Discussion on DC and AC Power Quality Assessment in Railway Traction Supply Systems

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Abstract—**The assessment of the power quality could be a valuable tool to foster the efficiency of the whole railway system by "awarding" the good power quality delivered and absorbed. Power quality is a well-addressed topic in conventional AC 50/60 Hz power systems and many procedures, algorithms and measurement systems were presented in international standards and widely discussed in the scientific literature. A less explored research field is the assessment of the power quality in the railway traction supply systems, through standardized monitoring techniques, in particular with reference to the DC and 16.7 Hz systems. This paper explores this theme verifying if main aspects of the standard measurement procedures and the definitions of some of main power quality indexes, well defined and widely used for conventional power systems, can be used also in railway traction supply systems with minor modifications.**

Keywords—Power system measurements, AC and DC railway system, AC and DC Power Quality, Power Quality measurements.

I. INTRODUCTION

In railway systems, electrical locomotives are single-phase loads for the traction supply system. As the speed and mechanical conditions of the train change frequently, these electrical loads can appear to have a low power factor, with high contents of harmonic currents injected, and negative-sequence currents generated [1]-[3]. So, the assessment of the Power Quality (PQ) could be a valuable tool to foster the efficiency of the whole railway system by "awarding" the good PQ delivered and absorbed. For this reason, there is a great interest in the research community and in the stakeholders in developing and applying PQ concepts also to railway system [4]- [9]. Despite of this interest on the generated conducted disturbances (f.i. voltage fluctuations, voltage and current unbalance, harmonics, reactive power compensation, etc.) [10]-[17], few researches address the problem of assessment of the PQ issues in Railway Traction power supply System (RTS), through a standardized monitoring techniques. So, at the moment, there is a lack of international standards that univocally define PQ indexes, measuring procedures, and the corresponding compatibility and immunity thresholds, with specific reference to the train supply system. Therefore, at present, some topics are completely uncovered, for instance PQ measurement in the railway system at DC or 16.7 Hz. A better situation can be found in AC 50/60 Hz system as there is a sound tradition in PQ measurement developed for other AC power system that are covered by comprehensive standards [18],[19]. However, these standards are not directly applicable to the RTS. The PQ assessment in common DC power networks, at present, is still an open issue and there are only a few proposals in the technical literature for definition measurement techniques of PQ disturbances [20]-[22]. The work presented in this paper is inserted in the context of the European project EMPIR 16ENG04 MyRailS [7]. One of the object of this project is to develop a metrological framework for calibration (comprising laboratory and on-board train calibration/measurement set-ups and robust data processing algorithms) to enable high accuracy energy and PQ measurements in RTS. To this aim, as a first step, before starting with new definitions, PQ indexes and measurement algorithms/instruments, well defined and widely used for conventional power systems, should be analysed to evaluate the possibility of an extension of their applicability to RTS. This paper is organized as follows. Section II shows a brief description of main railway supply power systems. Section III is focused on the applicability of some standard PQ measuring procedures to RTS. Section IV presents some PQ indexes identifying the limitations in their applicability and proposing some extensions. Finally, in Section V the conclusions are drawn.

II. DESCRIPTION OF MAIN RAILWAY SUPPLY POWER SYSTEMS

Energy, generated by power stations, is supplied to moving trains with a (nearly) continuous transmission lines running along the track that usually takes one of two forms: overhead line, suspended from poles or towers along the track or from structure or tunnel ceilings; third rail mounted at track level and contacted by a sliding "pickup shoe". Both overhead wire and third-rail systems usually use the running rails as the return conductor but some systems use a separate fourth rail for this purpose [1]. The technologies available in traction regarding the transmission of power, voltage levels and speed control of traction drive motors have led, over time, to the adoption of different technological solutions that persist to date. So that there is a wide variety of solutions still adopted in the same country, both in DC or AC supply voltage (see TABLE I. [2] and Fig. 1). In the AC system the energy is taken directly from main high voltage grid and reduced to lower level (i.e. 12.5 kV at 60 Hz, 20 kV at 50/60 Hz, 25 kV at 50/60 Hz, 2x25 kV at 50 Hz). These systems are adopted in Russia, Italy, France, Japan, India, former Yugoslavia, China, Great Britain, Hungary, Finland, and so on. There are also single-phase alternating current systems at the special frequency of 16.7 Hz at 15 kV. In details Norway, Sweden and northern Germany still use 16 2/3 Hz (50/3 Hz). Austria, Switzerland and southern Germany use to 16.7 Hz, (no longer exactly 50/3 Hz): in total, the single-phase European network at 16.7 Hz covers over 33,000 km. In the United States, the

TABLE I. WORLD ELECTRIC RAILWAY FEEDING SYSTEM AND ELECTRIFICATION DISTANCE [2].

