Monitoring Energy and Power Quality On Board Train

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***Abstract*— The European community for over a decade is supporting scientific and technological studies in order to make public transport low environmental impact. The metrological community plays a fundamental role in fostering this improvement. To this purpose, the paper describes the measurement setup and the results of an on-board DC train measurement campaign devoted to the accurate estimate of the energy exchanged between the locomotive and the DC feeder and the electrical energy wasted during the braking stage. These information are fundamental in the accurate determination of the energy saving margin, therefore, in the decision-making related to the infrastructure investment devoted to the energy efficiency improvement such as installation of reversible substation or on-board storage systems. Moreover, the paper provides a scientific contribution in the power quality definition for DC 3 kV railway systems.**

Keywords*— *Power and Energy measurement, Power quality, Railway system

I. Introduction

The efficiency of the European railway system is one of the aim declared in the white paper for efficient transport system [1]. An important contribution to this improvement, provided by the metrological community, is the development of means and methods aimed at estimating, with high reliability, the electrical energy fluxes on-board the locomotive and the quality of the power exchanged between the locomotive and the feeder. In this framework, a measurement campaign, part of the European Project 16ENG04 MyRailS [2], has been carried out on-board a DC 3 kV locomotive operating in commercial service. This activity has been carried out in collaboration with Trenitalia, the most important Italian railway company. The tests have been performed on the E464, a 3.6 MW locomotive widely used for commuter transport. In the measurement campaign, lasted about three month; 88 journeys have been monitored and about 2 terabytes of data have been recorded with a sample frequency of 50 kHz. The aims of this campaign are the monitoring of the energy exchanged between the train and the overhead supply contact line, the electrical energy recovered and wasted during a braking stage and the detection of electrical events occurring at the train pantograph. All these information are crucial in the decision-making related to the infrastructure investment devoted to the energy saving. For instance, as for the quantity of the electrical energy sent to the rheostats during a braking stage, the duration and the amplitude of the wasted pulsed power are valuable information for the design of on board storage systems and in the decision-making for the upgrade of the architecture of the railway supply system (i.e. installation of reversible substations). The power quality (PQ) at the pantograph is an important aspect linked with the efficiency of the system but it is relatively new research topic. Broadly speaking, PQ definition for DC system is not a well-assessed topic [3] and, in particular, the literature on PQ events for DC railway system is very poor [4]. The paper provides some events, which can be used to understand specific PQ phenomena that apply in railway system and can be considered as the base for future normative activity on this topic. The paper is organized as follows. Section II describes the test locomotive and the selected measurement points, section III provides all the information related to the measurement setup (transducers, acquisition system, etc…). Section IV presents the algorithm for the computation of the power/energy absorbed by the train, in section V some results of energy analysis are reported and section VI is devoted to a technical analysis on the measurement of chopped current absorbed by the braking rheostat. Finally, section VI present a selection of power quality events providing a preliminary explanation on the nature of these events.

II. E464-041 Trenitalia Locomotive: Test Case

The 3 kV DC locomotive E464 owned by Trenitalia has been considered as test bench. It is characterized by a rated power of 3.5 MW and a maximum speed of 160 km/h. Two inverters, with a rated voltage of 1.5 kV, series connected that supplies four asynchronous three-phase motors constitute the traction architecture. A second order low pass filter placed at the input stage limits the disturbances of the locomotive towards the overhead contact line and vice versa. In detail, an inductor of 8.5 mH (L_{filt}) and two identical capacitive banks (C_{filt}) of 17.1 mF each, connected at the input of each inverter, constitute the filter (see Fig. 1). In the following the voltage of the node between the two capacitive banks will be named $V_{\text{half\_filter}}$.

