A Testbed for Static and Dynamic Characterization of DC Voltage and Current Transducers

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Abstract — To establish a single European railway area, the European Commission requires, by 2019, that energy billings shall be computed on the actual energy consumed. So, in near future, all trains shall be equipped with an energy measurement system, whose measurement accuracy should be assessed and periodically re-verified, as required by EN 50463-2. For this purpose, the voltage and current transducers play a crucial role as their accuracy could determine the performance level of entire measurement system. To obtain reliable results, the accuracy of transducers should be tested with waveforms as close to real working conditions as possible. To assess the metrological characteristic of DC voltage and current transducers under real operating conditions, this paper presents a calibration set up able to generate up 6 kV for DC voltage and up to 300 A for DC current. The system is able to generate standard tests but also complex and non-stationary test signals which go well beyond the standard characterization procedures. As an example of its usage, some preliminary results of characterization of commercial voltage and current transducers are presented.

Keywords: DC railway system, power and energy measurement, voltage and current transducer, static and dynamic characterization

I. INTRODUCTION

In recent years, the implementation of efficient, reliable and environmentally friendly transport systems becomes imperative not only to comply with the international agreements on reducing greenhouse gas emissions [(1)-[4]], but to guarantee liveable conditions in urban areas. Furthermore, in a very competitive context, where other transportation modes are considerably improving their environmental performance and the energy costs are steadily increasing, it is crucial that railway transport reduces its energy use while maintaining or enhancing its service quality and capacity [5], [6].

One of the most important conditions for managing energy efficiency is the introduction of a meter-based energy settlement and billing system. A continuous energy metering allows for the passage from conventional cost to cost based on effective consumption for traction energy. So, new energy billing rules will be used into inter-operable railway networks. To establish a single European railway area, the European Commission requires, by 2019, that all energy billings shall be computed on the actual energy consumed [7], [8]. So, all trains shall be equipped with an energy measurement function (EMF), whose measurement accuracy shall be assessed and periodically re-verified, as required by EN 50463-2, [9].

To this end, accurate and reliable knowledge of the energy absorbed/exchanged between the train and the railway grid, that takes into consideration the harsh on board measurement conditions and the frequent non stationary electrical conditions, is essential, [2]. To assess the metrological reliability of the EMF under real operating conditions, calibration setups and procedures which go beyond the well-known procedures developed for pure sinusoidal or continuous regimes are required.

In addition to the power/energy measurement, 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 on AC system and a lot of procedures, algorithms and measurement systems were presented and widely discussed in scientific literature. A less explored research field is the assessment of power quality in DC system especially with reference to the railway system, [10].

In both the measurement purpose (energy and power quality measurement), the voltage and current transducers play a crucial role and their accuracy could determine the performance level of the whole system [11]-[25]. This aspect is recalled in [9], where some accuracy tests are defined for devices devoted to the measurement of the consumed and regenerated active energy of a traction unit. In [9], a generic energy measurement system is schematically considered made up of the following functions, which can be contained in one or more devices: Voltage Measurement Function (VMF); Current Measurement Function (CMF); Energy Calculation Function (ECF). In this document, the terms Measurement Function is used as a general term and encompasses the voltage sensor and current sensor that are considered devices implementing measurement functions. For each of these functions, accuracy classes are specified and associated reference conditions are defined. To prove the compliance with the accuracy class, some basic accuracy tests shall be made for VMF and for CMF. In both cases, some amplitudes are chosen and, under DC reference steady state conditions, the measured error at each measuring point shall be within the prescribed limits. These tests are repeated to verify further deviations due to the influence...
quantity (temperature, vibrations, etc.). The only test performed in dynamic conditions is a full scale step response: a step, intended to produce a change in the output signal from 0 % to 100 % of the output range, is applied to the input of the sensor. The time to reach the 90 % of the applied input value, from the 0 %, shall be not greater than a specified response time. It is apparent that the described tests are intended to a broad verification of transducers performances and are far from real working conditions (unsteady conditions, large superimposed ripple, etc.). Accuracy or response of transducers in these situations remain untested. So, at the moment, for DC railway systems, there is the lack of a metrological framework (comprising laboratory calibration, measurement setups and robust data processing algorithms) for calibration of devices as high accuracy energy and power quality meter able to verify the uncertainty limits under highly dynamic electrical conditions.