System Type			**km**	**%**	**Main Countries**
DC	Less than 1.500 V		5,106	2	Germany, UK, Switzerland, USA, Japan
	1.500 V to 3.000 V (Mostly 1.500 V)		22,138	9	Netherlands, France, Spain, Australia, Japan
	3.000 V or more (Mostly 3.000 V)		78,276	33	Russia, Poland, Italy, Spain, South Africa
Single-phase AC	50/60 Hz	< 20 kV	245	0	France, USA
		20 kV	3,741	2	Japan
		25 kV	84,376	36	Russia, France, Romania, India, China, Japan
		50 kV	1,173	0	USA, Canada, South Africa
	25 Hz, 11-13 kV		1,469	1	USA, Austria, Norway
	16.66 Hz	11 kV	120	0	Switzerland
		15 kV	35,461	15	Germany, Sweden, Switz.
Three-phase AC			43	0	Switzerland, France, Japan
Unknown			3.668	2	Kazakhstan, France
Total			235.816	100	

25 Hz frequency with 11-12 kV was adopted for single-phase AC electric traction. As for DC supply, in all classic urban transport trolley buses, trams, and metros, DC traction at 600-750 V or 1500 V is always used. The 750 V system is also used in metros on tires adopted in Paris, Montreal, Mexico City, Santiago, Lyon, and Marseille.

In the railway, the most significant electrical systems are the following:

- 750 V in DC;
- 1500 V in DC;
- 3000 V in DC;
- 15 kV in AC at 16.7 Hz;
- 25 kV in AC at 50/60 Hz.

Around the world, the development of electrified railways is greater than 200,000 km, namely, 17.2% of the global railway network [1]-[3].

A. DC

In Fig. 2 there is a simplified diagram showing a DC power supply system. The key feature of this system is a rectifier for conversion from alternating to direct current. Typically, a three-phase rectifier system with 6-pulse is used causing harmonics in the AC side and distortion in the voltage waveform, lowering the PQ. To reduce the harmonics, a more-modern rectifier design using a 12-pulse system featuring two sets of 6-pulse rectifying circuits, with AC input voltage phases 30° apart, connected in series or parallel, is used. In both cases, the adoption of a filtering system can improve the PQ level.

Normally, each track is fed in each direction towards the next substation. This allows a redundant supply and provides for continuity if one substation fails. The distance between sub-stations is about 5 km on metropolitan trunk lines and 10 km on other lines. Gaps in supply lines are located in the substations and in sectioning post for obtaining a zonal separation.

The gaps are usually marked by a sign or a light which indicates if the current is on in the section ahead. Since the current may have been switched off to stop an arc or because of a short circuit, it is important that the train does not connect the dead section to the live section by passing over the gap and allowing its busline to bridge the gap. Modern systems link the traction current status to the signaling so that a train will not be allowed to proceed onto a dead section.

