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Stefano Emilio Caria
Applied metrology and engineering, *INRiM*
Dipartimento Energia "Galileo Ferraris", Politecnico di Torino
Torino, Italy
s.caria@inrim.it

Ahmet Merev
TUBITAK National Metrology Institute (UME)
Gebze, Kocaeli, Türkiye
ahmet.merev@tubitak.gov.tr

Paolo Emilio Roccato
Applied metrology and engineering, *INRiM*
Torino, Italy
p.roccato@inrim.it

Serkan Dedeoglu
TUBITAK National Metrology Institute (UME)
Gebze, Kocaeli, Türkiye
serkan.dedeoglu@tubitak.gov.tr

***Abstract*— Driven by the increasing demands on traceable measurement systems and given the importance of having reliable electricity grids able to support renewable energy sources and the growing energy demand for electric mobility, there is an imperative need for an adequate grid components testing. The typical tests on high voltage electricity grid systems include the combined and composite voltage tests, during which lightning or switching impulses are superimposed on the High Voltage Alternating Current or High Voltage Direct Current. However, at present, there are inadequate traceable measurement systems that can be directly connected to the equipment under combined and composite high voltage tests, which may result in unreliable test results. Combined and composite waveform measurements are complex due to their characteristics. The aspect addressed in this paper is to verify the capabilities of the recording instruments used for measurements. Nowadays, there are a lot of off-the-shelf digitizers with adequate accuracy and uncertainties for the measurement of impulse voltage and current. In high voltage testing and calibration, these digitizers are used not only in the measurement of impulse voltage but also composite and combined voltages. The current IEC 60060 standard series do not provide evidence for the ability of such measurement systems to accurately measure combined and composite voltages. Furthermore, there is a lack of standardization in the IEC 61083 series for measuring instruments and software used for combined and composite wave shapes measurements. This paper includes the characterization results of commercial digitizers which are the brands of Dr. Strauss TR-AS 200/12 and National Instruments oscilloscope PXI-5124 on DC and lightning impulse (LI) performed by INRiM and TUBITAK. This paper arises in the context of the European project 19NRM07 HV-com² which support the standardization in high voltage testing.***

***Keywords—Characterization, Digitizers, Comparison, composite and combined voltages***

## I. INTRODUCTION

Combined and composite waveform are combination of slow phenomena such as direct (DC) or alternating (AC) voltage and impulse voltages that could be lightning or switching impulse and those complex waveforms are used in high voltage tests, as described in IEC 60060-1 [1]. These tests are necessary for a better resilience of the high voltage network.

The European Project 19NRM07 HV-com$^2$, of which this work is part, takes care of checking the traceability for the measurement of these high voltage tests realizing the entire test circuit and defining the characteristics required for each individual component of the reference measuring system in order to achieve the standard and be able to provide the tools for updating the regulation [2, 3].

Typically an high voltage measuring system is composed by:

- Voltage divider, that could be resistive, capacitive or compensated;
- Measurement connection system, which could be a cable or a fiber optic connection system;
- Digitizer, that has to acquire the waveforms;
- Software, which calculate the parameter that the standards require to measure.

The project aims to create the entire reference measurement system, this paper is focused on the digitizers.

The phenomena descripted before are extremely complex and it is necessary to verify the behavior of recording instruments used to measure them.

The digital recorders are used for recording the waveforms of impulse voltages and currents in testing and calibration laboratories. A great advantage of digital recorders lies in the computer-aided evaluation of digitized waveforms using special developed software. Nowadays, there are a lot of commercial type digitizers or special cards with adequate uncertainties for the measurement of impulse voltage and current. In high voltage testing and calibration, these digitizers can be used not only in the measurement of impulse voltage but also composite and combined voltages. In this case, the AC and DC performance of digitizers also have an important role in calibration uncertainty.

The acquisition system used for measuring composite voltages must be capable of measuring DC, AC and impulse voltages at the same time [4]. This work can be performed with a single card that can measure both slow and fast phenomena or it is possible to specialize the measuring system with two different cards, one for fast phenomenon that can be the same digital recorder used for impulse voltage and another for slow phenomenon that can be with a slower sample rate like a digital multimeter (DMM), Fig. 1 shows a principle scheme.

These two solutions could be used for the purpose of this paper, but them have some differences to take into account. A slow phenomenon, like AC component, requires to acquire at least one period to evaluate the amplitude of the voltage applied. Perform these measurements with a high sample rate oscilloscope leads to a fulfillment of the scope card's memory and it is time consuming for the algorithm.

