 50463-2 using the same criteria and thresholds shown in Section 3.

4.1. Uncertainty of the EMF

The EN 50463-2, in defining the reference conditions for the assessment of the metrological performance, indicates reference values for the influence quantities, among which Table 2 of the standard lists the harmonic distortion of the v_p and i_p waveforms themselves. Considering the immunity to harmonic distortion, with a permissible tolerance of 2 %, it is clear that the usual

distortion of 16.7 Hz railways is underestimated [22], with values up to 3 % being quite typical for the voltage and up to 8 % being typical for the current. Conversely, the distorted waveforms used to test the energy meter immunity by far overestimate it: 10 % in voltage and 40 % in current for the 5th harmonic in the verification of influencing quantities, 10 % to 30 % of the 3rd, 5th, and 7th harmonic in the phase-fired waveform test, both specified in EN 50463-2 [13].

The percentage error limits for the EMF appear in Table 3 of the EN 50463-2 and amount to 1.5 % and 3 % for active and reactive energy: the accuracy class of the VMF, CMF, and ECF must be selected accordingly. EN 50463-2, assuming that the errors ε in the VMF, CMF, and ECF are independent, states that the error of the EMF is the root-sum-square combination:

$$\varepsilon_{EMF} = \sqrt{\varepsilon_{VMF}^2 + \varepsilon_{CMF}^2 + \varepsilon_{ECF}^2} \tag{5}$$

The VMF comes in four possible classes of amplitude accuracy: 0.2 %, 0.5 %, 0.75 %, and 1.0 % for $U_{min1} \leq V_p \leq U_{max2}$; when $U_{min2} \leq V_p \leq U_{min1}$, the values are doubled. Correspondingly, the phase accuracy at the fundamental is 10, 20, 30, and 40 minutes for the first interval and 15, 30, 45, and 60 minutes for the second lower-voltage interval.

Similarly, for the CMF, four classes of accuracy are specified: The basic reference values are again 0.2 %, 0.5 %, 0.75 %, and 1.0 %, and they apply to $10\ \%\ I_n \leq I_p \leq 120\ \%\ I_n$, but the interval of *Area* 2 is then split into two subintervals, for $5\ \%\ I_n \leq I_p \leq 10\ \%\ I_n$ and $1\ \%\ I_n \leq I_p \leq 5\ \%\ I_n$, the first with a doubled accuracy limit and the second with an increase of five times.

The uncertainty for the active and reactive power terms at the fundamental is calculated explicitly in Annex B of EN 50463-2. The calculation is carried out with some simplifying assumptions (e.g. invoking the small phase difference between v_p and i_p vectors) in order to reduce the number of terms and thus the complexity of expressions.

However, including the effect of harmonic power terms in the analytical calculation of uncertainty requires significant effort. Not only is there an increase in the size of the expressions to replicate what has been done for the fundamental to the H harmonic terms, but cross-products between harmonics of different orders (resulting in the distortion power D_h) must also be considered. Then, the non-linearity introduced by the thresholds on the voltage and current for the definition of the four areas needs to be considered as well, although it is of marginal impact (it influences the results only for very small values of voltage and current, whereas most of the relevant values are expected in *Area* 1). A Monte Carlo approach, instead, is able to cope with the complexity of the system. It should be noted that for the generation of the input patterns at each trial, attention must be given to correctly determine the correlation between the harmonic components of the same vector and between v_p and i_p. They are, in fact, correlated to the train operating conditions and to the intensity of the traction and braking effort.

4.2. Experimental data

The analysis is based on measurements performed along the Swiss network (15 kV, 16.7 Hz) [14][22][23]. The measurement system was implemented with a Rogowski coil, a capacitive voltage divider on the locomotive roof next to the pantograph line, and a Dewetron 16-bit digitizer, using a sampling rate of 50 kS/s. The system was protected by low-pass filters on each

channel and overvoltage suppressors terminating on a solid effective local ground, represented by an equipotential metallic plate. The uncertainty of the digitizer (< 0.1 %, including one bit for over-range) is negligible in relation to the goal of the present analysis. The current and voltage sensors account for 3 % and 1.4 %, but repeatability is an order of magnitude better. The line (Zurich-Brig) was subject to intense traffic, so there are mixed harmonic terms of internal (the locomotive used for the measurements) and external (other trains in the same supply section) origin. The used loco was a Siemens Re460 in normal commercial service.

