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Power quality in DC railway system: A facility to characterize the on-board detection systems

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***Abstract* – The liberalization of the railway market and the aim of fostering the interoperability among European countries makes the monitoring of the quality of the power (PQ) exchanged between trains and supply system even more important. At the moment, definitions, procedures and techniques for DC railway systems are under development. In this contest, the paper proposes a reference generation system able to reproduce the voltage and current waveforms experienced at pantograph by a DC 3 kV locomotive. The system is able to generate simultaneously voltage and current signals up to 10 kV peak and 1.2 kA peak respectively. The AC ripple which can be superimposed has a bandwidth of 30 kHz for the voltage and 600 Hz for the current. Moreover, it is able to reproduce several PQ events both with an accuracy, in the worst case of 1%.**

Keywords: DC power quality, DC railway system, electric arcs,

I. INTRODUCTION

With the aim of establishing a single European railway area, European Union passed legislation that gives rail operators the ability to run services in and between other EU countries, opening up cross-border competition. The presence of several railway undertakings and an independent manager infrastructure in the new scenario make the quality of the power exchanged between the train and the supply system an important aspect which has to be monitored with continuity [1]. Moreover, an accurate knowledge of real-time power quality of the railway supply system is a valuable tool to foster a high efficiency solution for the whole railway system by “awarding” for good power quality delivered and absorbed.

The development of techniques and procedures for the detection of power quality events in DC systems is a new topic. The state of the art related to the power quality in DC railway system is provided by standard EN 50163 [2] that defines the main characteristics of the supply voltage of traction system and EN 50388 [3] that establishes requirements for the compatibility of rolling stock with infrastructure. Both standards provide information related to the voltage at catenary but, does not consider all the possible events that can occur in the supply system and does not provide exhaustive description of the procedures that have to be applied for the power quality monitoring. Another aspect that makes the power quality a key point is the electromagnetic compatibility between the traction system and the electrical information that flows in the tracks for signaling purposes. In this case, restrictions are defined, in the frequency domain, for the current absorbed and injected by the rolling stock. At the moment, there are no European or International standards that provide such limits and procedure to estimate them. Only procedures provided by National infrastructure manager are available [4]. Researchers and working groups of standardization technical committees are involved in the study, classification and definition of the power quality events and metrics in the railway system. Beside the standard definition of power quality for DC railway system, there is an increasing development of measuring systems for the continuous and accurate monitoring of the power quality events. An interesting diagnostic approach, strictly connected with the power quality monitoring, is the monitoring of the impedance variation in a defined frequency bandwidth measured at the pantograph of a traction unit. All these new systems that exploits the measurement of the voltage and current at pantograph involve the voltage and current transducers, the acquisition system and algorithms for the detection of the defined parameters. In real conditions, the electrical signals are very distorted with different events occurring in the same time. Moreover, the non-linearity of the transducers can introduce spurious harmonics or corrupt the harmonic estimation.

A system able to reproduce the real electrical conditions experienced at the pantograph of a 3 kV locomotive can contribute in the estimation of the reliability of the developed measuring system without equipping a locomotive with new measuring systems for testing purposes. In this context, the aim of this paper is to provide a reference generation system that allows the characterization of the power quality measurement-chain detection under realistic conditions. The proposed system is able to reproduce, with a declared uncertainty, the voltage and current at a pantograph of a 3 kV DC

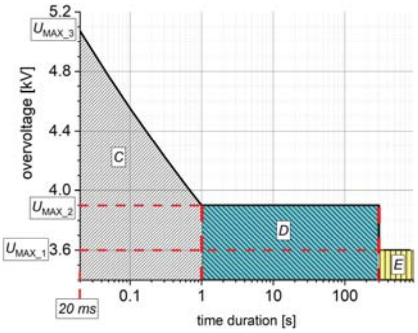

Fig. 2: Admissible overvoltage as a function of the time duration

locomotive, injecting both stead-state distortions (harmonics, inter-harmonics) and/or transient events with a frequency content of 30 kHz for the voltage and 600 Hz for the current. This facility can be used in the estimation of the reliability of the power quality and impedance monitoring systems that involves the voltage and current transducers the acquisition system and the detection algorithms in presence of multiple power quality events. An overview of railway DC power quality definitions is provided in Section II; Section III describes all the technical solutions adopted it the setting up of the reference generation system. Section IV provides an overview of the possible voltage and current waveforms and associated power quality events which can be generated.