A chopper and a two-element resistive bank manages the electrical energy generated during a braking stage that must eventually be dissipated: at first the inverters try to inject energy in the supply system in order to be re-used by another train. If the supply system cannot receive all this energy to

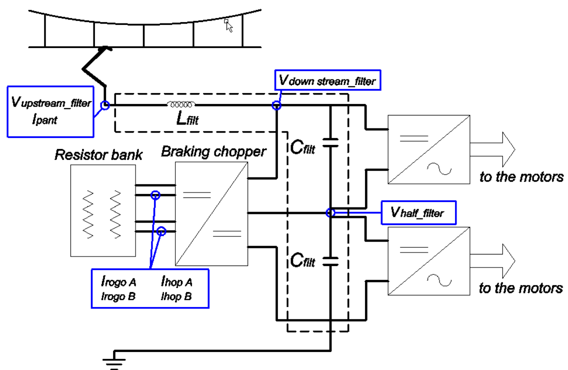

Fig. 1. Scheme of the E464 traction architecture, identification and positioning of the monitored quantities

avoid the raising the voltage level, the excess energy is dissipated in the rheostats. By regulating the chopper duty-cycle, it is possible to manage the amount of energy re-used, and thus injected in the overhead contact line, and the amount dissipated by rheostats. The parameter that controls the braking energy flux is the output filter voltage ($V_{downstream\_filter}$). In detail, for voltages lower than 3.8 kV, the energy is completely send back to the catenary, for voltages between 3.8 kV and 3.9 kV a mix of dissipative and re-generative braking is implemented, for $V_{downstream\_filter}$ higher than 3.9 kV a pure dissipative braking is applied.

Table I Braking Rheostat Characteristics

Parameter	Value
Maximum power	2 x 1200 kW
Resistance at 20°C (R_{rheost})	2 x 1.52 Ω
Maximum resistance variation 20 °C – 600 °C	5 %
Operating voltage	3.8 kV
Maximum rms current	900 A
Stray inductance	≤ 12 µH

Table I provides the main characteristics of the braking rheostat. The frequency of the chopped current is fixed at 260 Hz. In order to guarantee, during the braking stage, the equilibrium between the two voltages at the input of the traction inverters, potentially affected by small differences in the resistance value, the single resistive bank is alternatively connected to the inverters.

The measurement points in Fig. 1 are highlighted. Eight electrical quantities have been monitored. In detail, the voltage at the pantograph, $V_{upstream\_filter}$ and the total current absorbed by the locomotive I_{pant} are measured close to the locomotive ultra-rapid circuit breaker. To estimate the voltage drop across the braking rheostat, two voltages at the input of the braking chopper have been monitored: $V_{downstream\_filter}$ and V_{half_filter} detected, respectively, downstream the filter inductance and between the two series-connected filter capacitances. Four current transducers have monitored the chopped current flowing in the two braking rheostat sections; two different sensors, a Rogowski coil and an openable LEM probe, have monitored the same current. Fig. 2 shows a collection of pictures of the arrangement of the measurement system. The voltage transducers, the supply systems of the current transducers and the acquisition system have been placed in the ground-connector cabinet (Fig. 2 a). The transducers for the braking rheostats have been placed at the input box containing the rheostat elements and the cooling system (Fig. 2 b). The transducer for I_{pant} (Fig. 2 c) and the acquisition system (Fig. 3 d) have been accommodated in the HV switchgear.

III. Measurement Setup

The already installed measurement system commonly adopted for monitoring electrical quantities on-board trains acquires only voltage and current at pantograph with a typical sampling rate of 10 Hz, and do not perform any energy analysis. It is apparent that data obtainable from this kind of systems do not allow a comprehensive analysis of energy flows and not even detection and analysis of power quality phenomena such as electric arcs, rapid voltage or current variations of the pantograph, analysis of the behaviour of the chopper of braking resistors and so on. For this reason, a specific additional measurement system able to acquire with

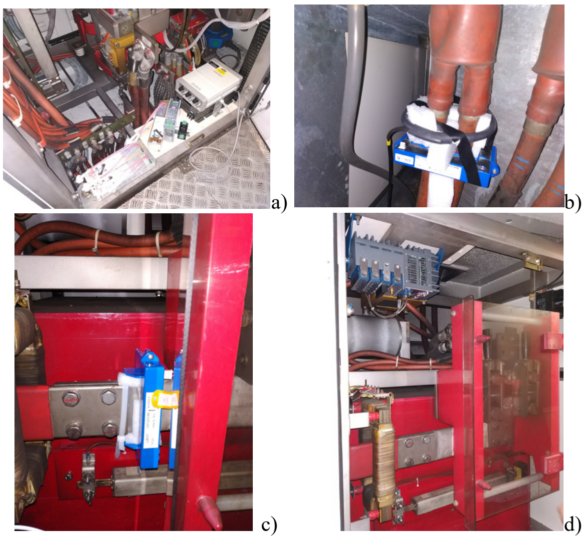

Fig. 2. Voltage transducers and measurement supply system a) current transducers for rheostat monitoring b), transducer for current measurement at the pantograph c), Compact Rio arrangement d)

