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Variability of pantograph impedance curves in DC traction systems and comparison with experimental results

Abstract *– The problem of the influence of the infrastructure on the rolling stock conducted emissions is considered, to define criteria for the quantification of the observed variability. Extensive analysis is done by means of simulation models, validated by experimental results during test campaigns in Belgium, France and Italy. The peculiarity of DC systems consists of the quite low substation impedance and the resulting low voltage distortion.*

Streszczenie *– W artykule przedstawiono zagadnienie oddziaływania emisji przewodzonych zaburzeń pochodzących od pojazdów trakcyjnych na infrastrukturę trakcyjną w celu zdefiniowania kryteriów i oceny zmienności tych oddziaływań. Przedstawiono wyniki wielokrotnych analiz przeprowadzonych z wykorzystaniem modeli symulacyjnych zweryfikowanych pomiarowo w trakcie testów we Francji, Belgii, i Włoszech. Przedstawiono specyfikę systemów zasilania trakcji elektrycznej prądu stałego wynikającą z niskiej impedancji podstacji trakcyjnych i stąd niskich odkształceń napięcia.* ***(Przebiegi zmienności impedancji mierzonej na pantografie w systemach trakcji elektrycznej prądu stałego - porównanie z wynikami badań eksperymentalnych)***

Słowa kluczowe: impedancja mierzona na pantografie, systemy trakcji elektrycznej prądu stałego, lokomotywy zasilane z sieci DC, modelowanie, symulacja.
Keywords: pantograph impedance, DC traction systems, DC locomotive, modelling, simulation

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Introduction

When considering the spectrum of the line current absorbed by a locomotive (or train) to evaluate interference to signalling circuits and compliance with the limits [1], it is evident that resonances and anti-resonances of the traction line impedance represent an issue. The reason is that low impedance situations (at anti-resonances, with the lowest impedance value determined by the series resistance) may result in current amplification, while high impedance situations (at resonances, with the maximum value determined by losses in the line conductors and supply system components) may lead to insufficient dampening of local oscillation of loco filter and transformer.

The focus here is on the conducted emissions of the single locomotive, while the superposition of the emissions caused by different rolling stock in the same supply section is not in the scope [7].

The frequency behaviour of the line impedance perceived by the trains at their pantographs (i.e. the “pantograph impedance” Z_p) is well-known from a theoretical point of view [5][6][9] and depends in principle on the supply section length, that is the distance between the two substations at each section end (or between the substation at one side with the other end floating). Substations represent low terminating impedance (thanks to both their low short circuit impedance and the possible use of filters, in case of dc systems) assimilated to a short-circuit (s.c.); the open-circuit end is indicated as o.c.. For this reason the broad range of real cases at a first approximation can be simplified to a s.c./s.c. or a s.c./o.c. terminated line. A more complete simulation of the entire railway line may be however preferable to give evidence of an all-comprehensive approach with the least approximation possible.

The Z_p curves may be thus evaluated once the per-unit-length parameters of the traction line are known [8], accounting for the spread of some parameters, such as the capacitance and conductance terms, influenced in general by moisture, dirt, catenary masts and other rolling stock.

Yet, many infrastructure elements may modify, even substantially, the expected behaviour derived from the theoretical calculations. Additional stray capacitance is brought into play by transformers (for substations, autotransformers and boosters), rectifiers and high voltage cables (connecting the former elements to the overhead line). These elements may feature a large variability of stray parameters because they are not subject to verification during acceptance or periodic maintenance, because their distance from the line is variable, etc.. It is thus understood that the variability in the Z_p response is correspondingly large and that this has influence on both the testing procedure of the rolling stock and on the quantification of the safety margins used to determine limit masks.

Problem description

As outlined above, the problem consists in the determination of the variability of the pantograph impedance over an entire network or for different networks of different countries. The term “variability” is intended here in a broad sense: average and standard deviation, percentiles, statistical distribution, min and max values.

This is part of the European Union funded project EUREMCO [3] that states in its objectives “The current authorisation process for placing into service rail vehicles according to Technical Specifications for Interoperability and national safety rules is a very long and costly process. (...) The EUREMCO objective is to harmonise and reduce the certification process of rail vehicle against Electromagnetic Compatibility (EMC). The main concept of the project is to specify the conditions for cross-accepted certification all around Europe, through sound scientific methodologies allowing for the identification of the “transfer functions” to be applied to results obtained on different test tracks in different countries, for the same power supply system.”