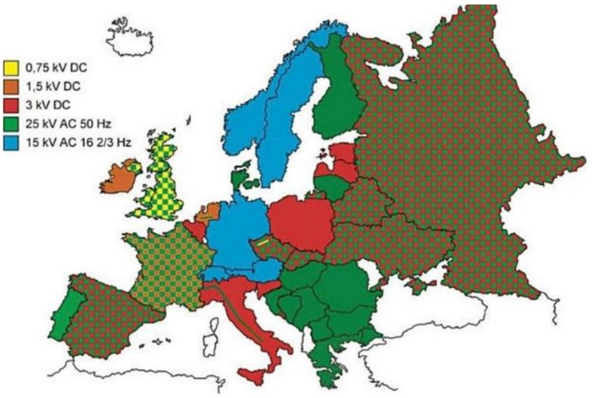

Fig. 1. European Electric Railway Feeding System

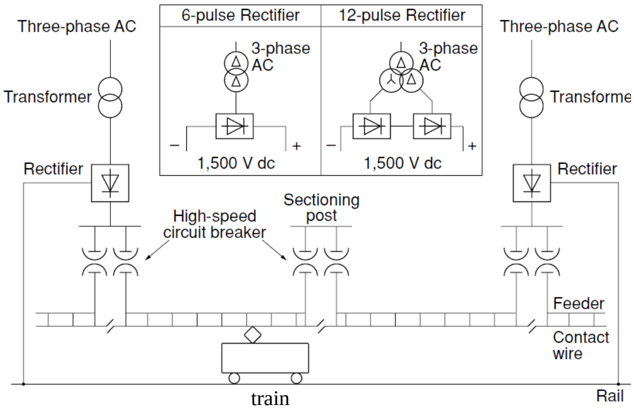

Fig. 2. Railway DC supply system [2]

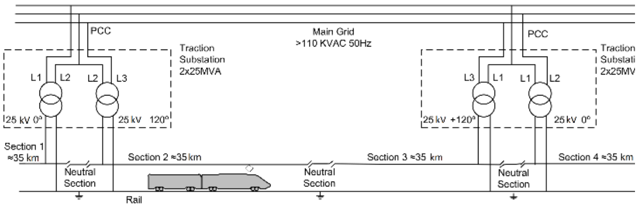

Fig. 3. Railway AC supply system

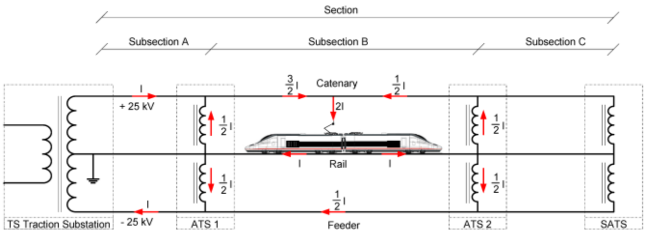

Fig. 4. Railway 2x25 AC supply system

B. AC

In Fig. 3 there is a simplified diagram showing an AC power supply system for railway. Since three-phase power from the utility is converted into two single phases, to ensure that the current is as close as possible in the three supply lines, a separate phase feeds each of the up and down tracks.

Overhead lines are normally fed in sections like DC rail systems, but AC overhead sections are usually much longer. The distance between sub-stations is about 20 km. Each subsection is isolated from its neighbor by a section insulator in the overhead contact as shown in Fig. 3. The subsections can be joined through special high speed section switches. To reduce the arcing at a neutral section in the overhead catenary, some systems use track magnets to automatically switch off the power on the train on the approach to the neutral section. A second set of magnets restores the power immediately after the neutral section has been passed. In recent year, the 2 × 25 kV system was introduced for high-speed rail, see Fig. 4. This system adopts autotransformers (ATS) supply 25 kV power to the trains, but transmits power at 50 kV to reduce energy losses. In this system, the current is mainly carried between the overhead line (catenary) and a feeder transmission line instead of the rail. The catenary and feeder are on opposite phases, so the voltage between them is 50 kV, but the voltage between the catenary and the running rails remains at 25 kV. Periodic autotransformers (ATS), every 10 km along the track, divert the return current from the neutral rail, step it up, and send it along the feeder line. This is very effective in reducing inductive interference in telecommunications lines. This system is ideal for high-speed and large capacity train because there are reduced voltage drops and EMI.

III. STANDARD PQ MEASURING PROCEDURE APPLICABILITY

There is a wide interest on the conducted disturbances in RTS (f.i. voltage fluctuations, voltage and current unbalance, harmonics, reactive power compensation, etc.). But at the moment, there is a lack of international standards that univocally define PQ indexes, measuring procedures, and the corresponding compatibility and immunity thresholds, with specific reference to the railway supply system. Obviously, the first attempt, before starting to define new PQ indexes or measurement procedures, must be to try the applicability, at least for 50/60 Hz RTSs, of what has already been defined for other power supply systems to verify the possible utilization of commercial and common PQ monitoring instruments. To this end, the next sections will refer to the IEC 61000 family standards [18][19], discussing the applicability of some of main PQ indexes identifying problems or limitations of their applicability to AC RTS. In addition, the possibility of an extension with minimal changes of the standard procedures to other RTS (DC and 16.7 Hz) will also be explored.