high sampling frequency content was designed, implemented, tested, installed on board. The system has been implemented with a National Instruments Compact Rio 9034: it is a stand-alone reconfigurable embedded chassis with integrated real-time controller and, thanks to its reduced size, it could be positioned on train as well as in the substations. Compact Rio 9034 is equipped with a 1.91 GHz Quad-Core Processor, 2 GB RAM DDR3, SD port for data storage and Kintex-7 325T Field Programmable Gate Array (FPGA) for hard real-time tasks. For this measurement campaign two NI 9223 voltage acquisition modules with 16 bit resolution, maximum voltage input 10 V, 50 kHz sampling rate, 4 channels each and synchronized sampling among all 8 channels were used. Furthermore, the GPS module NI 9469, capable of providing a Pulse Per Second (PPS) with an accuracy of 100ns has been used for time synchronization. Finally, the temperature module NI 9211, 14 Samples/s Aggregate, ±80 mV, 16 bits includes anti-aliasing filters, open-thermocouple detection, and cold-junction compensation for high-accuracy thermocouple measurements, has been used for monitoring the temperature inside the rheostat room.

For the measurement of the pantograph voltage, the voltage downstream the filter inductance and the voltage at the centre of the capacitances, resistive-capacitive voltage divider were used. The nominal transducer ratio is 1000/1 and this transducer is designed for making accurate high voltage in-line measurements, view and measure ac ripple & noise on DC high voltage and AC signal up to 10MHz, with an accuracy error of 0.25%.

Fig. 3 Measurement chain on-board train

For the measurement of the total current absorbed by the locomotive, the LEM HOP 2000 transducer has been used. The primary nominal rms current of this Hall Effect based transducer is 2000A, with an output voltage of 4 V. It has a flat frequency response from DC to 10 kHz with a supply voltage (±5%) is 15 V. The accuracy is <±2%. The accuracy is not so high but the possibility to insert the probe without interrupting the power circuit, its dynamic and the dimension of the window makes this a winning choice.

To measure the power dissipated by breaking rheostats, two types of transduces have been used for the current: LEM HOP 800 and Rogowski Coil. LEM HOP 800 have a nominal current of 800A and a bandwidth of 10 kHz. The same signals are measured with Rogowski coil because these probes have a wider band, actually up to 200 kHz. All the transducers were previously characterized at INRIM laboratories.

The measurement chain installed on-board the train is shown in Fig. 3. The supply system is connected directly to the train battery (1) for having a continuous monitoring of the trains signals even when the pantograph is not in contact with the catenary. Downstream the battery, a magneto-thermic switch (2) and a DC/DC 24V-24V (3) are present for safety and isolation reasons. There are also present a DC/AC 24V-220V converter (4) for the supply of the Rogowski Coil integrator (5) and a DC/DC 24V±15 V converter (11) for the supply of LEM HOP transducers (12). The acquisition system was made by a Compact Rio (7) with the GPS module (8), the temperature module (9) and two acquisition modules (10), directly connected to Rogowski Coil (6), LEM HOP transducers and Ultravolt transducers (13).

After the installation, the measurement system was set for continuous acquisition and storage mode for about three month. It had monitored 88 journey with about 2 terabytes of data recorded with a sample frequency of 50 kHz.