Within the scope of EUREMCO two parallel macro-activities are being carried on, simulation and measurements, aiming at converging to the validation of the implemented models and to the evaluation and interpretation of the measurement results, in order to derive sound and well-based conclusions on the expected behaviour and variability. The two activities regard the three most popular supply schemes, that is 15 kV 16.7 Hz, 2x25 kV 50 Hz and 1.5/3 kV dc, in the respective work packages 3, 4 and 5. In this work the results of the experimental activities aimed at validating the dc system models for 3 kV and 1.5 kV lines are presented, based on the experimental results of Belgium (3 kV), France (1.5 kV) and Italy (3 kV).

The considered French traction line is a 102.3 km section from Saran to Moussay. The line includes impedance bonds and is supplied by ten substations (ESSs); small errors in the positioning and the characterization of impedance bonds are not relevant to the overall pantograph impedance (i.e. the so-called “hot path”).

For what concerns the Italian traction line, a 43 km long section, from Firenze to Chiusi, is considered. Also in this case the line has impedance bonds and is supplied by three ESSs all equipped with a LC filter (with nominal values of components L=6 mH, C=360 uF).

Finally, the Belgian line section extends from Saint Ghislain to Tournay for a length of 36.75 km. Impedance bonds and three substations characterize the line, and the substations have a RC filter (R=6 Ω, C=8 uF) installed in parallel to the output terminals.

The modelled locomotive used in the measurements is the BB 36000 with the on-board filter reconfigured according to the supply voltage level: the values for the scheme shown in Figure 1 are L1 = L2 = 8.5 mH, L3 = L4 = 3.17 mH, C1 = C3 = 3.2 mF, C2 = C4 = 8 mF.

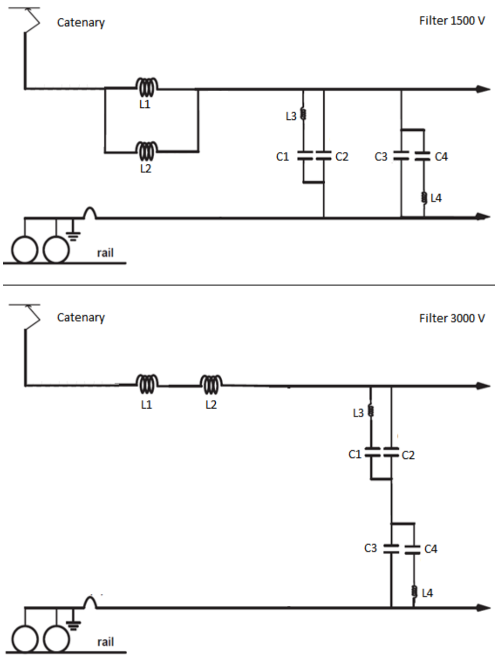


Fig.1 BB36000 on-board filter

Simulation results

This section is divided in three parts: 1) verification of the assumption that the substations are decoupling elements, that keep line sections almost separated and independent (tests made on Belgian line); 2) pantograph impedance for Belgian line; 3) pantograph impedance for the French line.

Substations as decoupling elements

The catenary currents flowing from remote substations into the supply section where the train resides (indicated by $I_{s,lo}$ and $I_{s,ro}$ in Figure 2) are negligible for most of the frequency range, in particular if filters at the output terminals of substations are used, that load the line with a large shunt capacitor.

For brevity the following notation will be used in displaying and commenting the results:

- Z_p [Ω] is the pantograph impedance, given by the parallel of the left and right line sections;
- $f_{r,n}$ and $f_{a,n}$ [Hz] are the resonance and anti-resonance frequency values (n=1, 2, ... indicates the first, the second, ... resonance or anti-resonance);
- $I_{p,l}$ and $I_{p,r}$ [A] or % are the two currents going to the pantograph from the left and right sides;
- $I_{s,l}$ and $I_{s,r}$ [A] or % are the two currents coming from the busbar of the nearest adjacent substations, that are in principle equal to $I_{p,l}$ and $I_{p,r}$ respectively;
- $I_{s,lo}$ and $I_{s,ro}$ [A] or % are the two currents coming into the substation busbar from other line sections, that are further away, and represents the level of coupling with the external adjacent line sections.