This document takes a step towards the development of enabling technologies that allow to improve the basic test procedures, thus allowing to evaluate the metrological characteristics of the DC voltage and current transducers even in complex conditions, including also real operating conditions. To this purpose, this paper presents a calibration set up able to generate up 6 kV for DC voltage and up to 300 A for DC current. The system is able to generate, in addition to basic test considered in [9], also complex and/or non-stationary test signals. Static tests are performed generating DC signals with the overlapping of a stationary disturbance defined by arbitrary frequency components. Dynamic tests are performed generating voltage and/or current with time varying amplitude that can be defined by user or derived from real signals obtained from experimental data. The full characterization of the presented test system is still on going.

II. HARDWARE & SOFTWARE DESCRIPTION

A simplified block diagram of the presented test system is reported in Fig. 1 and it can be divided into four sections composed by a series of subsystems:

The section with low amplitude signals: this is a PXI system with two generation boards (NI PXI 5422, maximum sampling rate 200 MHz, 16 bit, variable output gain and offset, up to 256 MB of on-board memory) and two acquisition boards (NI PXI 4462, input range ± 10 V, 24 bit, maximum sampling rate of 204.8 kHz).

The amplification section is composed by a transconductance amplifier (Fluke 52120 A, up to 120 A, up to 10 kHz, up to three in parallel) and by a high-voltage power amplifier (NF HVA4321, up to 10 kV, from 0 Hz up to 30 kHz) for current and voltage respectively.

The feedback section is composed by two reference transducers used to feedback generated waveform to the acquisition boards for comparison: CS-300 of Ohms LABS for current (300 A/30 mV, Accuracy 0.025%, thermal coefficient 20 ppm /°C) and internal INRIM reference voltage divider (10.000 V/1 V, Accuracy 0.02%), [6].

The last section includes the transducer under test (TUT).

Fig. 1. Block diagram of the Calibration System

A specific software was developed in the LabVIEW environment, adopting the event-based state machine approach for managing generation, acquisition and signal processing. Two different operation modes have been implemented:

• in static operation mode, the system performs a steady generation of DC voltage and/or current of arbitrary amplitude with the overlapping of a stationary disturbance defined by an arbitrary sum of sinusoidal components (range 0-5 kHz). These tests are aimed to characterize the behaviour also in presence of harmonics distortion coming from power supply system.

• in dynamic operation mode, the system generates voltage and/or current with time varying amplitude that can be defined by user or derived by real signals obtained from experimental data. These tests are devoted to characterize the behaviour with the signals that could be found in a real operating conditions. Current and voltage generation and acquisition are synchronized.

III. EXPERIMENTAL RESULTS

The presented system has been adopted for numerous experimental tests and further analyses are still ongoing. In this paper, the considered transducers under test were the LEM LV 100-4000 (4000 V/50 mA, Accuracy 0.9%, linearity <0.1 %), for voltage, and the LEM IT 200-s (200 A/200 mA, linearity < 0.001 %, Bandwidth DC - 500 kHz) connected to a resistive shunt of 0.1 Ω, for current. For sake of brevity, only some results are reported in the following.

A. Static Tests

Static tests are intended to perform measurements with a steady generation of DC signals of chosen amplitude with the overlapping of a stationary disturbance defined by an arbitrary sum of sinusoidal components. Nevertheless, the system does not immediately generate the configured waveform. To avoid a sudden change too high in the generated amplitude, the system provides a ramp of increasing values which, starting from zero, reaches the desired value after 1 s. Then, the measurements are performed and the results are stored. Finally, a descending ramp takes back the amplitude of the generated signal to zero. An example of soft start and soft stop adopted for static generation is reported in Fig. 2.
First results reported in Fig. 3 refer to the measured ratio error for voltage transducer, defined as

\[
\text{Ratio Error} = \frac{k_{\text{TUT}} V_{\text{TUT}}}{k_{\text{Ref}} V_{\text{Ref}}} - 1 \quad (1)
\]

while a simple DC voltage without any disturbances was generated.