II. PQ ACCORDING TO STANDARDS

Before starting with the description of the reference generation system, an overview on the in-force standards is provided in order to clarify the choices related to the generation capabilities of the proposed system. The main characteristics of the supply voltage traction system at European level are declared by [2]. The admissible long-term overvoltage, for the 3 kV supply systems is described in *Fig. 2*. Three different zones have been highlighted; zone *C*, *D* and *E*. Zone *C,* which describes the admissible long-term overvoltage, start from an event duration of 20 ms and stops at 1 s. the overvoltage limit curve is defined by the following formula:

$$U = U_{MAX\_2} \cdot t^{-0.0672} \quad (1)$$

The quantities $U_{\text{MAX-1}}$ $U_{\text{MAX-2}}$ and $U_{\text{MAX-3}}$ for a 3 kV supply system are equal to 3.6 kV, 3.9 kV and 5.07 kV respectively. For time duration between 1 second and 300 seconds, the maximum allowed voltage is 3.9 kV while for higher time duration the overhead contact voltage must not be higher than 3.6 kV.

For what concern the minimum allowed voltage, only one value is defined for the 3 kV supply system, it is equal to 2 kV and can last no more than 2 minutes [2]. For what concern the voltage distortions introduced by harmonics and transient events, nothing is prescribed in the [2].

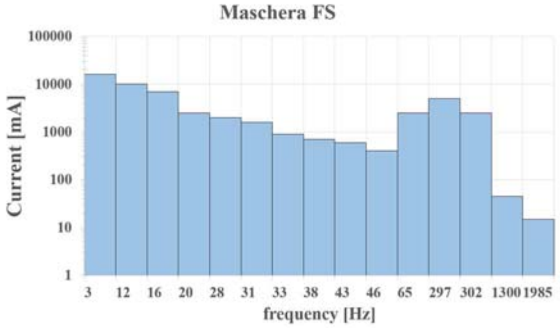

Fig. 1: Frequency content limitation for the Italian railway system known as "Maschera FS"

Standard [3] that deal with the compatibility between infrastructure and rolling stock, describes the possible overvoltage triggered by distortions due to grid instability or harmonics emissions. It has been noted that there is lack of examples for DC systems; all the examples refer to AC supply systems. In conclusions, the analyzed standard does not provide exhaustive information regarding the admissible voltage harmonic content for DC supply systems. The aim of the paper is also to provide examples of events that can affect the quality of the power for DC railway systems.

European National Infrastructure Managers provides prescriptions for the current harmonic emission of rolling stock. Such limitation is introduced in order to reduce the possible disturbances that such harmonics can induce in the tracks corrupting the signaling information circulating on them. Fig. 1 provides an example of current harmonic mask defined by the Italian Railway Infrastructure manager (RFI) [4].

III. REFERENCE GENERATION SYSTEM

A. Main characteristics

The aim of the generation system is to reproduce the power quality events occurring in a DC 3 kV railway supply system. Thanks to the measurement campaigns carried out within the European Research Project MyRailS [5], a collection of power quality events is available. The generation constraints have been defined thanks to the above mentioned waveforms and the analysis of railway standards that define some supply voltage characteristics.

Table I summarizes the characteristics of the reference generation system.

Table I. Generation system facilities.

Voltage peak	10 kV
Current peak	1.2 kA
Voltage bandwidth	DC-30 kHz
Current bandwidth	DC-300 Hz

The generation system uncertainty is, obviously, strongly related to the uncertainty of the voltage and current references and the one introduced by the acquisition channels. After a deep characterization in amplitude and frequency, performed at the Italian National Metrology Institute (INRiM), the relative uncertainty value in stationary conditions is below 60 µA/A for the current channel and 120 µV/V for the voltage channel. Given the low linearity error of the transducers considered, it can be assumed that for the generation of even fast PQ phenomena, the estimate of the relative uncertainty is less than 1%.

B. *The generation setup*

The generation system consists of two units: one for the voltage signal generation, one for the current signal generation. The two units have been implemented with PCI eXtension for Instrumentation Express(PXIe)chassis, each of which with an arbitrary waveform generator (AWG) National Instruments (NI) (100 MHz, 16 bit, ± 12 V), an acquisition module NI 4462 (4 channels, 24 bit, 204.8 kHz) and a synchronization module NI 6388H that allows to regulate the internal 10 MHz clock of the two units with the GPS signal with an accuracy of 100 ns. The two units are separated to maintain galvanic isolation since, in the case of combined transducers (as most of them for railway applications) under test, the simultaneous generation of voltage and current takes place with the current generation system at a floating potential with respect to ground potential. For the emulation of the voltage signal from the power supply line, a TREK amplifier has been used; it can reproduce signals up to 30 kV with a frequency bandwidth up to 7 kHz for the large signal and 30 kHz for the small signal. For the current generation a Sorensen SGX High Power DC Supply has been used. It can generate up to 1200 A and the output can be controlled with a low voltage signal. The voltage reference is a resistive-capacitive divider with an overall accuracy of 0.05 % in the frequency range from DC to 5 kHz developed at INRIM. The current reference is the ITZ 2000-S FLEX ULTRASTAB with an overall accuracy lower than 12 ppm. The output of this transducer is converted in voltage by a Guildline current shunt (1 Ω, 10 ppm). Both the voltage current generation units are remotely controlled by a Personal Computer (PC) thanks to the NI 8375 Remote control module with fiber optic connections. All the measurement setup is represented in Fig. 3.

