Statistical evaluation of measured voltage spectra in DC railways

Andrea Mariscotti

*Università di Genova, DINAEL, Via all'Opera Pia, 11A – 16145 Genova – Italy,
tel. +390103532169, fax +390103532700, andrea.mariscotti@unige.it*

*Abstract-*The problem of the evaluation of the Power Quality of railway networks is presented, focusing on the specific characteristics of DC railway networks, dominated by the characteristic and non-characteristic harmonics of the rectifier substations. Reference is made to the measurement data of the pantograph voltage and current taken on the Italian network; the results are then the aggregate statistical description by means of histograms and Fourier spectra.

I. Introduction

The broad term Power Quality encompasses voltage distortion and voltage waveform deformation during transients and network resonances. These phenomena have influence on focused technical problems, such as the correct sizing of locomotive input filters, the design of on-board static converters and control systems and the possible interference to signalling devices. A more general problem is that of electrical interoperability, that aims at ensuring the safe and efficient circulation of trains across different railway networks in different countries looking at the electrical issues. The Power Quality (PQ) is one of the most complex, since it involves several systems: the Traction Line (TL) and Power Supply (PS), the Rolling Stock (RS) and also the Signalling system, if the aspects of coupled disturbance and electrical or electromagnetic compatibility are included. The interaction between the TL and PS and the RS is responsible for (as identified in the EN 50388 standard [1]):

- voltage distortion due to RS conducted emissions and TL impedance at RS pantograph, extended in principle to all the trains circulating on a given section;
- possible distortion amplification and overvoltages due to line resonances;
- overvoltages produced by possible instabilities of modern on-board converters and control systems under particular circumstances.

The first item, seen as the combined effect of the ESSs and trains connected through the TL across a given railway network portion [2], may be addressed also as a supply voltage limit issue. The second item is in close relationship with the first one, since line resonances cannot be really separated by the line itself, except for a distinction of the frequency range where they occur with respect to the supply harmonics: the geometrical resonance of a line section between two Electric Substations (ESS) is located between one and few kHz, while resonances at lower frequency may originate in larger networks with interactions and loops between different portions of the network, that for DC railways are excluded, thanks to the decoupling operated by the rectifiers and their filters [2][4]. The third item is a complex task, whose simulation requires the accurate modeling of on-board converters and their inclusion in the network model and is beyond the present scope.

The modeling of the TL and PS [5][6], even if correctly supported by the correct per-unit-length values of the TL conductors and the equivalent circuits of connected elements, must cope with real world observations, where – to cite some – the real damping at TL resonances is influenced by the PS and RS elements, the sharing of the return current highly depends on the frequency, on the grounding method and on soil properties, the propagation and composition of RS emissions need to be understood depending on the synchronization properties and phase delay [7]. These observations are also relevant when sensible assumptions on the overall testing and modeling conditions must be defined: several parameters feature a range of admissible, even if unlike, values; worst case analysis, maybe helped by Monte Carlo simulations, is very attractive, but may produce unrealistic results, too expensive in view of their consequences, since they lead to unnecessary or overestimated countermeasures.

The measurement data used for the following analysis were recorded on the Italian DC 3 kV network (the conventional line, not the high speed line) within the activities of the EU project RAILCOM during 2008 [8]. The relevant aspect of this kind of measurement extended to very long lines and significant portions of a national railway network is that the evaluation relies solely on the measured local loco variables and not on the variables recorded at the several electric substations along the lines themselves.

II. The measurement system

The measurement system is composed of a Digital Acquisition System (DAS) and voltage and current probes, for the measurement of the pantograph voltage and current. The related metrological performances may be synthesized as:

- frequency range, extending from a few Hz up to 20 kHz, so that the usual operating frequency bands of signalling devices are included and several line resonances and harmonic components may be observed to ascertain the harmonic pattern; the sampling frequency is thus set to 100 kS/s for the considered measurement data;
- full scale, that includes the fundamental voltage and current components, even if they are then discarded for visualization purposes; the voltage full scale is only a matter of saturation of the DAS channel; the current full scale derives also from the range capability of the current probe and for a DC railway system at 3 kV the absorbed current may be very large, up to about 3 kA;
- sensitivity, that is due to the combination of the sensor noise and any internal hysteretic behavior or residual offset, and the DAS quantization noise (negligible for a 16 bit DAS);
- accuracy, that defines the quality of the above error statements, and that for the considered recordings is about 1% at $k=2$.

In addition, considering the specific use and environment, other features requested in general to such a measurement system are robustness, ease of use and reliability.