IV. Power and Energy Computation

In order to measure the energy flows during different steady state and dynamic conditions due to different working operations of the train, reference was made to the definition of the active energy E_a exchanged during a time interval T, thus:

$$E_a = \int_0^T P(t)dt = \int_0^T v(t)i(t)dt \qquad (1)$$

where *P(t)* is the instantaneous power, *v(t)* the considered voltage, *i(t)* the considered current, *T* is the considered time period. Appling this definition to sampled signals, it results

$$E_a = \int_0^{NT_c} v(kT_c)i(kT_c)dt \cong \qquad (2)$$

$$\cong \sum_{k=0}^{N-1} v[k]i[k] \cdot T_c \qquad (3)$$

where *Tc* is the sampling period, *N* is the number of sample in *T, v[k]* and *i[k]* the k-th samples acquired on voltage and current respectively.

So that it is apparent that the total amount of energy is the sum of all the N energy contributions, each of them is associated to one of the N sampling interval and obtained multiplying *Tc* by the k-th sample of voltage and current. In practice, it is useful to refer to the power associated to the k-th time interval as:

$$p[k] = v[k] \cdot i[k] \qquad (4)$$

that is the values are the k-th sampled values of instantaneous power. So that the total energy can be calculated by

$$E_a = T_c \sum_{k=0}^{N-1} p[k] \qquad (5)$$

The value obtained, applying the (4) and (5) to all the samples of voltage and current acquired during a whole journey, is the net balance of energy required for the journey.

In addition, it can be interested to evaluate separately the amount of energy, E_{diss}, dissipated by the train for the traction and the auxiliary services and amount of energy, E_r, generated by the loco during breaking and injected in the supply system in order to re-used by another train.

To this aim, starting from (4), it is possible to define the power dissipated in the k-th time interval $p_{diss}[k]$, simply considering only positive values of active power, thus:

$$p_{diss}[k] = \begin{cases} p[k] & if\ p[k] > 0 \\ 0 & if\ p[k] \le 0 \end{cases} \qquad (6)$$

Equally to define the power recovered in the k-th time interval $p_r[k]$, simply considering only negative values of active power, thus:

$$p_r[k] = \begin{cases} -p[kT_c] & if\ p[kT_c] < 0 \\ 0 & if\ p[kT_c] \ge 0 \end{cases} \qquad (7)$$

So that, dissipated energy E_{diss} and the recovered energy E_r during the time interval T can be calculated as:

$$E_{diss} = T_c \sum_{k=0}^{N-1} p_{diss}[k] \qquad (8)$$

$$E_r = T_c \sum_{k=0}^{N-1} p_r[k] \qquad (9)$$

The analytical treatment until here was conducted mainly referring to total active energy absorbed by train but, obviously, energy dissipated by the rheostats can been computed by using the same approach. In this case, all the active energy is always positive and thus dissipated.

V. DC Current transducers under chopped waveforms

The accurate measurement of the braking chopped current is a very challenging task since the signal has the basic information in DC but this signal has continuously fast pulsed transient event during the conductive stage of the chopper. The current to be measured is pulsed from 0 A to a peak value that can varies from 900 A to about 1300 A depending on the amplitude of the supply voltage. The width of the pulse depends on the braking strength and on the receptivity of the supply line. The maximum duty-cycle is of 50%. This kind of signals is particularly challenging for transducers as they have to start their measurement from DC and to have, at the same time, a very high frequency bandwidth to properly follow the transient event. With the aim of performing a scientific activity on this topic, two probes with different measurement principles and bandwidths have been used to measure the same quantity: an openable LEM sensor based on the zero flux principle with a bandwidth from DC to 10 kHz and a Rogowski coil with a bandwidth from some hertz to 200 kHz. The Rogowski coils have a wider frequency bandwidth but they act as a high pass filter so that DC component is eliminated and signal average values is zero (see the uncompensated waveform in fig. 4). Nevertheless, the shape of initial signal can be recovered with proper signal processing that estimates the negative floor and sum it the signal recovering the DC component (see the compensated waveform in fig. 4). In the adopted procedure, the estimation of the negative floor was done each pulse as the negative floor depends on the duty cycle. After compensation, energy results of a complete journey performed by Rogowski coil and Hall effect transducer differed less than 0.5%.