C. *Software implementation*

The application used for remote control of voltage and current units is developed entirely in LabVIEW. In order to correctly generate power quality phenomena, it is necessary to know the time difference between the voltage generated and the current generated. For this reason, the synchronization modules have been used which guarantee a delay with respect to the signal derived from the GPS of ± 100 ns, so a delay between the two units at worst of ± 200 ns which can be neglected with a generation frequency of 100 kHz. The generation of long-lasting waveforms, or of entire railway journey, was obtained through the streaming mode. This mode is used when the memory of the generation module is not sufficient to contain all the data to be generated. It consists of loading in memory the data into blocks with successive iterations. During the generation of the *j-th* block, *the j+1-th* block is loaded into memory and so on. Taking into account the generation frequency, the capacity and the writing speed of the memory, it is possible to find a balance whereby the generation can last for an indefinite time. A further feature of the software, in order to improve the smoothness of the waveform, is the re-sampling of the signal to be generated, based on interpolation, with the end of increasing the number of points and the sampling frequency

IV. EXAMPLE OF TRANSIENT EVENTS

In order to characterize the on-board detection systems, it must be considered that the voltages supplied to trains are often distorted and subject to ripple; these distortions are much larger than those experienced on the usual

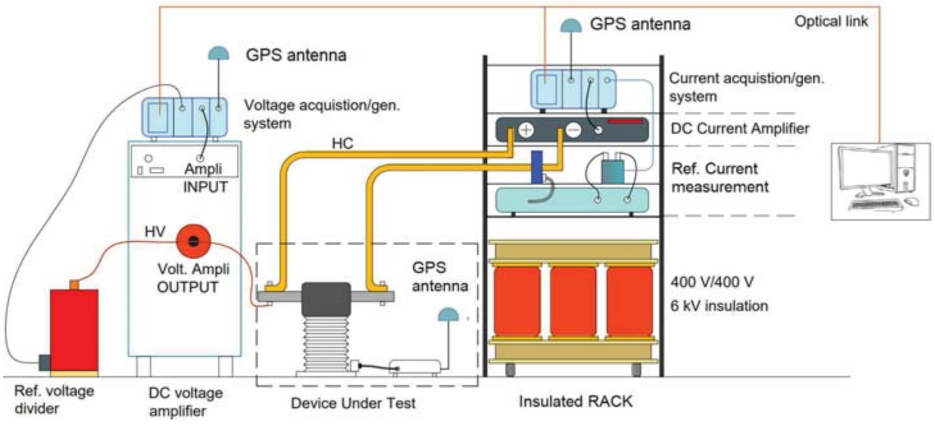

Fig. 3 Measurement Setup

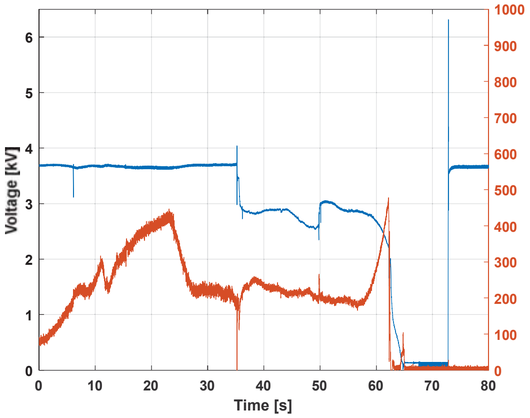

Fig. 5: Voltage dip

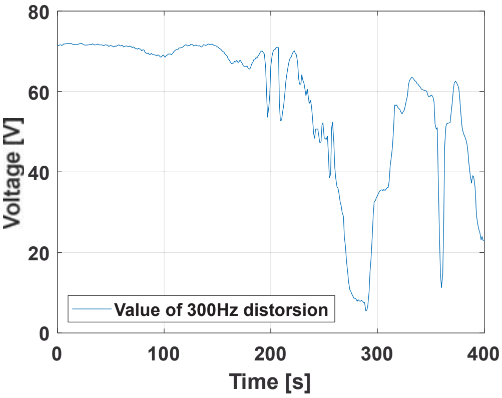

Fig. 4: 300Hz distortion over time during Bardonecchia – Torino journey

electricity network. At the same time, the currents drawn by trains also contain high levels ripple, and step changes in magnitude associated with train acceleration and braking [6]. Arcing phenomena, generated by a bad pantograph-to-line contact quality, can further introduce transient distortions.