III. The DC 3 kV railway system

The measurement system was run on the Italian railway network, supplied at 3 kV DC. This railway network is supplied by several electric substations (ESSs) equipped with two (or more) rectifier groups, fed each by a double secondary winding transformer with star-delta connection on the secondary side, so to ensure the so called twelve pulse reaction; the twelve pulse reaction, thanks to the phase rotation between the two secondary winding of 30° electrical degrees, ensures that the characteristic harmonics on the AC side current are of the type $12k\pm1$ and those on the DC side voltage are of the type $12k$, with k integer. The transformer primary winding is connected to the High Voltage network usually at 132 or 150 kV; the most common rated power is 5750 kVA and the rated voltage at no load is 3600 V. The operations and several characteristics of DC ESSs are reported in detail in [9]. The rectifiers have a resonant LC filter connected in parallel at the DC side terminals, tuned on a nominal resonance frequency of 100 Hz, that undergoes a slight shift due to the additional loading of the traction line and any locomotive at the output [10].

For practical reasons the harmonic pattern of the DC output voltage $V_{ESS}(f)$ features both characteristic and non-characteristic harmonics due to the following factors:

- imperfect twelve pulse reaction, due for instance to asymmetry of the secondary windings, responsible for residual characteristic harmonics of the type $6k$, with k odd integer;
- negative sequence component at supply frequency on the HV input line, that produces non-characteristic harmonics of the type $2k$, and in particular the one at 100 Hz, enhanced by the resonant behavior of the ESS filter;
- other harmonics on the HV input line, that produce higher order even harmonics on the DC side.

These factors may vary from ESS to ESS and over different times of the day. A train travelling on the line and getting power from different ESSs will thus experience a slightly variable pantograph voltage spectrum $V_p(f)$. It is underlined that $V_p(f)$ doesn't correspond exactly to $V_{ESS}(f)$, since the voltage drop on the traction line between the two depends on the absorbed current spectrum $I_p(f)$, on the respective position and on the frequency too. Analogously the DC pantograph voltage $V_p(0)$ differs from the ESS output voltage $V_{ESS}(0)$; it is particularly relevant in terms of "available useful voltage", a parameter used for interoperability assessment [1].

The present analysis aims at establishing the statistical properties of the pantograph voltage by analyzing the statistical distribution of the most significant components.

IV. Assessment of the statistical properties of the pantograph voltage

By recalling the main features of DC lines listed above, for the pantograph voltage V_p it is expected that:

- the relevant harmonic components include at least 100 Hz, 150 Hz, 200 Hz, 300 Hz, 600 Hz and 1200 Hz;
- the 100 Hz is amplified by the resonance of the output DC filter as already explained in [10];
- other components may be present due to the influence of the same rolling stock where the DAS is installed.

A. Statistical representation

The statistical properties of the V_p spectrum are here analyzed with the help of a series of measurements taken on the Florence – Rome line, characterized by a very high cruise speed and very large current at the limit of the ESSs capability. The total measurement time is approximately five hours over four days of tests; the FFT time window T=0.1 s (so with frequency resolution df =10 Hz), for a total of M=163554 time windows.
The geographical location of the measured line section is shown in Figure 1.

Figure 1. Geographical location of the considered line, between Florence and Orte on the Florence-Rome line

The aggregate results of the statistical analysis are shown below in Figure 2 and Figure 3, where on the left for each frequency bin of the spectrum the corresponding histogram is displayed and on the right only the most relevant supply harmonics and their pdf are considered.
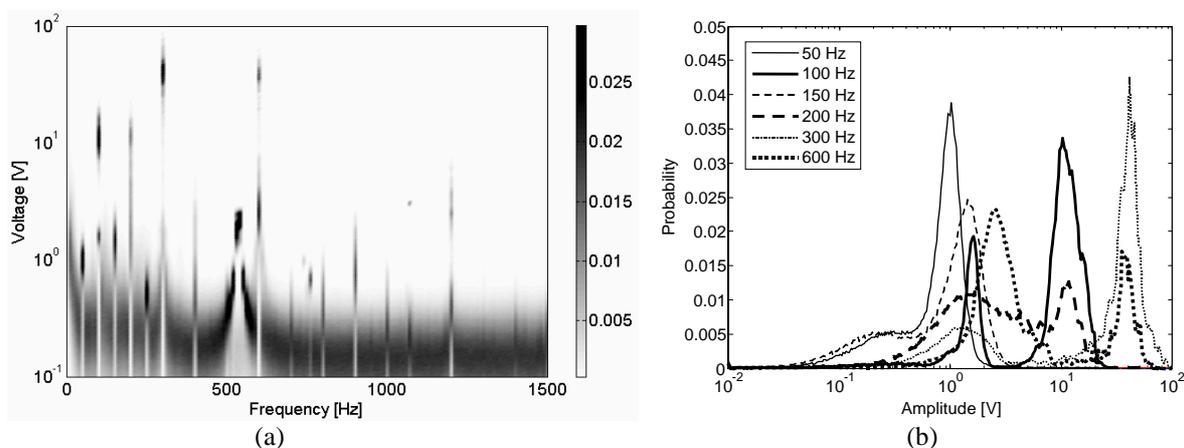

