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Recent results on the Power Quality of Italian 2x25 kV 50 Hz railways

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***Abstract* – The recordings of the pantograph voltage and current waveforms across Italian and French high speed railway lines (both Autotransformer 2x25 kV 50 Hz systems) are analyzed to estimate some Power Quality indexes: harmonic spectra, harmonic distortion, displacement factor and fundamental component, in various rolling stock operating conditions. These indexes, that define the electrical interface between the rolling stock and the power supply, are all relevant in order to assess both the impact of the rolling stock on the network and the suitability of the latter to ensure agreed performances (electrical interoperability).**

I. INTRODUCTION

The service conditions and the performance of the rolling stock taking power over a portion of a railway network are subject to the electrical interaction of the traction supply line and the rolling stock, while it is moving with different operating profiles and loading conditions. Rolling stock units are both separate lumped electric loads and distributed interacting loads, electrically coupled by the traction line. The compliance assessment is based on the evaluation of various Power Quality (PQ) indexes derived from the pantograph voltage and current waveforms. Current distortion is local to a single load, while voltage distortion is the byproduct of the interaction with the traction line impedance. Details of the PQ indexes are reported in [1]: harmonic distortion and overvoltages are considered in this work with attention to train operating conditions, attempting at separating its own contribution from the underlying network distortion.

Autotransformer 50 Hz railway networks are the most modern solution for high performance electric transportation systems. Focusing on the interaction between the power supply and the rolling stock, the following European standards apply:

- the EN 50163 [2] specifies the voltage characteristics of the supply voltages of traction systems in steady and transient conditions;
- the EN 50388 [3] sets up the requirements for the acceptance of rolling stock on infrastructure and defines requirements of the power supply at the interface between traction unit and fixed installations.

Rolling stock emissions depend highly on its operating conditions and the position along the line, that in turn influences the pantograph impedance curve. Emissions are studied by means of the Fourier transform over a suitable time window, a tradeoff between frequency and time resolution, in order to track characteristic and non-characteristic components also during transient conditions. The Hamming window is also extensively applied to prevent adverse effects when analyzing transients and in general when the fundamental frequency undergoes unavoidable fluctuations [4][5]. Hamming window is an advisable choice for practical reasons: it is widely accepted and it is used by the national standards collected in [6].

In the following the PQ indexes that will be analyzed are summarized and for their definition reference is made to available publications [6][7]. Recordings were made during the first test campaign of the European Union funded project EUREMCO [8].

II. POWER QUALITY ANALYSIS

The rms value of the pantograph voltage V_p is related to the so-called useful voltage, $U_{av,u}$, that is the power supply index that is evaluated to assess the adequacy of the infrastructure (power supply network) to the prescribed performance of the circulating rolling stock. For high speed interoperable lines the lower limit is 22500 V (as it will be considered in the present case), while for conventional interoperable and classic lines the limit is lowered to 22000 V [3]. The $U_{av,u}$(train) index is thus evaluated as the mean value for one particular train at each time step where the train is absorbing traction power (ignoring steps when the trains is stationary, regenerating or coasting). The useful voltage is different from the minimum values specified in [2], where the lowest permanent voltage and the lowest non-permanent voltage values (19000 and 17500 V respectively) indicate extreme cases related to correct train operation and safety of on-board equipment.

The useful voltage is analyzed selecting acceleration

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phases that represent network loading as prescribed by the EN 50163 standard [2]. The useful voltage is made corresponding to the rms value of the fundamental that results from the calculation of the Fourier transform of the pantograph voltage; the Fourier time window is varied between 0.1 and 0.2 s ensuring a satisfactory time and frequency resolution over the entire frequency interval, subdivided in the dc-3000 Hz and 1-15 kHz ranges.

The results consist of rms values and spectra of the pantograph voltage and current including its dependence on the train speed and tractive effort. Statistical and graphical processing is used to better highlight and interpret signal characteristics [6].

III. RESULTS: FUNDAMENTAL COMPONENT VERSUS OPERATING CONDITIONS AND TIME

The rms of the fundamental of the pantograph voltage V_p is plotted in Fig. 1 for an entire train run to give a graphical representation of $U_{av,u}$(train). The two sudden reductions occur during the acceleration phases of the full speed test run shown in detail in Fig. 2: a current absorption of 250A causes a voltage drop of about 200V.