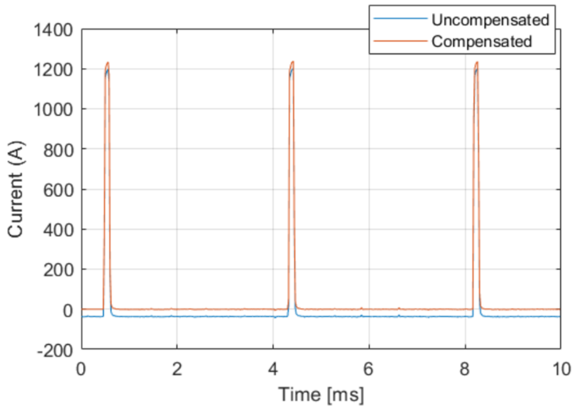

Fig. 4. Rogowski current before and after compensation

It is also interested to analyse, to the different response of the two different transducers at the pulse solicitation. Fig. 6 reports the different shape of the same impulsive current transduced by the Rogowski coil after compensation and the Hall effect transducer. Rogowski transitions are sharper due to the wider frequency bandwidth but the reached level is slightly lower. The Hall transducer shows a little underdeviation during the negate slope of the pulse.

VI. ENERGY ANALYSES

Fig. 5 shows the values of the instantaneous power absorbed by the train along the Bardonecchia-Torino way, as an example of data analysed for a complete journey. Intense braking and acceleration phases due to the high difference in altitude between the two stations (about 1000 m) characterize this journey. The negative power is the one that train sends back to the supply line during the braking stage.

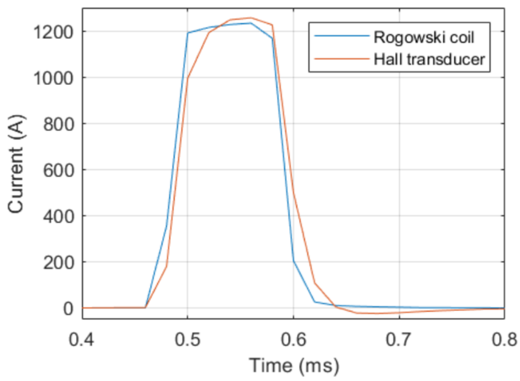

Fig. 6. Comparison between impulsive response of Rogowski

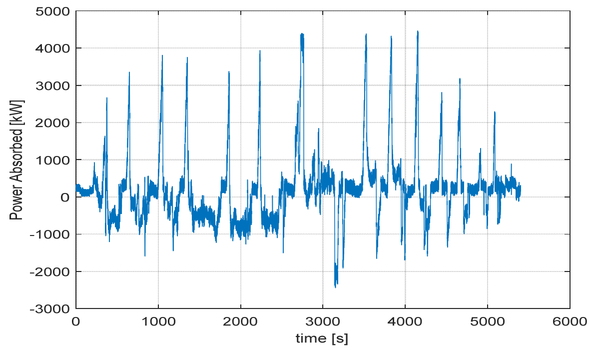

Fig. 5. Time behavior of the instantaneous power during the Bardonecchia – Torino way

Table II: Braking Energy Analysis of several drafts

RAILWAY DRAFTS	Absorbed Energy [kWh]	Breaking Energy [%]	Wasted Energy [%]	Recovered Energy [%]
Acqui terme Alessandria	282.5	23	20	3
Alessandria Acqui terme	397.9	6	4	1
Alessandria Savona	978.9	21	9	12
Savona Alessandria	940.3	22	14	8
Alessandria Voghera	372.4	15	6	9
Voghera Alessandria	327.7	23	5	18
Novara Domodossola	982.9	15	9	6
Domodossola Novara	837.5	19	14	5
Mortara Novara	201.0	10	5	5
Novara Mortara	231.6	23	12	12
Novara Domodossola	962.0	17	17	0
Domodossola Novara	843.7	15	11	4
Bardonecchia Torino	302.4	150	50	100
Torino Bardonecchia	1580.8	8	1	7

Table II shows the total absorbed energy values compared with the total electrical energy generated during the braking for different journeys. The breaking energy is then splitted into wasted and recovered energy. Moreover, it is apparent that for most of the journeys, a remarkable percentage of the braking energy is not recovered and wasted. These figures depend on the capability of the DC supply system to receive such energy and obviously it changes in different days.