Figure 2. (a) Pantograph voltage spectrum distribution and (b) histograms of selected supply harmonics

The supply harmonics are clearly visible and are repeated in the right hand side graph:
- the two harmonics at 100 and 600 Hz show two peaks in their respective pdfs; if the thing may be explained for the 100 Hz component, by observing that it depends on the negative sequence 50 Hz component on the High Voltage AC side, the explanation of such behavior for the characteristic component at 600 Hz is not yet clear;
- the other supply harmonics at 50 and 150 Hz has a clear unimodal pdf;
- the 200 Hz component has a broad pdf, since it is produced by different mechanisms that have variable relevance along the explored railway line.

The frequency component at 520 Hz, that features a significant bandwidth and some frequency leakage, is in relationship with the same locomotive that hosts the DAS and its on-board converters.
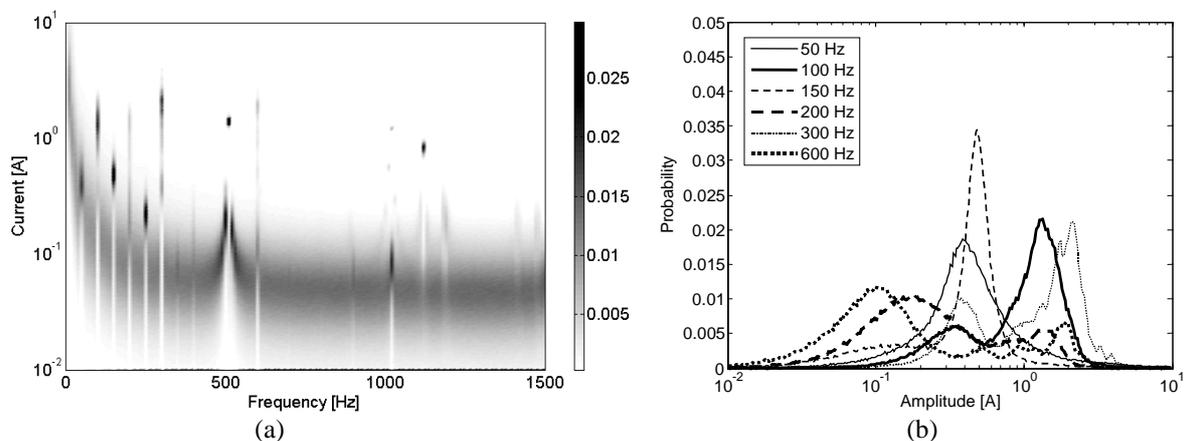

Figure 3. (a) Pantograph current spectrum distribution and (b) histograms of selected supply harmonics

The same frequency components may be observed in the spectrum of the absorbed current (Figure 3), but with different amplitudes and distributions; in particular, the 600 Hz current component is smaller than the 300 Hz component, with respect to a similar amplitude of the two corresponding voltage components, due to the larger inductive reactance.

B. Comparison with theoretical results

The relationship between the DC side characteristic harmonics V_n, with $n=6h$, h integer, and the nominal DC output voltage V_{d0}, under the assumption of a perfectly flat output current, is [11]:

$$V_n = V_{d0} \frac{1}{n^2-1} \sqrt{(n-1)^2 \cos^2[(n+1)\mu/2] + (n+1)^2 \cos^2[(n-1)\mu/2]} \tag{1}$$

for the firing angle delay $\alpha=0$, as it is for natural commutation rectifiers. The value V_n highly depends on the value of the commutation overlap angle μ, so (1) is plotted below in Figure 4 for some common values of μ.
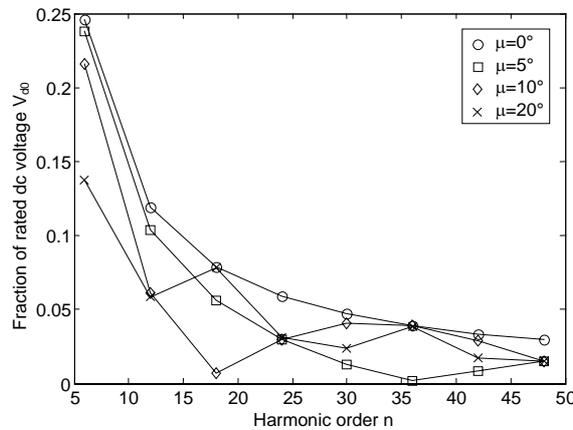