The train load effect can be evaluated for each operating condition for two successive speed profiles: stationary, acceleration, coasting, braking. These four phases are shown in different tones of grey in Fig. 2, ranging from light grey to black respectively. The minimum absorbed current is nearly 10 A due to the on board auxiliaries. The maximum current is reached during acceleration phase at about 250 A. Color coding will be used throughout this and the successive sections when showing results that are related to the train operating conditions.

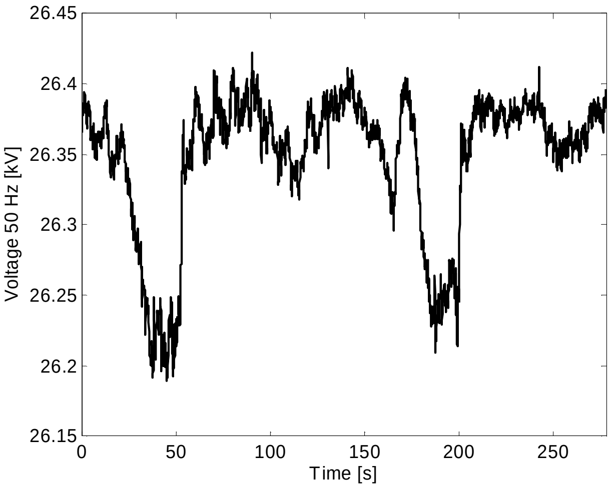

Fig. 1. Voltage at fundamental during a full speed run

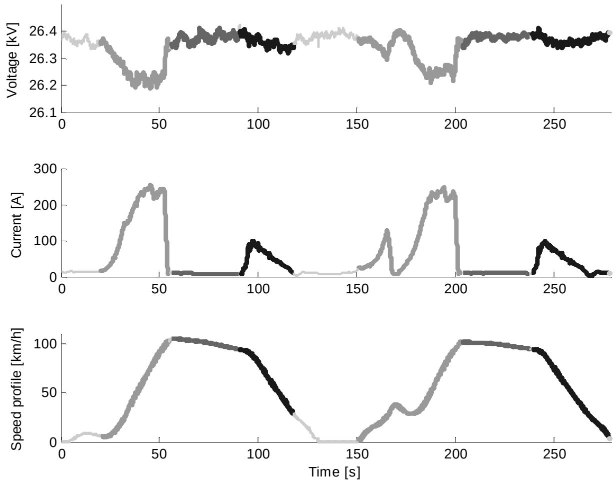

Fig. 2. Pantograph voltage and current during a typical test run consisting of two complete acceleration-cruising/coasting-braking profiles.

The train load effect is better interpreted if the fundamental of V_p is plotted versus the fundamental of I_p, as it is shown in Fig. 3. The V-I plot (also called Lissajous chart or curve) is often used to highlight correlation versus some operating condition or external variable: while standstill and coasting conditions have no clear correlation, V_p and I_p are inversely proportional in acceleration as expected.