VII. COLLECTION OF POWER QUALITY EVENTS

From a first analysis of collected data, numerous interesting events and trends have been detected. For sake of brevity, three transient events are shown and discussed: i) the high frequency oscillation experienced on the voltage at the pantograph, ii) the arc voltage events and iii) the effect of the connection of locomotive auxiliary burdens. In the end, the analysis in the frequency domain for a specific journey has been provided and discussed.

A. High voltage oscillation

The record of the voltage at the pantograph shows many fast deep/swell voltages. Fig. 7 provides an example of the amount of such fast transient events detected on one journey on the line Bardonecchia – Torino. As can be seen, voltage deeps of hundreds of volts occurs, in some case, even deep of one thousand of volt is detected. The reason of such events is under study. A correlation between some of these fast oscillation on the voltage at the pantograph with the current absorbed by the train has been found. Fig. 8 shows the

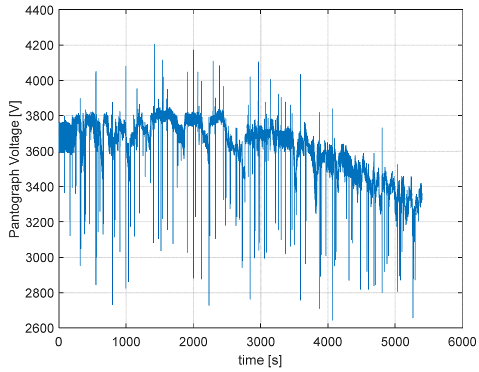

Fig. 7. $V_{upstream}$ recorded during the Bardonecchia – Torino journey

occurrence of the transient oscillation on the voltage at the pantograph of about 1 kV of peak-to-peak of magnitude in correspondence of a step on the total current absorbed by the train of about 10 A – 15 A. This behavior could be introduced by the insertion of a filter of an electrical burden installed on board one of the coach carried by the locomotive.

B. Pantograph to overhead contact line arc events

One important event that can affect the quality of the power exchanged between the train and the supply system is the electrical arc that can occur between the pantograph and the overhead line due to detachments between the two electrodes of the sliding contact. The effect of one of such event conducted on the overhead contact line and measured during the measurement campaign is shown in Fig. 9. As described in [6], an electric arc provokes a voltage deep whose deepness depends on the distance between the two sliding contacts, it can ranges between tens and hundreds of volts. During the voltage deep, even the current at the pantograph decreases, following a damped oscillation behavior. The current oscillation frequency mainly depends on the cut-off frequency of the locomotive input stage filter.

C. Connection of locomotive auxiliary burden

A particular event has been detected on one of the journey along the line Alessandria – Novara. Fig. 10 shows the current and voltage at the pantograph and the voltage downstream filter recorded during a transient event. The current steps up through a damped oscillation behavior from 40 A to 70 A for 250 ms reaching a peak value of 110 A. This current behavior provokes an opposite voltage oscillation on both at the pantograph and downstream the filter. This behavior can be explained by the connection/disconnection

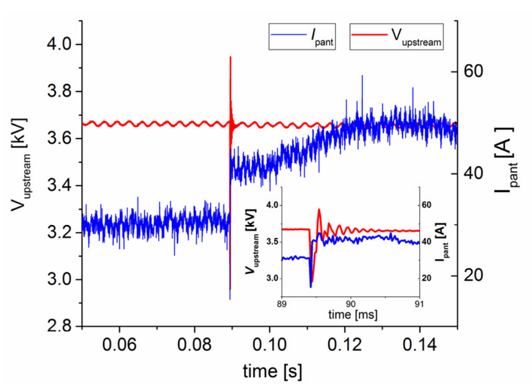

Fig. 8. Voltage and current at the pantograph during a fast transient event.