The measured v_p and i_p waveforms are used to derive the harmonic spectra and calculate the harmonic power terms. These terms are the input to the evaluation of uncertainty.

Data are organized in the measured harmonic vectors H of index n ($H_n = [V_n \ I_n]$), each tagged with a given operating condition oc, traction or braking intensity int, and speed sp (the state vector $s_n = [oc_n \ int_n \ sp_n]$). As anticipated, the harmonic components of each vector are not independent, as they are all tagged under the same state vector s_n, and the probability is very high, such that in a similar state, they will replicate with similar amplitude and phase conditions. Conversely, harmonic vectors associated with different operating conditions will show less similarity, as pointed out in [34], Figure 10 – a graphical representation of such differences.

An overview of the data behaviour using a persistency plot is given in Figure 1. The voltage waveform is quite stable, with a peak-to-peak spread of 2 kV, so 10 % of the full range, visible at the top (and bottom) of the curve. The current intensity is evenly distributed between low values for coasting and standstill, and large values for intense traction and braking.

Figure 2 shows the distribution of the measured records in terms of the mentioned state vectors, showing the correlation between the speed and the flowing current, either absorbed (traction) or regenerated (braking). At a low speed, a small positive current corresponds to the initial acceleration at a standstill. At a high speed, further acceleration requires a large current, as indicated by the current intensity at about 300 A. The

likely braking current, at a speed of 80 to 100 kmph, corresponds to initial deceleration from cruising at commercial speed.

The measuring instrumentation can achieve the 0.2 % accuracy most stringent requirement of the EN 50463-2 for the purpose of this analysis: the overall uncertainty voltage and current probes is of 1-3 % ($k = 2$), including the impact of installation that is predominant, but repeatability is more than an order of magnitude better [22].

4.3. Monte Carlo method

The components of the harmonic vectors are not independent: depending on the specific state condition, the internal components will align with a more or less precise pattern of emissions; additionally, external components will behave independently, depending on the state conditions of other trains or injected by the feeding network. When the input quantities are not independent, for the assessment of uncertainty they must be accompanied by the mutual probability between each pair of them, contained in a covariance matrix [35], sec. 5.2. This approach is complicated and, as anticipated, has few chances to work in practice, as the harmonic components have different origins.

A different approach is thus followed here: all the harmonic components of the spectrum of one record can be applied at once, preserving the underlying correlation between them as resulting from the evidence of the measured data. Randomness is ensured by treating each harmonic component as a random variable with a distribution estimated from the original data.