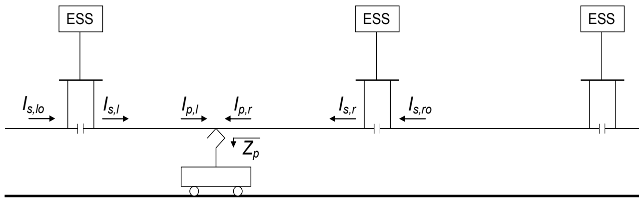


Fig. 2. Sketch of the current distribution around the train

As said before, the low substation output impedance causes the decoupling of the line sections, so that the Z_p for a train residing in a supply section features the same line resonance for almost all the positions along the same section. For the line portion that extends a few hundreds meters in front of the substation the impedance values are quite low and with little or no resonance and then, when the train has passed the substation and moves to the next supply section, the Z_p shows the new resonance frequency of the new line section.

One of the most critical positions for the verification of the assumption of isolation of the adjacent supply sections (that is km 8.000 from the beginning of the line), as resulting when the experimental data were processed, is shown in Figure 3.

For the left section shown in Figure 3 (two upper graphs), the current “skipping” the first substation keeps negligible for all frequencies, with an exception for the traction line resonances, the first one occurring at about 4 kHz. The resonant behaviour alternates between the two currents, $I_{s,lo}$ and $I_{p,l}$, but the former keeps much smaller than the latter over the remaining frequency interval. Considering the right section (shown in Figure 3 in the lower two graphs), the rule is followed over the entire frequency interval; the largest ratio occurs at 8 kHz and is about 1 to 5. In all other cases, where major resonances of the current do not occur, the current supplied from far substations is limited to a few % maximum, and this demonstrates the assumption.

Pantograph impedance for Belgium, France, Italy

The expected behaviour of the pantograph impedance Z_p may be summarized as follows: the DC and low frequency values are influenced by the longitudinal resistance, that in turn depends on the distance of the train from the nearest substation; the main resonance depends on the length of the line section between two substations that almost completely decouples it from the adjacent sections (as discussed above); this main resonance is followed by harmonically related higher order resonances; other smaller resonances may be present due to the influence of specific elements, such as feeding cables; the anti-resonance depends on the train position and moves with it, with the amplitude influenced by the longitudinal resistance at high frequency, thus including the effect of losses and skin effect.