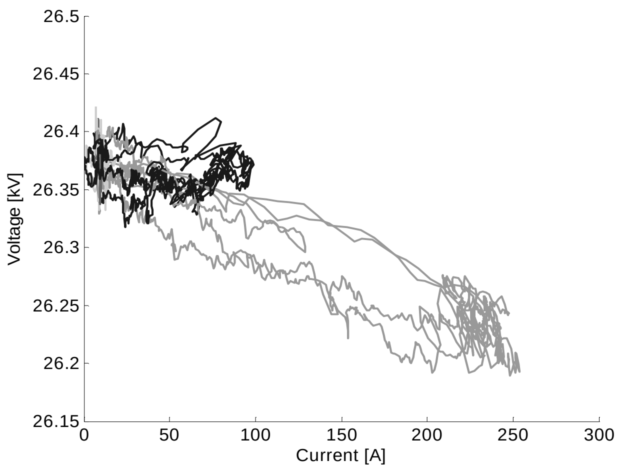

Fig. 3. VI plot of the fundamental

IV. RESULTS: VOLTAGE AND CURRENT HARMONIC SPECTRA

A frequency spectrum extended up to 15 kHz is shown in Fig. 4, which illustrates the combined result of the cumulated single-frequency spectra computed over about 530 s of the recordings in the AV Turin-Milan section. The cumulative distribution function is considered by displaying for each frequency bin the voltage levels where the probability of exceedance p is >95% (light gray), 80%<p≤95% (medium gray), 60%<p≤80% (dark gray), 40%<p≤60% (black), 20%<p≤40% (dark gray), 5%<p≤20% (medium gray), and p≤5% (light gray). The asymmetrical disposition of regions near the boundaries is due to the log-scale visualization of the small amplitude values, to avoid cluttering with large light-gray regions.

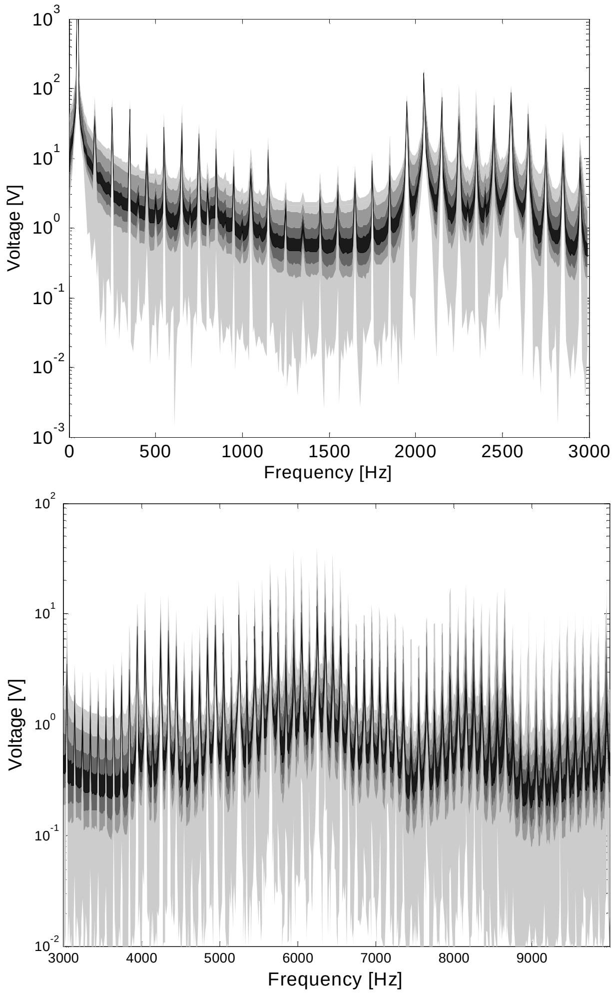

Fig. 4. Statistical distribution of the pantograph voltage spectrum (see text above for definition of histogram bins)

The fundamental at 25 kV has a negligible dispersion, as expected when the power supply system is correctly sized. Even harmonics are all very low and with a significant dispersion. Odd harmonics are related to the supply or to the train: the distinction of the contributions is a common exigency when post-processing and interpreting measurement data; V-I plots are again used in the following to this aim.

Nearly all trains operating under 25 kV ac supply are nowadays equipped with four-quadrant input converters responsible for the odd harmonic pattern. These converters are usually operated interlaced in banks of two or four and the resulting harmonics are located around the corresponding multiple of the switching frequency of the single converter; normally this value is between 1500 and 2500 Hz and in the following section this will be demonstrated by analyzing the correlation of the various voltage and current components. A preliminary analysis is shown in Fig. 5, where three spectra are shown for three different values of absorbed current intensity, roughly made correspond to the train operating condition.