A. *PQ Monitoring Location*

Generally speaking, the choice of locations where to install PQ monitor devices is dependent upon the objective of the survey [26]-[32]. If the monitoring objective is to diagnose an equipment performance problem, then the monitor should be placed as close to the load as possible. This applies to performance problems with both sensitive electronic loads such as computers and adjustable speed drives, and electrical distribution equipment such as circuit breakers and capacitors in normal AC power system. For compliance monitoring related to service contracts, the monitoring location should be at the point of common coupling (PCC) between the customer and the system. So, in railway system, the monitoring of PQ indexes can take place in two main locations giving different information from different point of views: on board train and in the supply station. Monitoring on board train keep trace of PQ issues that the specific monitored train have faced during its journey connecting at different substations along its track. Monitoring a supply line within a substation gives information about problems of a specific supply site of a railway track that during the time of the day and in different days of the week has to feed different trains that pass from there. Both of them are interesting point of view. The first is mainly of interest of the train owner, the second is of interest of infrastructural manager. The two installation locations have very different impacts in terms of applicability of standard techniques of PQ measurements. With reference to 50/60 Hz system, PQ monitoring in substation, is quite similar to monitoring any power system with the peculiarity of having few very big and time varying loads so that even a commercial PQ monitoring instrument can be installed and profitably used. In this case, detection thresholds should be set accounting the particular system as discussed in the following. On board monitoring is much more complicated due to the structure of the supply system. In fact, due to dead neutral sections (see Fig. 3), in normal working conditions, the supply is periodically disconnected each few minutes (with a speed of 100 km/h, the distance of 10 km is covered in 6 minutes). A PQ monitoring device sees these events as periodic short interruptions (with a speed of 100 km/h, 110 m, the length of neutral section, is passed in about 4 s) that remarkably affects the calculation of all other PQ parameters. For this reason [18] introduces flagging concept: during a dip, swell, or interruption, the measurement algorithm for other parameters (for example, frequency measurement) might produce an unreliable value. The flagging concept avoids counting a single event more than once in different parameters (for example, counting a single dip as both a dip and a frequency variation), and indicates that an aggregated value might be unreliable. If during a given time interval any value is flagged, the aggregated value (at 3s or 10 min) which includes that value shall also be flagged. With the described timing, all the 10 min vales would be unreliable. With shorter time aggregation (i.e. 1 min), only 10% of results is expected to be unreliable so obtaining much more useful data. Anyway, it is possible to refer to 3 s values although even for these values about 0.2% has to be considered unreliable. For DC and 16.7 Hz RTS, commercial PQ monitoring systems and standard measuring procedures are not directly applicable in any locations, as their working lays on the synchronization with a 50/60 Hz signal that in both case is missing. In addition, even with specialized monitoring devices, due to dead sections in DC (see Fig. 2) and neutral sections in AC (see Fig. 3), the same issues previously described would arise for on board monitoring.

B. *Measurement aggregation Time*

In [18], the basic measurement time interval prescribed for PQ measurements is about 200 ms (exactly 10 cycles of 50 Hz and 12 cycle of 60 Hz). The 10/12-cycle values are then aggregated over two main intervals: about 3 s (150/180 cycles for 50/60 Hz), and exactly 10-min interval of absolute time. The 10/12-cycle measurement have to be re-synchronized at every UTC (coordinated universal time) 10-min tick with a partial overlapping of measurement data. It would be desirable to select the same time intervals also for all RTSs. In DC system the same time intervals can be adopted defining them with reference to the absolute time. A difficult arises in the 16.7 Hz: where in 200 ms there are 3.34 cycles. In order to reach an integer number of cycles the time intervals should be defined as about 180 ms (exactly 3 cycles) and about 3 s (50 cycles) and exactly 10-min. With the described extension in the basic measurement time and in the aggregation intervals, the measurements for all AC supply systems (DC, 50/60/16.7 Hz), can be almost resynchronized each 10 s because in 10 s there is an integer number of all basic measurement periods at nominal frequency. Anyway, for on board monitoring, 10 min time interval is useless for issues previously described. A shorter time interval (f.i. 1 min or less) could be adopted for this kind of monitoring.