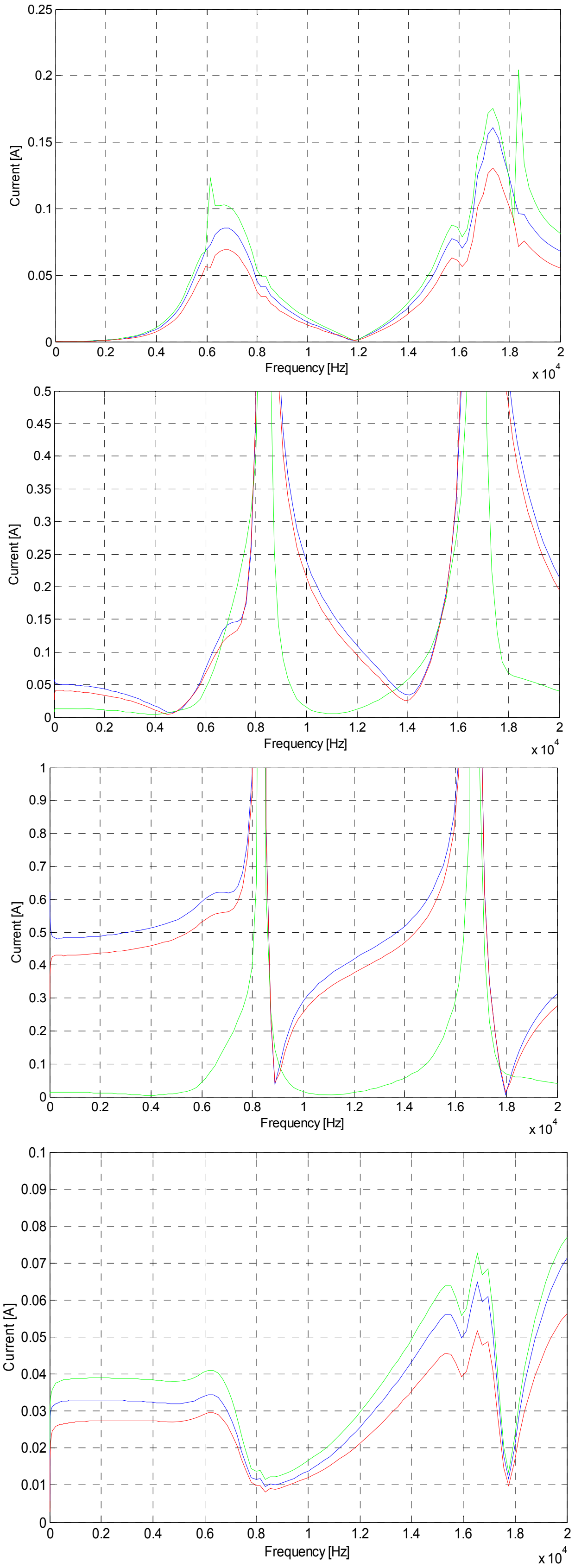


Fig. 3 Test of the current distribution at km 8.000 of the Belgian line: $I_{s,lo}$ (first), $I_{p,l}$ (second), $I_{p,r}$ (third), $I_{s,ro}$ (fourth): contact wire current (blue),messenger current (red), parallel feeder current (green)

This behaviour is shown in Figure 4, where it is noted how the substation at km 64.500 creates a minimum of Z_p and the resonances at its left and right are located at different frequencies, due to the differences of the two respective line sections. The minima between two resonances are the anti-resonance moving with the train position and with slightly larger values than the dc longitudinal resistance.

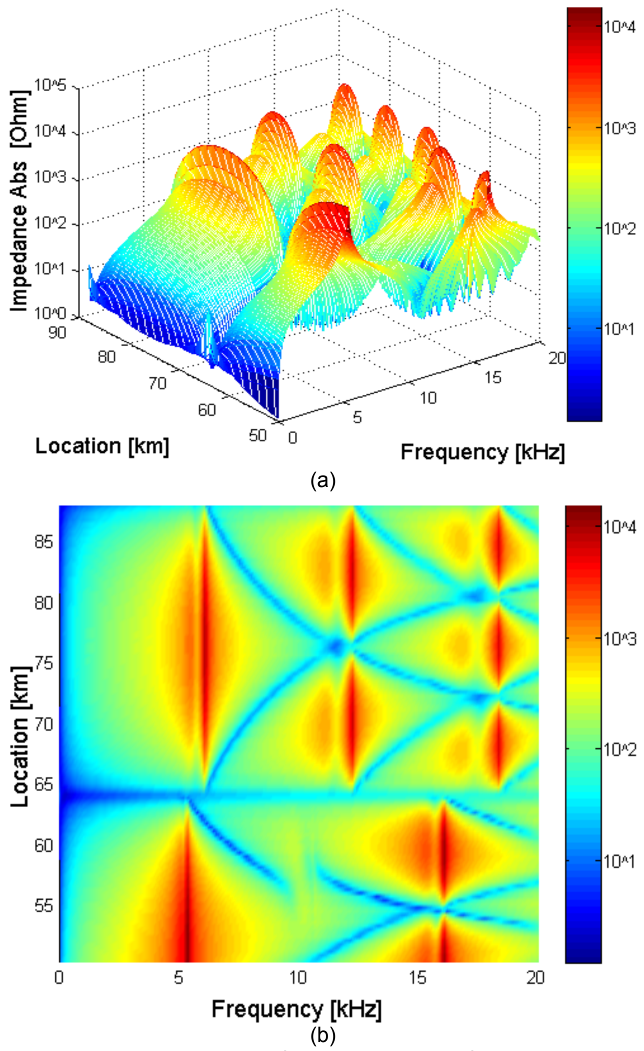


Fig.4 3-D and 2-D plot of the amplitude of the pantograph impedance Z_p for Belgium as a function of the train position

The analysis of Z_p for different train positions is shown in the following Figure 5 and Figure 6 for Belgium and France, respectively. There may be observed curves that show almost no resonance phenomena (corresponding to positions very close to substations). The curves are in general grouped depending on the supply section where the train resides, featuring different slopes and/or resonances, due to the different inter-substation distances.