Figure 4. Theoretical amplitude of characteristic harmonics $n=6h$, h integer, for some overlap angle μ values

From Figure 4 for a rectifier operating with only 6-pulse reaction, it is expected a 6th harmonic V_6 ranging between 14 and 25% of V_{d0}, that is V_6=504-900 Vrms, and a 12th harmonic V_{12} ranging between between 6 and 12% of V_{d0}, that is V_{12}=216-432 Vrms. A 12-pulse operated rectifier produces ideally a 12th voltage harmonic V_{12}, with the same amplitude as above, with no 6th voltage harmonic; by practical considerations concerning the feeding transformer asymmetry (in turns ratio and reactance of each winding) and past experience it is expected a 1-2% of V_{d0}, that is V'_6=36-72 Vrms.

If the LC resonant filter attenuation is taken into account, the following simplified reasoning applies [4]: the filter has a tuning frequency of about 100 Hz (108 Hz at no load, lowering if the additional line reactive terms are considered) and then a roll-off starts with a slope of 40 dB/decade, so at 300 Hz (3 times above 100 Hz) an attenuation of 0.11 is expected and at 600 Hz (another octave above 300 Hz) the attenuation becomes 0.028. This first evaluation doesn't take into the due consideration the factor of merit of the filter and that the attenuation curve stays above that of a perfectly damped filter for approximately two octaves above the resonance frequency. The two attenuation values computed with the correct filter transfer function are then 0.15 and 0.03. The new ranges for the two main characteristic harmonics are thus V_6=75.6-135 Vrms and V_{12}=6.55-13 Vrms. Moreover, these attenuation values are valid only for the pantograph voltage in front of the ESS itself, where the additional line voltage drop is negligible; for any other position along the line the attenuation is larger but cannot be computed a priori, since it depends on the absorbed pantograph current. For example, at 100 Hz, by assuming an average 1 Arms absorbed current (as shown above in Figure 3) and a line impedance of approximately 1 Ω/km, a reduction of 1 V/km with respect to the theoretical value is expected. For the 600 Hz component the line impedance may be assumed simply six times larger; the absorbed current is broadly varying and the voltage drop may range from 0.5 to 12 V/km,

With reference to Figure 2, taking into account that the current sourced by the ESS is normally large on the considered lines and that thus the commutation angle is one of the largest attainable, the distribution of the 300 Hz component between 20ᵒ and 90 V matches the theoretical value, under the assumption that the rectifiers have only 6-pulse reaction; the 600 Hz component has a bimodal pdf, where the smallest value matches the lowest theoretical value (again corresponding to a large commutation angle), while there is no explanation for the largest value, set to the same values of the 300 Hz component. The harmonics on the AC side that could produce

an additional 600 Hz component to sum to the pre-existing characteristic harmonic would be the 11th and 13th, but the required amplitude would be unpractical. In fact, as an approximation the relative amplitude on the AC side transfers as 0.707 that amplitude on the DC side; this means that the required AC side harmonics should have a relative amplitude of 15-20%! Another explanation may be that the filter capacitor of one ESS is disconnected or faulty and this almost cancels out the filter attenuation, except for the voltage drop on the series inductance.