IV. PQ INDEXES ANALYSIS

In the following, some of the main PQ indexes are discussed in term of their applicability to monitoring a RTS. For the definition and the measurement procedure, reference was made to standards [18],[19]

A. *Voltage Interruption*

A voltage interruption applies when supply voltage falls below a certain threshold (i.e 10% of nominal amplitude) for a certain time. For detecting of an interruption, reference is made to the value of U_{rms}(½): the r.m.s. voltage measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle. The characterizing parameter of the phenomenon is the duration, [18]. For all AC RTS, this index can be defined and measured in similar way. For DC RTS, there is only needing of defining amplitude of DC and, to this aim, the arithmetic mean value of samples measured in 20 ms and refreshed each 10 ms could be adopted but even longer time interval can be chosen with minor loss of information. With this extension, the monitoring of this parameter in the substation can be performed for all RTS. Instead, monitoring of this phenomenon on-board train is not a trivial task due to normal and periodic interruption that train supply has due to neutral or dead sections. For interruption of duration around 4 s, it is very difficult to distinguish a true PQ phenomenon from interruptions due to the normal disconnection of the supply system. Additional information could help (train position and velocity), but it is practically impossible to monitor properly short interruptions. For durations less than 1 s (at 300 km/h the neutral section is passed in about 1.3 s) and longer than 10 s (at 40 km/h the neutral section is passed in about 10 s) interruptions can be correctly detected and measured. The accuracy in the duration measurement is limited at half cycle due to the synchronization with the zero crossing prescribed by the standard [24]. The effect has greater impact in the 16.7 Hz system. An enhanced resolution is preferable and it is obtainable if a new amplitude value is calculated at each new sample acquired [22],[23].

B. *Voltage Dip and Swell*

Voltage dips and swells are defined in a very similar way to interruptions: a voltage dip/swell applies when the value of U_{rms}(½) falls/rises below/above a certain threshold. The adopted thresholds are 90% and 110% of nominal amplitude, respectively. These events are characterized measuring the duration and the minimum/maximum voltage magnitude during the event, [18]. With minor extension of the definition, as already done for interruption, these parameters can be measured in all RTS and can be monitored both in the substation and on-board (neutral and dead sections are not a problem for dip detection as they produce an interruptions). Nevertheless, in practical application, some difficulties arise in the properly detection of these phenomena. In fact, the nominal voltage and their permissible limits according with [25] are reported in TABLE II. Moreover in [25] the following indication can be found:

a) under normal operating conditions, voltages shall lie within the range [U_{min1}, U_{max2}];
b) under abnormal operating conditions the voltages in the range [U_{min2}, U_{min1}] shall not cause any failures;
c) the duration of voltages between Umin1 and Umin2 shall not exceed 2 min;
d) the duration of voltages between U_{max1} and U_{max2} shall not exceed 5 min;

TABLE II. NOMINAL VOLTAGE AND THEIR PERMISSIBLE LIMITS.

Electrification system	**Lowest non-permanent voltage**	**Lowest permanent voltage**	**Nominal voltage**	**Highest permanent voltage**	**Highest non-permanent voltage**
Symbol	***Umin2***	***Umin1***	***Un***	***Umax1***	***Umax2***
Unit	***[V]***	***[V]***	***[V]***	***[V]***	***[V]***
DC (mean values)	500 1.000 2.000	500 1.000 2.000	750. 1.500. 3.000.	900.. 1.800. 3.600	1.000. 1.950. 3.900
AC (r.m.s. values)	11.000 17.500	12.000 19.000	15.000[a] 25.000[b]	17.250 27.500	18.000 29.000

a) 16,7 Hz.
b) 50 Hz and 60 Hz.

e) the voltage of the busbar at the substation at no load condition shall be less than or equal to U_{max1}. For DC substations, it is acceptable to have this voltage at no load condition less than or equal to U_{max2}, provided that when a train is present, the voltage at this train's pantograph(s) is in accordance with Table II and its requirements;
f) voltages between U_{max1} and U_{max2} shall only be reached for non-permanent conditions such as regenerative braking, move of voltage regulation systems such as mechanical tap changer;
g) lowest operational voltage: under abnormal operating conditions U_{min2} is the lowest limit of the contact line voltage for which the rolling stock is intended to operate;
h) recommended set values for undervoltage tripping relays in fixed installations or on board rolling stock are from 85 % to 95 % of U_{min2}.