The already announced variability for positions near to and far from the substations is quite evident: the level of the Z_p curve in the low frequency interval is conditioned by the length of the line to the nearest substation, the resonance frequency is common to all train positions inside the same supply section provided that the substation is not too close, that flattens any resonance (blue curve in Figure 5).

It is worth also considering the influence of the substation filter as a reactive element that might influence the resonant behaviour, not only simply reducing the termination impedance to nearly a short-circuit condition. Analogously, the on-board filter also might influence the pantograph impedance curve. To this aim some of the considered line sections are simulated with and without substation filters (as it is the case for Italy, where substations are equipped with a 6 mH + 360 uF LC resonant filter, as per nominal values) and with and without the on-board filter (that for the BB36000 is a combination of LC elements, configured for the traction supply voltage, either 1.5 or 3 kV, as shown in Fig. 1 tested for Belgium and Italy. A pure current generator is used to replace the on-board converters and test the pantograph impedance at the pantograph port.

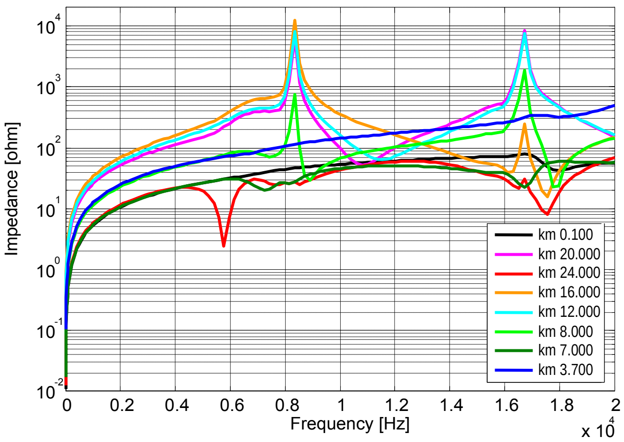


Fig. 5 Amplitude of Z_p for various train positions (Belgium)

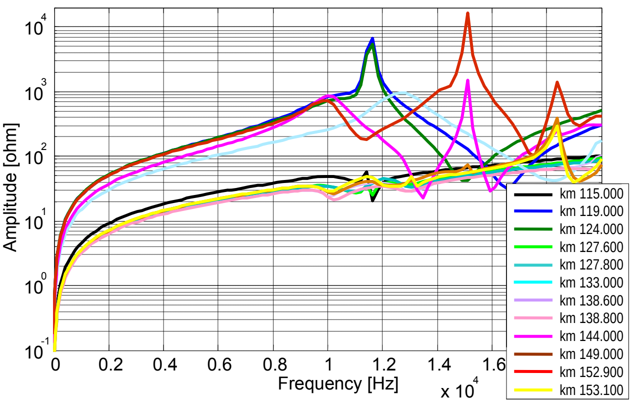


Fig. 6 Amplitude of Z_p for various train positions (France)

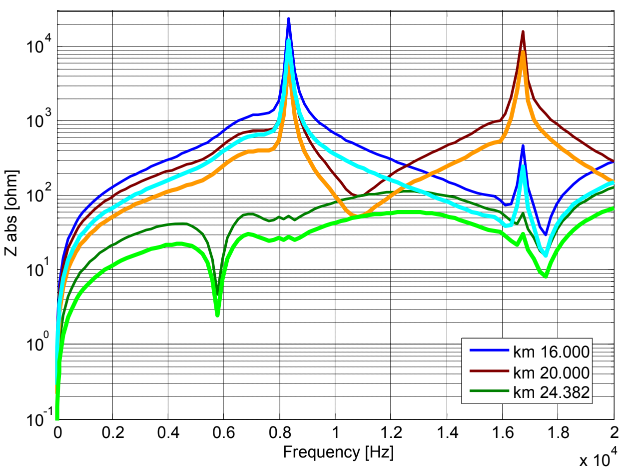


Fig. 7 Amplitude of Z_p for three train positions (Belgium): base case (solid dark thin), with on-board filter (solid light thick)

As it might be expected, the curves for the case with on-board filter are lower than those without. The on-board filter seen from the series inductor side is in parallel to the line impedance and its effect is an almost constant reduction of the amplitude, without changing resonance and anti-resonance frequencies.