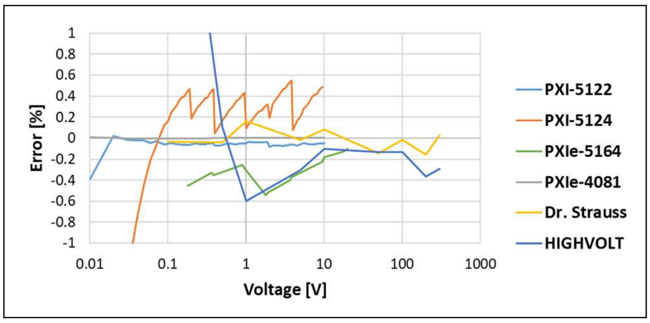


Fig. 3. Error on DC measurements

The other digitizers are good from the voltage of 1 V up to 300 V, considering that these acquisition systems are used with a voltage divider with a smaller scale factor than those used with NI cards, it is an acceptable error.

*B. Lightning Impulses (LI)*

The measurements on Lightning Impulses (LI) are performed by a standardized software developed and validated, for different parameters, as defined in IEC 60060-1 [1]. In particular the following values are calculated:

- Peak value, alias Test Voltage, represent the maximum value of the test voltage curve computed by the software;
- $T_1$, front time, is a virtual parameter defined as 1/0,6 times the interval T between the instants when the impulse is 30 % and 90 % of the peak value;
- $T_2$, time to half-value, is virtual parameter defined as the time interval between the virtual origin, instant preceding the 30% of the peak value point, of the test voltage curve, by a time 0,3 $T_1$, and the instant when the test voltage curve has decreased to half the test voltage value.

For LI were measured the waveforms available of the CRIC 300 impulse calibrator with different input voltages: 1 V, 5 V and 10 V for National Instruments scope cards, while with Dr. Strauss and HIGHVOLT systems were measured also 50 V, 100 V and 300 V.

Given the steepness of the event to be measured, NI PXIe-4081, which can be used as a digitizer, does not have a sufficient sampling frequency. For this reason, measurements were made only with scope cards.

For every waveforms were performed 10 measurements to reduce the statistical uncertainty component $\mu_A$ [4].

Fig. 4 shows the percentage error of the measurement of peak voltage of the impulses. In the first graph could be appreciate all the digitizers measurement errors, while in the second are expanded the results of the National Instruments scope cards.

For the peak voltage of the LI the autocalibration of the scope cards has a negligible effect and can be omitted, this is due to the algorithm that, performing the measurement of the peak voltage as differential voltage, limits the error due to the thermal drift.

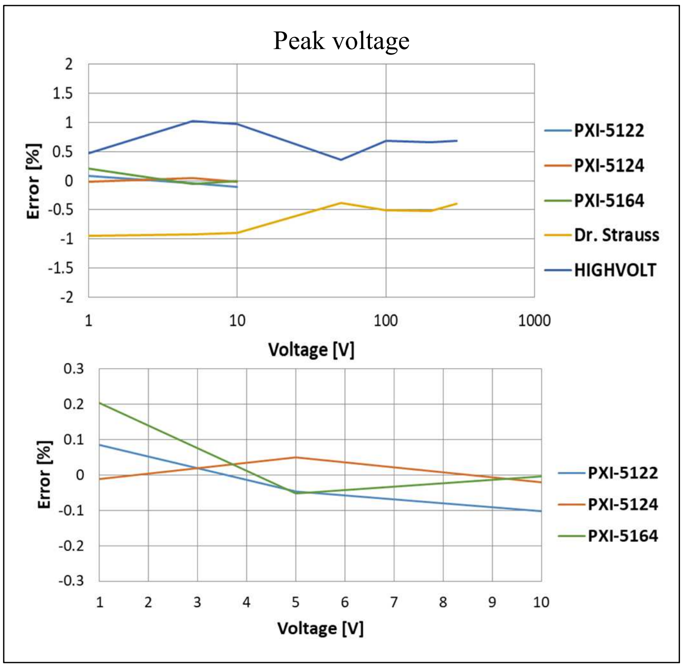


Fig. 4. Error on peak voltage measurement of LI

Fig. 5 shows measurement errors of the time parameters for the front time $T_1$, also in this case the first graph collect all the digitizers' measurements while the second one is focused on NI's scope cards, with a limited voltage range.

For $T_1$ the NI's and the HIGHVOLT the error is quite stable, this behavior allows an easy, constant, correction during the data analysis, while for Dr. Strauss it is necessary to correct point by point, with respect to the voltage input value.

For these measurements, also without the autocalibration the NI PXI-5124 performs a stable measurements.