It is apparent from the recalled requirements that supply voltage is expected to be less stable than normal power system. So, tight detection thresholds (i.e. ±10%) would results in continuous unuseful event detections. These large variations (see TABLE II.) are allowed as the power absorbed by trains is not negigleble with respect to the short circuit power of substations and so it is normal that significant voltage drops applies when train requires a significant amount of power. Moreover, during on board monitoring, an increased drops are expected with the increasing of the distance from the substation due to increasing of the supply impedence. As side consideration, it is obvious that in this situation flicker measurement is useless. With the described indications, the dip/swell detection and classification is much more complicated as, in general, it is necessary to manage the comparison with 4 thresholds and calculating different time intervals for different threshold crossings. Limit assessment requires information also on the presence of trains in substation and on the braking state. This paper is within the MyRailS project activity [7] that includes extensive PQ monitoring, both in substation and on-train, in different RTSs that, at the moment of writing, are going to be scheduled. Anyway, to have an idea of realistic experimental data that should be analyzed, some preliminary results are here reported. Fig. 5 reports the voltage at pantograph of a 3 kV DC RTS measured on board of train E412 during its leaving from a substation. Fig. 6 reports the corresponding absorbed current. The level of voltage is high as expected in substation and at each consistent increment of absorbed current the voltage drops remarkably. The level is higher than U_{max1} but it should be not considered a voltage swell as train is close to a substation (time 0-20 s and 40-70 s).

But as soon as a certain speed was reached, the brakes were activated to stop the train, as it was a brake testing (time

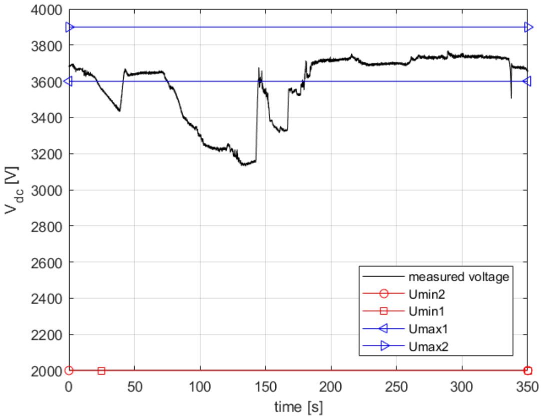

Fig. 5. Supply voltage measured on board of loco E412

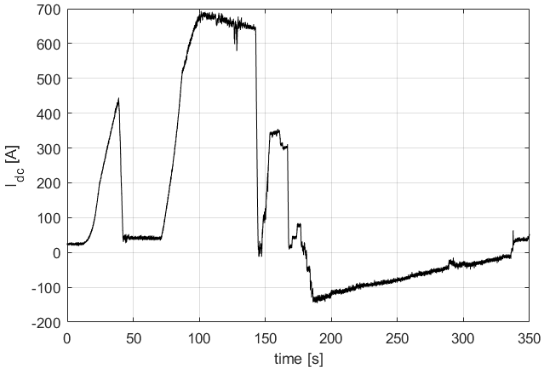

Fig. 6. Absorbed current measured on board of loco E412

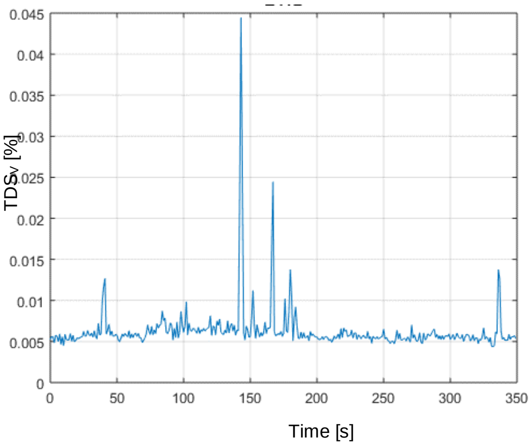

Fig. 7. Total Spectral Distortion of signal in Fig.5

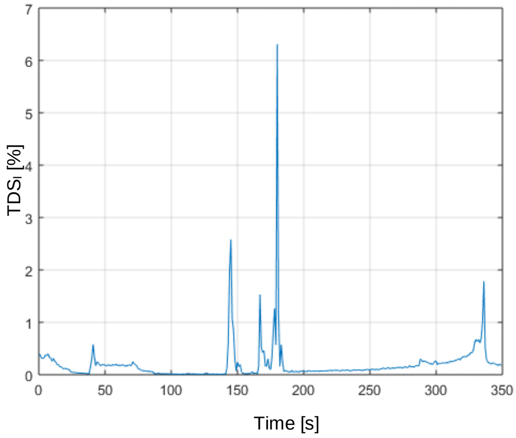

Fig. 8. Total Spectral Distortion of signal in Fig.6

180-340 s). Also in this case the tension increases but for the regenerative braking.