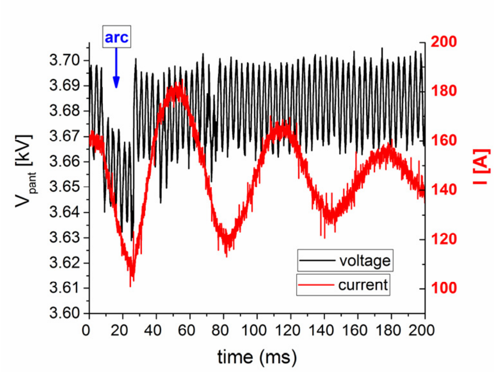

Fig. 9. Effects of arc voltage events measured at the voltage and current at the pantograph

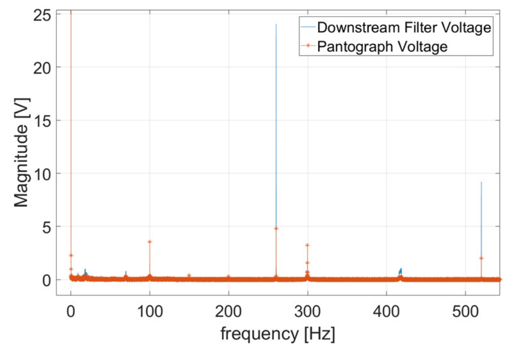

Fig. 12. Voltage spectrum during a braking stage

of a locomotive auxiliary burden. In fact, an event occurring at the overhead contact line is filtered and it is not present downstream the filter, in this case, the event occurs downstream the filter. The higher amplitude oscillation detected downstream voltage respect to the voltage at pantograph proves this explanation.

D. Harmonic component on Voltage Line and Rheostatic current

An important event of power quality is the presence of the 300 Hz tone introduced by the hexafase AC/DC converter present in the substation. For the analysis of this tone a Fast Fourier Transform (FFT) operation was performed on successive periods of 1s duration. Fig. 11 shows the behaviour of the 300 Hz ripple along the Bardonecchia-Torino line. As can be seen, a greater amplitude is detected in the Bardonecchia station and decreases gradually towards the Torino station.

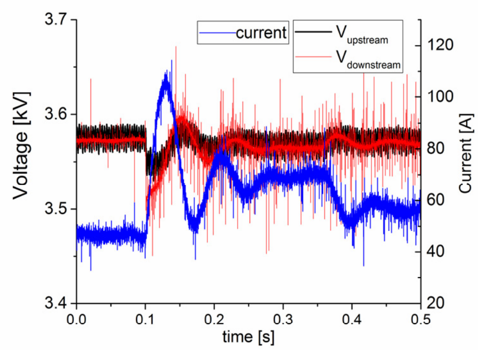

Fig. 10. Effects of the insertion of an auxiliary burden on the current and voltage at the pantograph and voltage downstream the filter

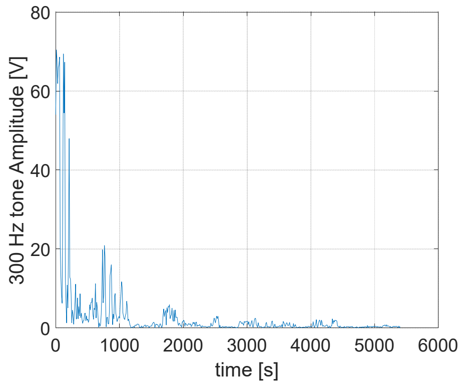

Fig. 11. Behavior of the 300 Hz pantograph voltage ripple along the Bardonecchia – Torino line

CONCLUSIONS

The paper have presented the technical solutions and the setup arrangement for the measurement of the power/energy absorbed and generated by a 3 kV DC locomotive, operating in commercial service, the amount of electrical power/energy recovered and wasted during a braking stage and the quality of the power at the pantograph. Post-processing algorithms for correcting the measured braking chopped current and the algorithm for the computation of power and energy have been described. A huge amount of data have been collected for the 88 journey monitored. A collection of interesting results for what concern the electrical power generated during the braking stage and the capabilities of recovering this energy has been provided. Moreover, a collection of power quality event has been presented and discussed; a first description of possible reason of such event is also provided. This contribution is a valuable starting point for future activities related to the standard definition of power quality events and to the development of PQ event detecting systems.

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