It is apparent a remarkable effect of the warming up of TUT on its gain: only after 3 hours the considered transducer reaches a steady state. Moreover, the level of applied voltage makes the phenomenon larger reaching a deviation of 0.5 % for 4 kV. As regards the final level of the ratio error, there is a difference of 0.2 %, depending on the amplitude of the DC component.

A second type of test was performed generating a steady DC voltage at nominal value (3 kV) with a single superimposed sinusoidal component with a constant amplitude (i.e. 5 % of Vdc) and frequency (i.e. 50 Hz). To this aim, a generation frequency of 5 MHz and a sampling frequency of 200 kHz were adopted. With this signal, at the same time, it is possible to evaluate the gain error in DC when distorted conditions apply and the AC gain error and the phase shift introduced by TUT, at the considered frequency. The measurement of the three parameters was repeated 10 times to have an evaluation of stochastic effects in the measurement setup. Then, the frequency of component was incremented from 50 Hz till 2150 Hz with a step of 100 Hz and the entire measurement process was repeated.

Fig. 4 shows the DC gain error, measured when different frequency components are present in the signal, and the standard deviation. This parameter is substantially unaffected by the presence of the sinusoidal component.

Fig. 5 shows the AC gain and phase errors measured on the superimposed sinusoidal components. The system acts as low pass filter with a -3 dB cut frequency slightly higher than 2 kHz.

These tests were repeated also with different DC components (form 2 kV to 5 kV with step of 500 V) with substantially identical results; thus, it is possible to conclude that the sinusoidal component does not affect the DC accuracy and the AC frequency response is not affected by DC components amplitude.

Tests similar to those conducted for the voltage were also conducted for the current.

In this case, heating produces far less significant effects and the transducer rapidly reaches the steady state. Also in this case the ratio error is influenced by the amplitude of the continuous component and there is a reduction of 0.2% for each amplitude halving (see Fig. 6).

Stationary but distorted conditions were performed with a DC current (200 A) with a single super imposed sinusoidal component with a constant amplitude (i.e. 5 % of Adc) and frequency (i.e. 50 Hz) to evaluate the DC gain error and the AC gain and the phase errors introduced by TUT, at the considered frequency.

Similarly to Fig. 4 and Fig. 5, Fig. 7 and Fig. 8 show, respectively, the DC gain error and the AC gain and phase errors, when sinusoidal components with different frequencies are present in the signal, and the standard deviation.

The DC gain error is substantially unaffected by the presence of the sinusoidal component; the AC error gain decreases
linearly with frequency reaching the -3 dB cut-off frequency at about 8 kHz. This performance is substantially lower than that expected from transducer datasheet and this is probably due to the characteristics of the adopted shunts. Investigations are still ongoing on this topic.

B. Dynamic Tests

One of the most noteworthy features of the presented system is the capability of reproduce also dynamic working conditions. To this aim, the test system was designed and implemented to be able to reproduce a piecewise sequence of linear behaviours.

As first possibility, the user can describe the desired signal in terms of time segments that will be consecutively generated. The k-th segment starting at instant $T_k$ is completely defined assigning its duration, $D_k$, and the parameters $A_k$ and $B_k$ that define the linear behaviour inside the segment:

$$Y(t) = A_k \cdot (t - T_k) + B_k \quad for \quad t \in [T_k, T_k + D_k] \quad (1)$$

Note that: 1) a value for $A$ equal to zero corresponds to a constant behaviour; 2) $B_{k+1}$ equal to the last value of previous segment $T_k$ ($B_{k+1} = A_k T_k - B_k$) assures waveform continuity across the segments. In addition to the manual definition of time segments, a specific procedure was developed to analyse signals coming from a field acquisition and to extract their main features to reproduce linearly, during the time, the level of voltage or current, within a chosen accuracy. For this aim, the analysed signal is segmented in time intervals in which the time behaviour can be approximated with a linear function, respecting the accuracy limit, and the corresponding parameters are calculated.