C. Harmonic & Interharmonic

In [19], spectral pollution is evaluated by Fourier series expansion: each group of M samples forms a time window on which DFT is performed; the window width T_N determines the frequency resolution $f_C = 1/T_N$ (i.e. the frequency separation of the spectral components) for the analysis. Therefore the window width T_N must be an integer multiple N of the fundamental period T_1 of the system voltage: $T_N = N \times T_1$. The sampling rate is in this case $fs = M/(NT_1)$ (where M = number of samples within T_N). The adopted window width is 10/12 (50/60 Hz systems) fundamental periods ($T_N \approx 200$ ms in both cases). To improve the assessment accuracy, the obtained spectral components are grouped obtaining reliable pollution indexes (harmonic and interharmonic subgroups) and deriving cumulative pollution index: THD, THDG ([19]). Obviously, the same approach can be used in motoring RTS at 50/60 Hz.

Only on board monitoring is complicated by periodic disconnections due to neutral section so preventing to adopt longer aggregation time interval. In RTS at 16.7 Hz the procedure can be applied with minor changes: the number of analysed cycle should be 3 ($T_N \approx 180$ ms). On this basis, harmonic subgroups and the consequent THD index can be properly calculated. Only the interharmonic pollution cannot be evaluated. In fact, due to the reduced number of periods adopted, the interharmonic components are no more calculated. In order to calculate also interharmonics, time window should be enlarged till 10 period ($T_N \approx 600$ ms) but this would result in a reduced time resolution for fast transitory harmonic events. In DC RTS, there is no basic periodicity to account, so it is meaningless to talk about harmonic and interharmonic pollution. Anyway, it could be useful to refer also in this case to 200 ms for time window so obtaining components, groups and comprehensive indexes in similar way to that adopted in other systems but in this case it is more appropriate to speak generically about spectral pollution including all components. To this aim, as an extension of THD defined in [19], an index of Total Spectral Distortion (TSD) can be defined as ratio of the r.m.s. value of the sum of all the spectral components (Y_h) up to a specified index (h_{max}) to the reference value (Y_{ref})

$$TSD_Y = \sqrt{\sum_{h=1}^{h_{max}} \frac{Y_h}{Y_{Ref}}} \qquad (1)$$

where the symbol Y should be replaced, as required, by the symbol I for currents or by the symbol U for voltages. As for the reference value, the average value of acquired samples (DC value) can be used. For current, it could be also possible to adopt as reference value the train nominal current because otherwise when DC current value becomes nearly zero this results in unstable values of index. As an example of application, Fig. 7 and Fig. 8 report the TSD measured on the voltage reported in Fig. 5 and on the current reported in Fig. 6 adopting . In both cases, the DC components are adopted as reference values. The TSD levels are very low in both cases, only the parameter of the current distortion reaches non negligible levels at some specific time instants but this effect is due the nearly zero current DC value. Nevertheless, also in this case the average value of distortion is low. Although there is no basic periodicity, even in DC system it is useful to have a specific index to monitor separately the pollution around 50 Hz. In fact, the presence of this component is particularly feared by the managers of the DC railway system as it directly affects signaling systems. For this reason, there is already present a specific monitoring system that alarms and disconnects the system when the level of 50 Hz component reaches a non negligible level. To this aim, the (1) should be modified to include only spectral components that are located at frequencies near to the multiples of 50 Hz. For formal definition, reference should be made to Harmonic subgroup reported in [19]. For all RTS, a not trivial task is to define the compatibility/immunity thresholds. However, there are already some amplitude levels for harmonic currents defined for ensure compatibility.

V. CONCLUSION

This paper discussed some aspects of the assessment of the power quality, through standardized monitoring techniques, in the railway traction power supply systems. To this aim, the supply systems considered were the AC 50/60 Hz, AC 16.7 Hz and the DC. Some limitations to the power quality monitoring performed on-board the train have been reported, warning about possible negative effects on the reliability of the measured results, due to dead sections in DC and neutral sections in AC. Two extensions of definitions of basic measurement time intervals adopted in AC 50/60 Hz ware proposed to become applicable also in AC 16.7 Hz and the DC system. Finally, the measurement procedures of some of the main power quality index, well defined and widely used for conventional power systems (interruption, voltage dip/swell and harmonics), were analysed and extended with minimal changes to become compatible with all railway systems.

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