The state vectors are clustered selecting a certain number of bins for each of the three components: $b_1 = 3$ for the operating condition, distinguishing positive and negative current for tractioning and braking, and situations of null speed and low current for standstill; $b_2 = 16$ for the effort intensity int (8 positive for tractioning and 8 negative for braking); $b_3 = 8$ for the speed sp. The combination of three bins defines a cell. The set of N records is then reduced to $M = b_1 \ b_2 \ b_3$, following the clustering of the state vector: each cell is linked to the original records, but is also loaded with the resulting relative frequency (given by the number of state vector components clustered under
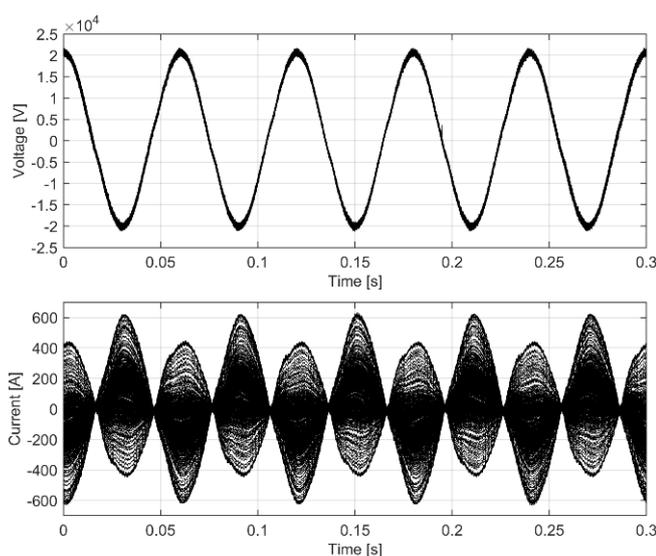
Figure 1. Time-amplitude distribution of synchronized 5-cycle snippets: larger intensity during braking can be recognized, as well as a displacement factor close to unity (clean zero-crossings of the current in correspondence of the voltage zero-crossings).
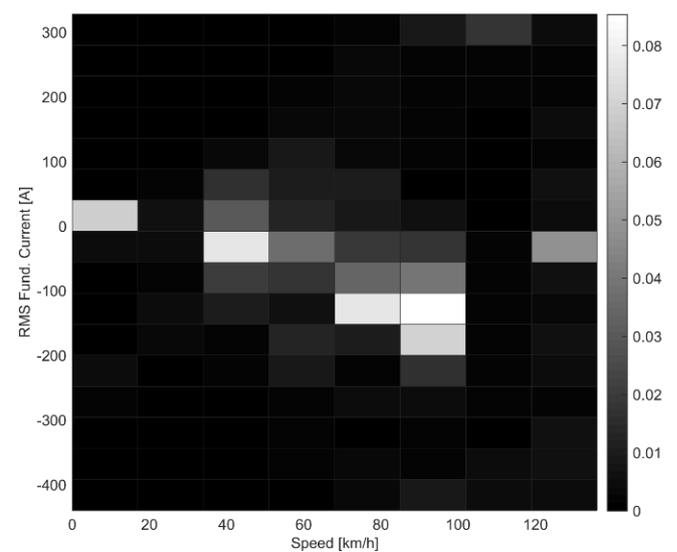
Figure 2. A histogram of the fundamental rms current and speed, showing standstill (almost 0 speed and 0 current), the wide range of braking at various speed, with intense braking when decelerating from a cruising speed of 120-140 km/h, and intense accelerations (300 Arms at 80-120 km/h) that last for short time intervals.

the same cell) and with the estimate of the probability distribution of amplitude and phase of each harmonic component. To this aim it is understood that the number of records clustered into a single cell must be sufficient to achieve statistical significance. As shown in Figure 2, many cells are empty because a particular combination of *oc*, *int*, and *sp* is either unlikely or impossible, e.g. at standstill, the speed is 0, and the current is very low, supplying only the auxiliaries. Furthermore, coasting and cruising are extremely rare at a low speed, only in the case of traffic problems. Referring to the specific case shown in Figure 2, only about 50 % of the cells contain data (about 200 samples), 20 % of which have prevailing amplitude (as indicated by the white and light coloured cells).

With random sampling and an a priori determination of the Monte Carlo trials, the number of trials K for a given coverage probability p can be determined based on the Guide of Uncertainty in Measurements [35]:

$$K > \frac{10^4}{1-p} \tag{6}$$

For $p = 95$ %, the minimum number of trials $M = 2 \cdot 10^5$.

5. RESULTS

The calculated EMF values consist of four energy values: active energy during tractioning E_{AT}, active energy during braking E_{AB}, reactive energy during tractioning E_{RT}, and reactive energy during braking E_{RB}. Correspondingly, four energy terms are calculated for the contribution of harmonic power terms, calculating the harmonic active power terms into E_{AT} and E_{AB}, and the nonactive harmonic power terms into E_{RT} and E_{RB}, quantifying their contribution by a 'delta term' with the same naming convention. In order to assess the relevance of the harmonic power terms, the focus is on the average impact on the respective energy term and on the estimated dispersion. The results are synthesized in Table 1.

The Swiss system shows a peculiar behaviour whereby the active power in traction conditions would be lower if harmonics are included in the calculation. This occurs for braking, which features a higher harmonic distortion and has a reverse power flow. In addition, a peculiar behaviour of the 3rd harmonic (50 Hz) should be also accounted for, being both a network supply harmonic and the result of the leakage of the onboard auxiliaries, which work at 50 Hz and not at the traction fundamental (50/3 Hz = 16.7 Hz).