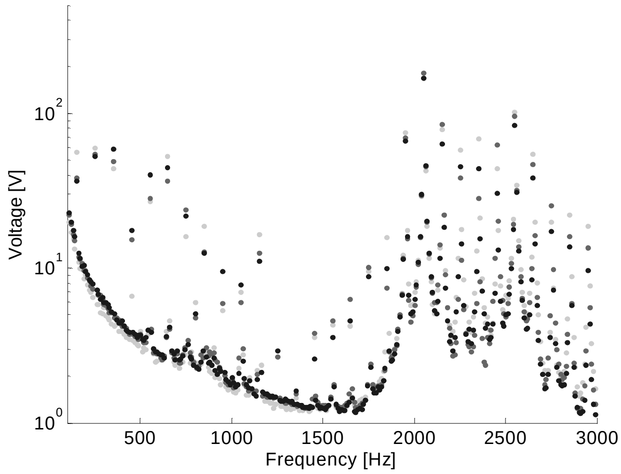

Fig. 5. Pantograph voltage spectrum for the Italian network over [5-3000] Hz frequency range; the absorbed current conditions are "low" (thick light gray), "medium" (medium thickness gray), "high" (thin black)

V. RESULTS: CORRELATION OF VOLTAGE AND CURRENT COMPONENTS

V-I plots are shown in the following figures for frequency components that will be shown to belong to the supply or to the train distortion pattern. The supply is responsible for the large part of the distortion in the low frequency portion, where the voltage and current amplitude are weakly correlated each other and to the train operating conditions. The following figures are divided into three groups: 1) low order harmonics usually assigned to the power supply, 2) locomotive harmonics resulting from the Pulse Width Modulation pattern of the on-board converters, located in the usual frequency range of 1500 – 2500 Hz and 3) higher frequency components due to many different sources, but not in direct relationship with the tractive effort.

The three gray shades regard the absorbed current intensity as before: "low" absorbed current conditions (light gray), "medium" (dark gray), "high" (black).

Low order harmonics appear in Fig. 6 to Fig. 8. The plots centered on the supposed frequency interval of loco emissions show a clear correlation. It is interesting to observe also the increasing voltage/current ratio, that indicates an increase of the traction line impedance (see Fig. 9 to Fig. 12).