When considering also the effect of the substation filter (see Figure 8), again the main line resonance (for the blue and brown curves) is not changing, but a dampened resonance is preceding it at about 9 kHz when the effects of the two filters are combined.

For the train position in front of the ESS it is worth underlying that anti-resonances with a steep profile may occur and that their frequency may change depending on the combination of the ESS and on-board filter values; the anti-resonance is responsible for an amplification of the pantograph current components around 5.5 and 9.5 kHz in this example, but potentially affecting the entire frequency interval used for audiofrequency track circuits [12]. A similar change is observed at higher frequency (between 13 and 15 kHz) for train positions far from the substation, potentially influencing also in this case the audiofrequency track circuits. It is worth observing, however, that due to the very low short circuit impedance at audiofrequency thanks to the substation filters and the large series impedance ensured by the on-board filter inductor, the pantograph current components for dc systems are much lower than those expected in ac systems.

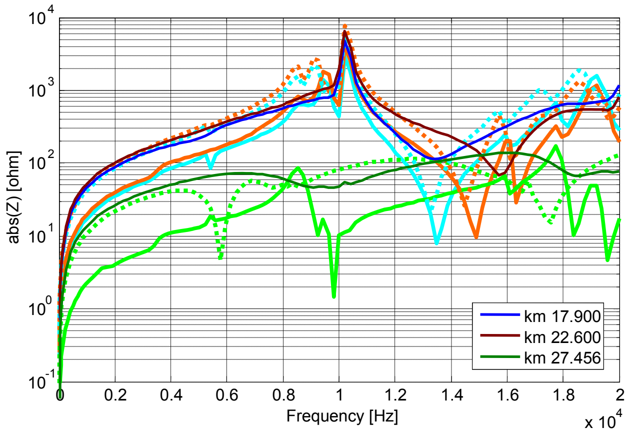


Fig. 8 Pantograph impedance for three train positions (Italy): without ESS filter (solid dark thin), with ESS filter (solid light thick), with ESS + on-board filters (dotted light thick)

It can be concluded that the positions close to the substation feature a large variability in terms of amplitude and frequency value of resonance and anti-resonance.

Validation

Validation of the simulation models is performed by comparison with on-site measurements and this is what should be called more properly as evaluation of model adequacy; we will use the terms “validation” and “adequacy” with this meaning. Both voltage and current at the pantograph are available and may be used for the validation; however, since the model of the locomotive is only approximate and does not include the details of the on-board converters, using the pantograph impedance was preferred. The validation of the simulator and the implemented model was developed around three main elements:

- the pantograph impedance as the quantity that conveys information on the line impedance, that it can thus be theoretically calculated only for the harmonics components sourced by on board converter;
- the criteria used to determine if the correspondence between experimental and simulated results is *satisfactory*, that is a more general concept than saying that the experimental and simulated curves match;

• the sensitivity of the results to some model parameters, that drive the tuning process of model parameters and that for an unbiased and trustable validation shall be limited to unknown system parameters within their most likely ranges, dictated by credibility and technical judgement.

The pantograph impedance as the reference quantity

The pantograph impedance is calculated directly as the ratio of the pantograph voltage and current spectra. Due to the efficient filtering at substations and the low supply impedance, high frequency spectrum components are of negligible amplitude. Moreover, given the peculiar switching frequency of the on-board front-end converter of 300 Hz, the locomotive and substation harmonics overlap; only frequency resolutions of fractions of Hz with longer observation windows and the control of the frequency leakage allow to separate the two terms, based on the fact that the substation harmonics are multiples of the national grid frequency, not always corresponding to the nominal 50 Hz and fluctuating with time.

The instability of the fundamental frequency instabilities is revealed as relevant spectrum lines around the nominal fundamental frequency and nominal harmonic frequency values [10][11]. When a time window for leakage suppression is applied, the instabilities may be observed as spectrum lines outside the main-lobe width of the same window; within it, all the frequency values contribute to a unique frequency bin and the resolution on the frequency axis is limited by the width of the window main lobe. So, the effectiveness of the spectrum representation to separate and track locomotive components depends on the selected frequency resolution and on the used smoothing window. Given the deviation of the fundamental frequency δf_1, the expected deviation at the components of harmonic order h is thus $\delta f_h = h\,\delta f_1$; the observation time and the frequency resolution df shall be selected accordingly, in order to have enough frequency bins that separate the locomotive and the substation rectifier components; the choice of the smoothing window is then also dictated by the necessity of effectively separating two strong components separated by a few bins, requiring a significant roll-off and side-lobe suppression. For the minimization of the noise variance and to better distinguish noise and persistent components, spectrum averaging is recommended.