The analysis was then refined to better identify the unusual 600 Hz value and to put it in relationship to a specific recording and thus to a specific ESS. The recordings on the same line section taken at different days and positions were separated, and the harmonic distributions were clustered in the main exceptional behaviors shown in Figure 5.
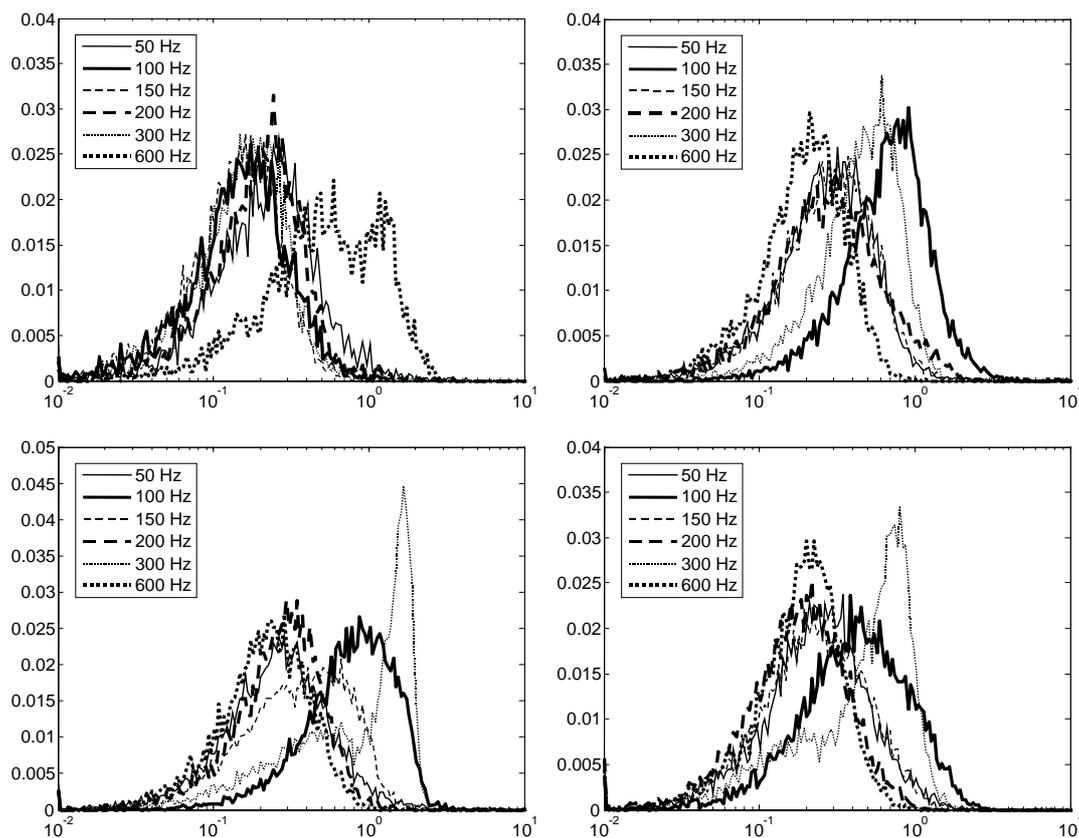

Figure 5. Clustering of exceptional voltage harmonic components distributions (x-axis "Voltage [V]", y-axis "Probability" for all graphs): unusual 600 Hz component (upper-left), large 300 Hz and 100 Hz components (upper-right), lack of 12-pulse reaction for one ESS while approaching (lower-left) and leaving it (lower-right)

With reference to the two graphs shown in the lower part of Figure 5, the two 300 Hz component distributions complement each other and have been recorded in front of an ESS that fails in implementing 12 pulse reaction: on the left graph the train is approaching the ESS with a degrading profile towards lower voltage values, due to the longitudinal voltage drop increasing with the line length; the same happens when the train passes in front of the ESS and leaves it, again increasing the line length between the train and the ESS. The contemporary increase of the 100 Hz indicates an abnormal asymmetry of the feeding transformer, rather than a faulty or disconnected LC filter. On the contrary the upper-right graph with a particularly large 100 Hz component with respect to the 300 Hz one indicates that also an abnormal negative sequence on the High Voltage AC side must be taken into account.

In normal cases (with correctly operating ESSs and position along the line mid way between ESSs) the distributions of the amplitude of the considered harmonic components are located between 0.1 and 1 Vrms and if plotted on a linear scale they all have approximately the shape of a Poisson or Rayleigh distribution.

V. Conclusions

In this paper a preliminary characterization of the statistical properties of the pantograph voltage distortion is presented for the Italian 3 kV DC railway line. Since the most relevant contribution is given by characteristic and non-characteristic harmonics of the substation rectifiers, several of the observed properties may be extended to other DC railway systems with a similar power supply system. The presented results are significant in several fields: the Power Quality issue and the identification of the voltage distortion is relevant to the electrical interoperability of rolling stock across different networks; the pre-existing voltage distortion (and consequent current distortion) must be considered for the correct sizing of any input filters and for the design of the static converters control systems, in order to solve and optimize stability and performance problems; the presence of voltage and current harmonics may influence coupled noise and interference to nearby electronic circuits and is a knowledge base for reasoning on the possible interference to signalling devices. To authors' knowledge it is the first time that the statistical distributions and the ranges of the pantograph voltage based on real measurement data are made available.

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