An example of voltage dip that can be used for the characterization of the dip detection system is shown in Fig. 5.

During the traction phase, due to a fault in the power supply system, a voltage drop occurs. Apparently, in this condition the power supply system cannot sustain an increase in the absorbed power, therefore in the following traction the system turned off.

A power quality phenomenon common in the railway world is the electric arc, predominant at high speeds and with low temperatures characterizing the winter periods. Due to the high arc temperature, the overhead contact line can be damaged and deteriorate in performance over time. Furthermore, the sudden voltage variations trigger transients and strong harmonic distortions on the current due to the input filter of the locomotives as shown in Fig. 6 [7]. The problem of emissions provided by the current transient is acute because these can interfere with the signaling system, to such an extent that the infrastructure manager establishes the limits for the harmonic content. Therefore, a facility that emulates real waveform with such particular characteristic could be very useful in this context [8].

Another power quality phenomenon that characterizes the railway system is the voltage ripple (300 Hz for AC grid at 50 Hz power frequency) which is due to the AC / DC conversion stage in the substation. Fig. 4 shows an actual ripple measured during the Bardonecchia - Turin route. By the means of a generation system able to reproduce actual waveforms, this phenomenon could be reproduced in laboratory and its effects on the performances of the on board train instrumentation are analyzed.

As reported in the specifications, this system can generate voltages up to 11 kV, therefore widely capable of replicating overvoltage phenomena. In railway systems, in order to reduce losses, the voltage level tends to be higher than the rated voltage of 3kV. In particular situations, for example in the evening when traffic is significantly reduced, the line voltage may be close to regulatory limits. Fig. 7 shows the trend of the line voltage during the Bussoleno - Turin section around 10 pm. The voltage is always higher than 3.5 kV and has an average of 3728V, a

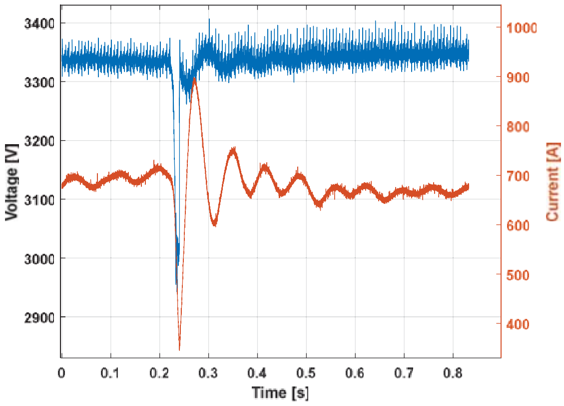

Fig. 6: Electric arc during the traction phase

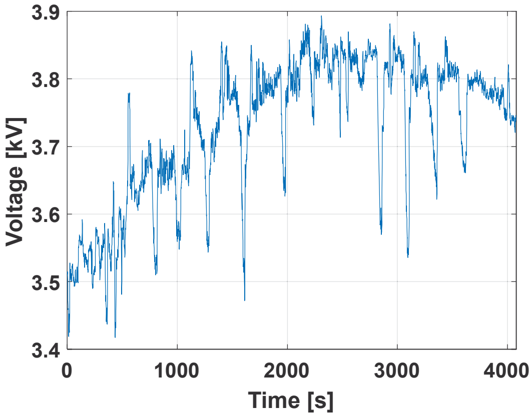

Fig. 7: Line voltage during Bussoleno – Torino

value approximately 25% higher than the rated voltage. Using situations such as the one shown in figure 7, it is possible to verify, even in dynamic conditions, the performance of the entire voltage control system on board the train, also impacting the rheostatic braking system and therefore on energy consumption.

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CONCLUSIONS

A setup for the characterization of the on-board detection systems for DC railway application has been described. It allows to emulate signal as voltage dip and swell, electric arcs, bad-contact between pantograph and catenary and other PQ phenomena. The relative uncertainty for voltage and current is overestimated at 1% but a more precise analysis in dynamic conditions is under evaluation.

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