The on-board converters have each a fundamental switching frequency of 300 Hz, with a factor of 4 of interleaving, resulting in a 1200 Hz first characteristic component on the pantograph side. The other components at multiples of 300 Hz are recognized as due to the substation ripple, so that in principle they shouldn't be used to calculate the desired Z_p values. On the other hand the amplitude of the higher order components of the on-board converters decreases quickly with the harmonic order and significant components of locomotive emissions can be observed up to 1.2 kHz. The preliminary comparison between the simulated values and the estimation from the measured voltage and current is shown in Figure 9; the matching below 3 kHz is good and we are trying to improve the signal pre-processing in order to isolate relevant components. Some differences at very low frequency are due to the need of improving the model with the resistances of the busbars, cables and overhead wires connecting the rectifiers to the line; this aspect is not relevant to correctly model resonances and propagation of disturbance in the track circuits operating frequency interval, but is needed for a general correctness of the model itself.

An analysis of the deviation of the fundamental frequency was performed, focusing on 1200 Hz that was the frequency of the first theoretical harmonic of on board inverter. The analysis was performed, choosing a 4th order Blackmann-Harris window of 10 s of time duration, reaching a base frequency resolution of 0.1 Hz and an effective frequency resolution of about 0.25 Hz. In Figure 10(a) the results of the analysis around 1200 Hz are shown: at 1200 Hz there is the 24th harmonic of the 50 Hz fundamental and the fundamental component of the on-board converter set. The two can be distinguished and it is easy to observe that frequency spread of the locomotive emissions is negligible, while the one of the substation harmonic is about 0.3 Hz. Once the time intervals are identified where the substation and the train harmonic components are separated, the pantograph impedance is then calculated using the measurement data of this interval. In this case it would be possible to extend the frequency range beyond 3 kHz, by selecting carefully the harmonic components effectively due to loco converters. However the long observation window required causes the resulting pantograph and current voltage spectra to lose their significance because of the non stationarity of the signals: the components at the same frequency would be subject to significant variations over the said observation time, variation that is lost due to the averaging.