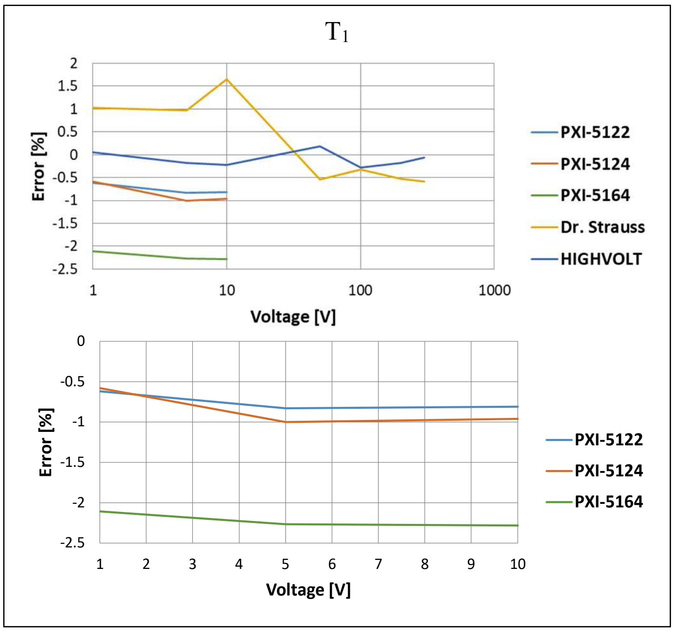


Fig. 5. Error on $T_1$ parameter measurement of LI

Fig. 6 shows measurement errors of the time parameters for the time to half value $T_2$, the first graph shows the error measurements of all digitizers while the second one is focused on NI's scope cards.

For the NI's the error is quite stable and also for this parameter the behavior allows an easy, constant, correction during the data analysis, while both for HIGHVOLT and for Dr. Strauss it is necessary to correct point by point.

Also, for $T_2$ the non-self-calibrated NI card has a stable result.

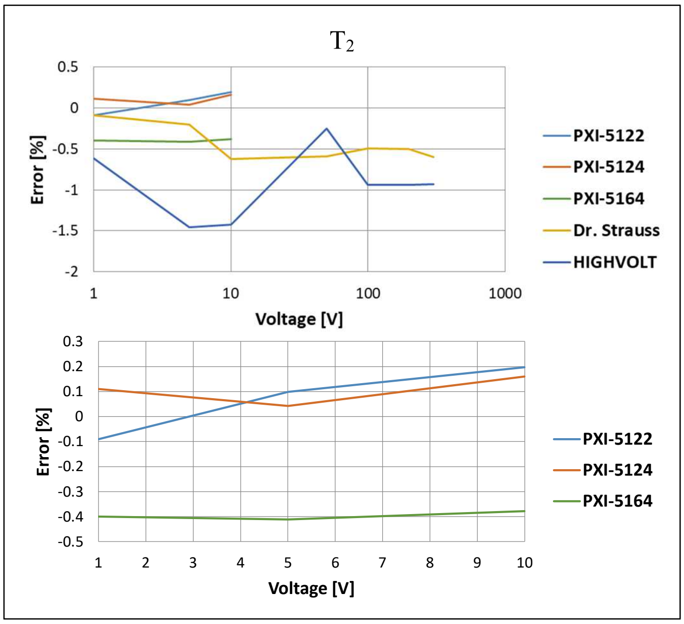


Fig. 6. Error on $T_2$ parameter measurement of LI

### C. *Consideration on measurement results*

Concerning NI system: from the results it is recommended to perform an autocalibration every time that it is necessary to measure DC waveforms with scope cards.

It is possible to evaluate that for slow phenomena the error measured with DMM is at least one order lower than scope cards. Due to the high input impedance of DMM, above 10 GΩ for voltage up to 10 V as scope card span voltage or 10 MΩ for higher range, there is a negligible influence of the DMM parallel at the input stage of scope NI-5122. Basing on this consideration and specific measurements, our proposal is to perform combined and composite test with the use of two specialized instruments: one for slow phenomena such as NI PXI-4081 and one for fast phenomena like NI PXI-5164 or NI PXI-5124.

Another important consideration is the necessity to perform self-calibration of the digitizer in the NI's scope cards for direct measurements, to reduce the effect of drift, otherwise the measurements is not reliable. Instead, if the measurement is a differential voltage it seems that it is not mandatory, but considering this work we suggest following the manufacturer's instructions and carrying it out every time it is necessary to make a measurement.

From this study it seems that Dr. Strauss and HIGHVOLT systems that we tested, although they are excellent measurement systems, they are not suitable for use as national reference systems for composite and combined voltage waveforms without specifically characterization and comparison.

## IV. Uncertainty Budget

The project has the aim to realize a reference measurement system, so the uncertainty has to be the lowest possible.

For this reason the target of uncertainty is 0.5% for the digitizers to be used for the reference measurement system.

In this paragraph we report the uncertainty budget calculated for DC and LI, the calculation and contribution will be deeply described.