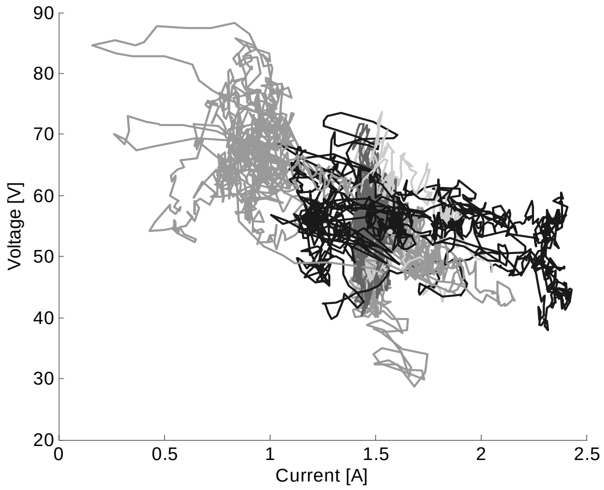

Fig. 6. V-I plot of pantograph quantities at 250 Hz

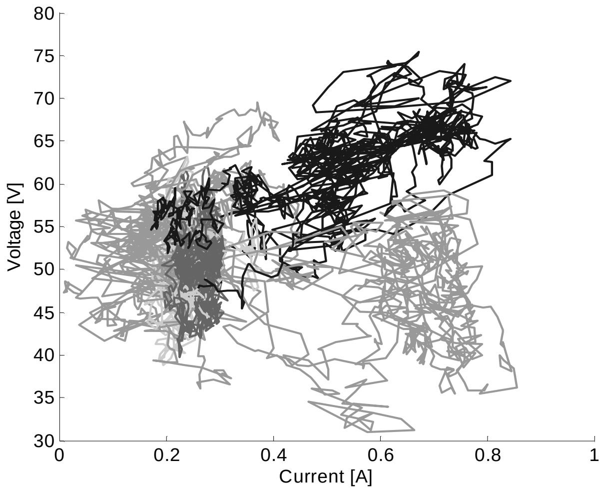

Fig. 7. V-I plot of pantograph quantities at 350 Hz

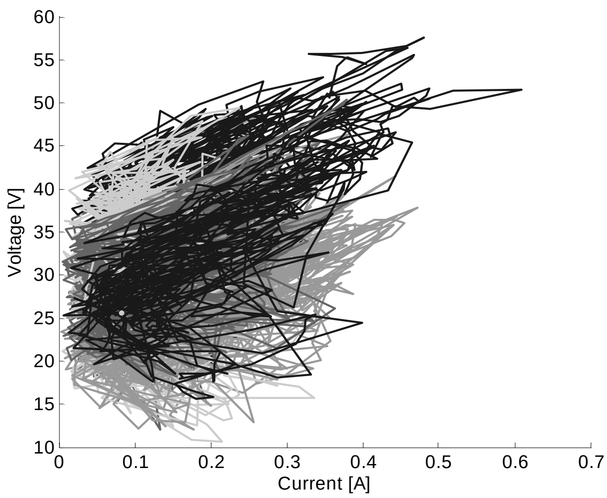

Fig. 8. V-I plot of pantograph quantities at 550 Hz

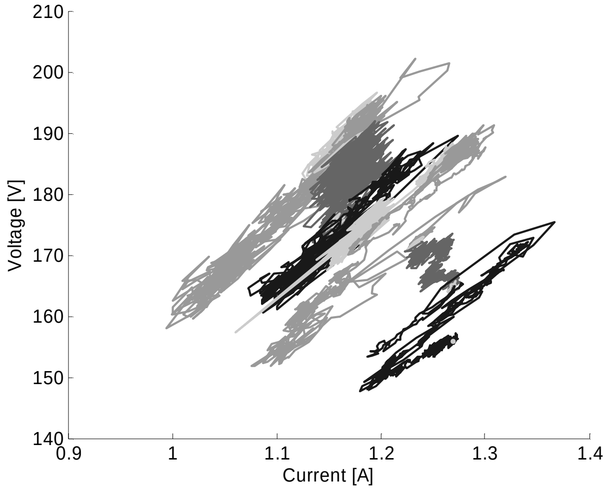

Fig. 9. V-I plot of pantograph quantities at 2050 Hz

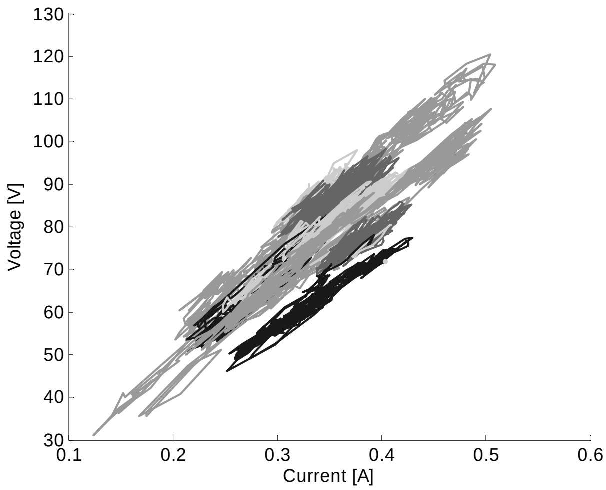

Fig. 10. V-I plot of pantograph quantities at 2150 Hz

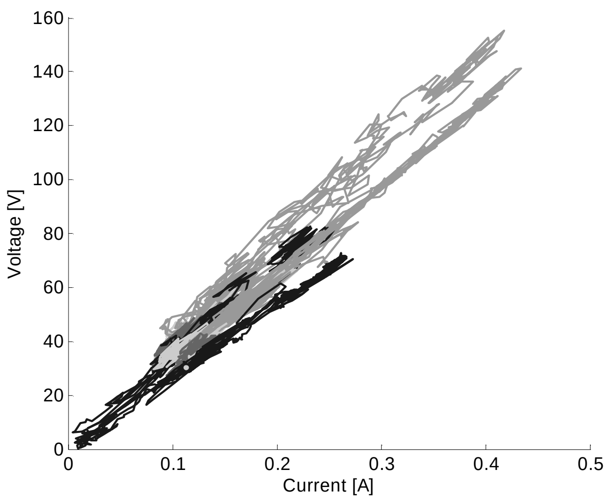

Fig. 11. V-I plot of pantograph quantities at 2250 Hz

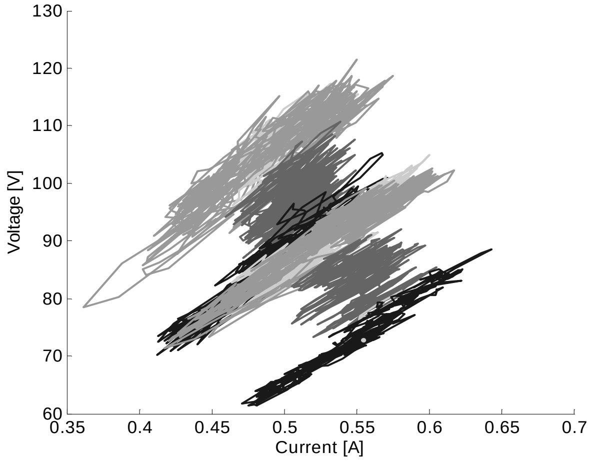

Fig. 12. V-I plot of pantograph quantities at 2550 Hz

Going to higher frequency, beyond the supposed interval of locomotive characteristic emissions, the V and I components are again uncorrelated, as it is shown for 2950 and 3050 Hz in Fig. 13 and Fig. 14, respectively. The V/I ratio decreases, since the traction line impedance is approaching an anti-resonance point.

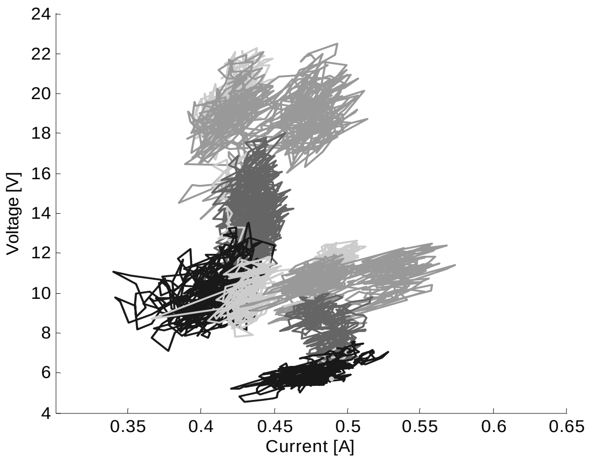

Fig. 13. V-I plot of pantograph quantities at 2950 Hz

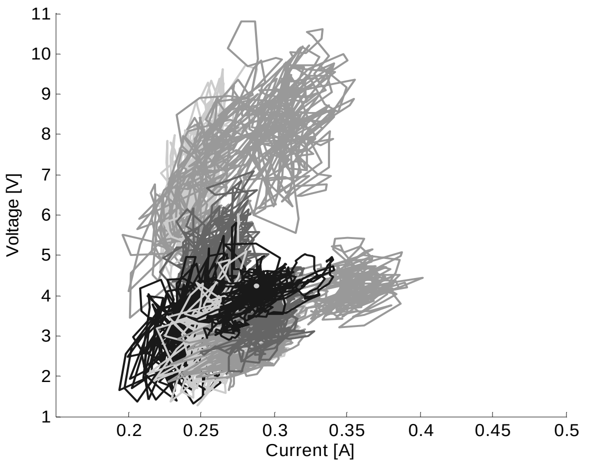

Fig. 14. V-I plot of pantograph quantities at 3050 Hz

VI. CONCLUSIONS

The reported results regard the measured pantograph voltage and current during test runs on the Italian High Speed line between Milan and Turin, fed at 25 kV 50 Hz.

The first more direct use is the quantification of the individual and total harmonic distortion of the line voltage as perceived by the test locomotive, as well as the line reaction to the load step changes. Results may be expressed as worst-case maximum values or as a statistical distribution, e.g. by showing a coarse histogram of the relative frequency for each component of the frequency spectrum of pantograph voltage and current.

Then, regarding the identification of the single components appearing in the spectrum as originated by the locomotive or due to the underlying traction line distortion, the use of correlation between voltage and current quantities and versus train operating conditions is shown. The results confirm that low order harmonics are uncorrelated from the train operating conditions and evidence of correlation is found in the frequency interval where locomotive emissions are very likely, if the existing technology and design choices for four-quadrant converters are considered. As a confirmation, going beyond the first group of harmonics of the on-board converter the correlation is again lost.

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