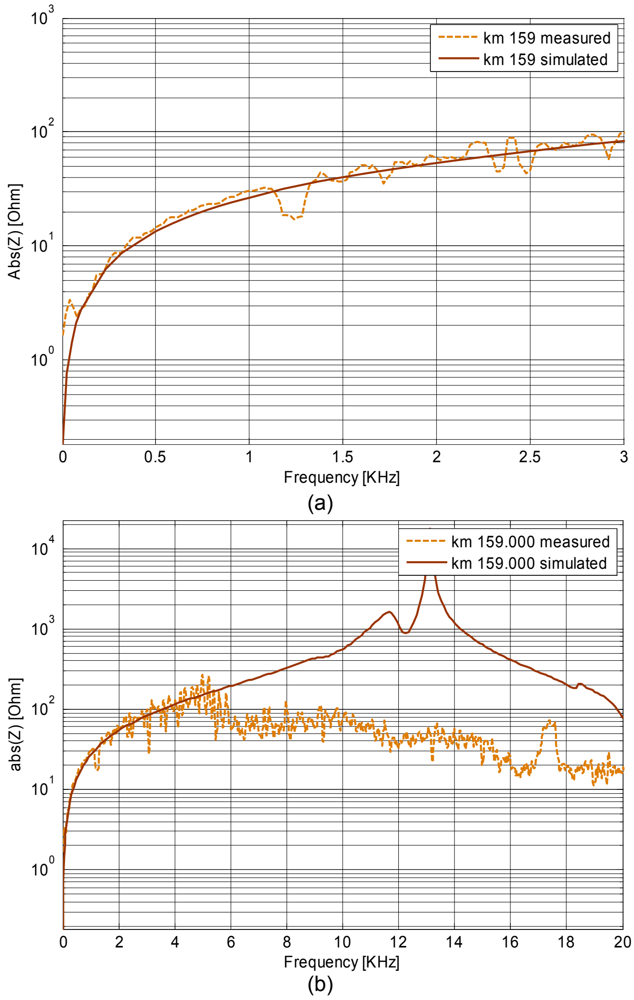
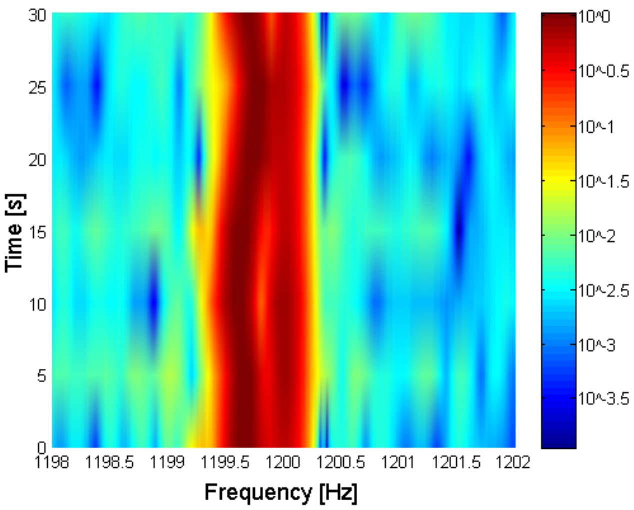
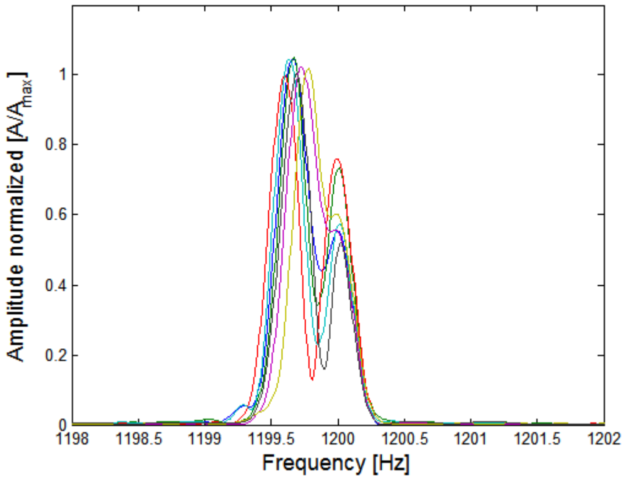


Fig 9. Comparison between Z_p of simulation results and estimated from the measured voltage and current: (a) below 3 kHz, (b) entire frequency range



(a)



(b)

Fig.10 Frequency analysis of substation and train harmonics components: (a) time-frequency map with SHort Time Fourier Transform, (b) normalized amplitude around 1200 Hz (France)

Conclusions

The variability of the pantograph impedance for different networks of different countries has been considered and analyzed by means of simulations; the main parameters influencing the pantograph impedance have been identified. The problem of the validation of the simulation models and algorithms was addressed by comparison with experimental results. The results confirm that the substations decouple the supply sections of the traction line, where the frequency behaviour of the pantograph impedance varies with the train position, the section length and is not appreciably influenced by adjacent line sections. Substation filters, as for the Italian line, reduce pantograph impedance and, for a train near the substation, change the resonance and anti-resonance frequencies. The presence of a loco on-board filter causes a reduction of amplitude of the pantograph impedance, without changing resonance and anti-resonance frequencies.

Due to the specific configuration of the locomotive used for the tests, its characteristic harmonics overlap with those of the substation, being located at multiples of 300 Hz. Locomotive harmonics components can be separated only when the deviation of substation harmonics due to the fundamental frequency variations is relevant. The 50 Hz fundamental is subject to nation-wide and continent-wide frequency fluctuations that may bring the substation harmonics far enough to be separated from those of the locomotive, synchronized to a stable on-board reference frequency. Even so, when using long observation times, the so obtained results are poor in time resolution (and thus with respect to train position) and the characteristics of the pantograph voltage and current are lost. Moreover, in DC systems the harmonic content is much lower than AC systems thanks to substation filters and large on-board filters, so that in general the use of generated harmonics to determine line characteristics is not so effective.

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