### A. *Uncertainty budget for DC voltages*

For DC we considered:

- $u_{B1}$ Discretization of the boards
- $u_{B2}$ Uncertainty of Calibrator from last calibration Noise of the boards
- $u_{B3}$ Software uncertainty

Except $u_{B2}$, other sources of uncertainty have a rectangular probability distribution, so that were divided by $\sqrt{3}$. While $u_{B2}$ is an expanded uncertainty, so was divided by 2.

TABLE II. Uncertainty contributions of NI PXI-5122 range 10 V

| | |
|---|---|
| $u_{B1}$ | 0.061% |
| $u_{B2}$ | 0.001% |
| $u_{B3}$ | 0.10% |

The expanded uncertainty was calculated with:

$$U = k * u_{ref} = 2 * \sqrt{u_A^2 + \sum_{i=1}^{n} u_{Bi}^2} \quad (1)$$

Table III shows the expanded uncertainty calculated for each digitizer, it can be seen that all digitizers have an uncertainty that is within the target.

TABLE III. Expanded uncertainties for DC measurements

| **Digitizer** | **Expanded uncertainty U** |
|---|---|
| NI PXI-5122 | 0.14 % |
| NI PXI-5124 | 0.31 % |
| NI PXIe-4081 | 0.12 % |
| NI PXI-5164 | 0.14% |
| Dr. Strauss TRAS 200-12 | 0.10% |
| HIGHVOLT HiRES S4D | 0.20% |

### B. *Uncertainty budget for impulse voltages*

For impulses we considered:

- $u_A$ Statistical type-A uncertainty
- $u_{B0}$ Uncertainty of the calculable calibrator
- $u_{B1}$ Discretization of the boards
- $u_{B2}$ Software uncertainty

Except $u_{B0}$ and $u_A$, other sources of uncertainty have a rectangular probability distribution, so that were divided for $\sqrt{3}$.

TABLE IV. UNCERTAINTY CONTRIBUTIONS OF NI PXI-5122 LI 1.2-50

| | |
|---|---|
| $u_A$ | 0.053% |
| $u_{B0}$ | 0.100% |
| $u_{B1}$ | 0.007% |
| $u_{B2}$ | 0.100% |

TABLE V. EXPANDED UNCERTAINTIES FOR LI MEASUREMENTS

| **Digitizer** | **Expanded uncertainty U** | | |
|---|---|---|---|
| | **$U_p$** | **$T_1$** | **$T_2$** |
| NI PXI-5122 | 0.16 % | 1.08 % | 0.32 % |
| NI PXI-5124 | 0.15 % | 0.70 % | 0.32 % |
| NI PXI-5164 | 0.10% | 0.50% | 0.30% |
| Dr. Strauss TRAS 200-12 | 0.21% | 0.60% | 0.40% |
| HIGHVOLT HiRES S4D | 0.17% | 0.60% | 0.40% |

Is it shown that all the digitizer could be useful used to measure peak voltage and time to the half value within the uncertainty target, while for time to peak there is only the NI PXI-5164 that could be used for our purposes, unless to accept a higher uncertainty.

### *C. Uncertainty of the digitizers*

The uncertainty of the digitizers for DC measurements are reported in Table IV that highlights that a scope specialized for DC measurements like NI PXIe-4081 has a better uncertainty respect to the others systems.

The uncertainty of the digitizers for LI measurements are reported in Table V where it is always a compromise between high sample rate and high definition.

NI PXI-5164 is the only measuring instruments that has all the characteristics that are necessary to measure both DC and LI with the uncertainty that we proposed. It should be noted that the software that allows to measure combined and composite waveforms could be really complex and the related data may consume a lot of memory.

## V. CONCLUSIONS

Based on the reported results it is possible to do some important considerations. The best solution is to measure the combined and composite waveform with two different cards paralleled, specialized for slow and fast phenomena.

In this way it is possible to exploit the characteristics of the single measuring instrument, to measure slow phenomena with a DMM and the fast phenomena with an oscilloscope card that have:

- a high sample rate, mandatory to acquire the LI phenomena with an adequate number of samples,
- a sufficient resolution to have high accuracy on the peak value.

With the solution proposed the amount of data to be captured and archived is limited to a high sample rate only during the impulse phase.

It is possible to use also one single scope card with a resolution at least of 14 bit and a high sample rate, in this case the software would be capable to save a sufficient number of samples to measure correctly slow phenomenon.

The other solutions could be used, but it is necessary to accept a higher uncertainty for time parameter if the measuring system has a sample rate slower than 200 MS/s, or for peak value of the LI if the resolution is not 12 bit or more.


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Identification of certain equipment does not imply recommendation by the authors, nor does it imply that the equipment is necessarily the best available for the purpose.

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