In general, however, it is apparent that the harmonics in the Swiss system contribute a non-negligible but moderate active power (in the range of 0.3 % to 1.26 % for the Area 1 and Area 2

figures, which are the most relevant, following the approach of the EN 50463-2). These mean values are supported by the estimated standard deviations of the same order, showing that the distributions are moderately dispersed.

What is relevant is the amount of nonactive power carried by the harmonic terms, which is an order of magnitude larger than the reactive power at the fundamental Q_1 for Areas 2 to 4, and comparable to Q_1 in Area 1. This implies that neglecting harmonic nonactive power largely underestimates the nonactive power flow, the current exchange, and power losses in the system. The nonactive power mean values have significant dispersion, indicating that there are several factors affecting their value and distribution: the vehicle's overall operating condition; the traction and auxiliary converters' operating points; the influence of the traction line impedance; and its resonant behaviour and that of other trains nearby in the same supply section.

In addition, it should be noted that while rolling stock is limited in order for the displacement factor at the fundamental to be inductive, there is no such limit for harmonic terms, for which capacitive behaviour is also possible, with the consequence of network instability and resonances.

6. CONCLUSIONS

Active harmonic power terms for the power and energy budget of railways are significant comparable to the required uncertainty and accuracy classes in the EN 50463-2 standard. Conversely, nonactive harmonic power terms are much more relevant and account for an exchange of nonactive power – several times – occurring at the fundamental, for which limits of input displacement factor are applicable.

In the EN 50463-2 standard, the assessment of uncertainty is carried out analytically for the active and reactive terms at the fundamental. However, the assessment of the relevance of harmonic power terms and the impact of their variability is much more complex and cannot be carried out analytically.

In this work, the active and nonactive power terms above the fundamental of a 16.7 Hz system were considered. The approach to the estimation of the uncertainty of the energy terms (otherwise defined at the fundamental per EN 50463-2) is indirect: A Monte Carlo analysis is used, based on the observed distributions of the voltage and current harmonics at the pantograph, derived from the measured data. The distributions are derived from the datasets measured and collected during the testing days on the Swiss network, taking into account the locomotive operating conditions, the speed, and the effort during tractioning and braking (called the 'state vector'). The considered data thus form a snapshot of the rolling stock and network conditions for one of the busiest lines in Switzerland. Statistical distributions for feeding to the Monte Carlo analysis are derived using a hybrid approach: The distribution of each component is estimated based on the clustered data for each operating condition (traction/braking/standstill, power absorbed /regenerated, and speed), whereas the correlation between components is indicated by the average spectrum vectors for each operating condition and between operating conditions.

The results confirm that the harmonic active power terms influence the EMF and the calculated energy by an amount similar or slightly larger than the required uncertainty. The nonactive energy terms are much larger than that which is calculated on the reactive power at the fundamental, and they should be specifically addressed concerning their correct

Table 1. Ratios of harmonic energy quantities to the corresponding ones at the fundamental, as average and standard deviations (E_{xy} with x = active, reactive and y = traction, braking).

Quantity		Area 1	Area 2	Area 3	Area 4
$\Delta E_{AT}/E_{AT}$	av.	-0.0025	-0.0155	-0.0623	0.0253
	s.d.	0.0016	0.0123	0.0463	0.0620
$\Delta E_{AB}/E_{AB}$	av.	0.0028	0.0126	0.1098	0.1010
	s.d.	0.0013	0.0141	0.0973	0.0976
$\Delta E_{RT}/E_{RT}$	av.	1.5027	40.388	8.3024	10.6219
	s.d.	2.0311	354.06	4.2682	1.2378
$\Delta E_{RB}/E_{RB}$	av.	0.9261	8.7617	10.2674	39.0149
	s.d.	0.4377	74.6449	23.0604	55.6961

interpretation and management, as their values are well beyond any values that might be interpreted as EMF 'uncertainty'.

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