The algorithm works analysing a time segment of signal with a first attempt for duration (f.i. $D_k=1$ s) and it exploits the linear least squares fitting for calculating the $A_k$ and $B_k$ parameters. The values obtained with these parameters are compared with the real samples values, calculating the maximum deviation. If it is below the chosen tolerance, the algorithm continues to try to extend the duration of the segment (f.i. +10%) and to repeat the estimation of the parameters until the tolerance is exceeded. The values obtained at previous step are stored as final results. If, at the first attempt, the check of tolerance goes wrong, the algorithm continues to decrease the duration of the segment (f.i. -10%) and to repeat the estimation of the parameters till the tolerance is reached. Then, in both cases, the algorithm goes to the next segment incrementing the starting point. In the following research the continuity of the waveform through the segments is imposed as a constraint, in order to avoid abrupt changes in amplitude. It is apparent that number of segments depends on complexity of waveform but also it changes with the chosen level of accuracy, [13].

As an example, Fig. 9 and Fig. 11 show the field acquisitions of supply voltage and absorbed current by E412 Locomotive for 350 s with a sampling frequency of 20 kHz during a test of electrical braking (7 millions of samples each). As expected, there are high amplitude variations for current according the different working conditions and, consequently, the voltage has inverse behaviour but with a less wide amplitude variation.

Fig. 10 and Fig. 12 report the piecewise sequence of lines calculated from the algorithm. For the voltage approximation, to meet the tolerance of 1%, 66 time segments were needed. For the current approximation, to meet the tolerance of 1.5%, 46 time segments were needed. Obviously, the accuracy limits are the maximum values of deviation found in the considered time segment, but clearly the average deviation could be much lower.

Fig. 13 and Fig. 14 report the statistical analyses of all the obtained deviations between the original and the approximated waveforms of voltage and current, respectively. In both cases, the average values are around zero and standard deviations are lower than the 0.5% of the nominal value. These results show the effectiveness of the procedure to stay far below the chosen limits. The obtained coefficients are then processed through a Labview software in order to generate the low voltage signals reproducing a scaled version of the field acquired waveforms.
For these tests, a generation frequency of 100 kHz and a sampling frequency of 10 kHz were adopted. These values are consistently lower than those used in the state tests due to memory allocation problems associated with the high duration of the test. The amplitudes of the low voltage signals were calculated accounting voltage and current amplifier gains so that, after amplification, the peaks of signals reach the desired values. For voltage the same peak value of actual original voltage was reached, whereas for current the original peak value was reduced till 200 A to meet transconductance specification. In this paper, voltage and current tests were performed separately, but for specific needs (i.e. Wattmeter...
characterization) both generations and acquisitions can be performed simultaneously and in a synchronized way. For the characterization of TUT performance, the maximum value of deviation between measured amplitude and the corresponding value obtained by the reference transducer, within one second, is calculated. For the voltage transducer the maximum measured deviation was 21 V (0.7% of nominal value, see Fig. 15). While for current transducer the maximum measured deviation was 0.7 A (0.035% of nominal value, see Fig. 16).

IV. CONCLUSION

This paper presented a calibration setup that allows to improve the basic test procedures adopted for the assessment of the metrological characteristic of DC voltage and current transducers that are used in energy measurement in railway system. The system is able to generate up to 6 kV for DC voltage and up to 300 A for DC current in steady state conditions, to implement the standard tests, but it can also generate complex and non-stationary test signals which go far beyond the standard characterization procedures. In addition, a specific hardware and software procedure was developed to supply the transducers with waveform derived from real operating conditions. The procedure showed, at the same time, good accuracy in reproducing the desired waveform and a simple implementation. As an example of effectiveness, some preliminary results of characterization of commercial voltage and current transducers were presented.

V. ACKNOWLEDGMENT

The results here presented are developed in the framework of the 16ENG04 MyRailS Project. The latter received funding from the EMPIR program co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation program.

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