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Performance Evaluation and Comparison of a Low-Cost, PLL-Based Acquisition System under Off-Nominal Conditions

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Abstract— **In the last years, strong changes of power network architectures and operation have led to make use of huge quantities of instrumentation, spread around the grid. In fact, there is a strong need to perform very accurate measurements of electrical quantities in many nodes of the network, mainly due to the strong penetration of distributed generation. Recently, also the main Italian utility has asked for such kind of instrumentation. Its main feature must be to perform accurate measurements in all actual conditions. Such conditions include the instrumentation operation during off-nominal condition of the network. To this purpose, in this paper, a low-cost acquisition system developed by the authors, is recalled. Then a full comparison with off-the-shelf products during ideal or not power source is provided. Obtained results highlight the potentialities of the developed system for its implementation in both laboratory or medium/low voltage networks.**

Keywords— Low-cost Acquisition Board; Leakage, Phase Locked Loop, Accuracy, Characterization, Windowing, Harmonics, Not-sinusoidal, Microcontroller;

I. Introduction

When measurement acquisition is concerned, a variety of expensive acquisition systems are available on the market to fulfil all kind of final applications. A first application classification can be made on the basis of the measurement campaign location: in-field or laboratory campaign. At the one hand, when measurements are performed inside a laboratory, the working conditions are typically good enough to obtain satisfactory results. On the other hand, in-field measurements require all kinds of precautions to avoid any possible disturbances introduced by the non-controlled environment. For example, a frequent problem faced in-field is the not known frequency of the measured signal. In addition, focusing on measurements on power systems, frequency is a quantity that varies continuously in the allowed range 50 Hz ± 1 % [1]. Hence, the stability required by any acquisition system is not guaranteed.

A second classification, instead, can be made on the economical availability for the application. For Transmission System Operators (TSOs), for example, it is easier to invest money in expensive measurement equipment to monitor their networks. On the contrary, Distribution System Operators (DSOs) are forced to contain spending and to find new cheaper solutions to obtain the same results (as the one proposed in [2-3]). DSOs issues are mainly due to the meshed characteristic of a Medium or Low Voltage (MV and LV) network. In fact, the presence of thousands of nodes, limits the spread of expensive monitoring solutions, with the effect of a limited monitored portion of grid, except for the critical nodes.

In light of the aforementioned, authors proposed in [4] a simple acquisition system to answer both the criticalities arose in this Section: adaptability for in-field operations and inexpensiveness for laboratory purposes or for being implemented inside low-cost application spreadable in the distribution networks. Different works can be found in the literature presenting low-cost solution for either power systems [5-6] or biomedical purposes [7-8]. In [9] instead, the low-cost acquisition board has been already implemented in a smart meter and controlled via LabView software. However, among them, none used a Phase Locked Loop-based (PLL) hardware to prevent spectral leakage phenomenon, although it is a well-known and scientifically tackled topic [10-11].

Starting from the satisfactory results of [4, 12], in this paper authors wanted to extend the study to include a very critical aspect when power systems supply is concerned: the off-nominal, sinusoidal or distorted conditions. Such a non-ideal status of the supply voltage could cause serious damages to the equipment; therefore, its study is mandatory. Consequently, this topic is tackled in almost all power systems research areas: electric machines [13, 14], insulating materials [15], and metering [16]. Furthermore, authors completed the study providing a full comparison among off-the-shelf data acquisition systems (DAQ) and the proposed one considering the existing reference literature [17-19] and the related Standard [20]. Such a comparison is provided for both technical and economic point of view. Tests aimed at assessing the performance of the proposed solution but, at the same time to confront it with expensive but common DAQs available on the market.

In this regard, the proposed solution adopts an even cheaper and new micro-controller with respect to [4].

In the following: Section II gives a brief description of the leakage phenomenon and the typical solutions to it, in Section III the proposed acquisition board solution is presented including the novelties introduced with respect to [4]. Section IV lists all the tests performed on the different DAQs. In Section

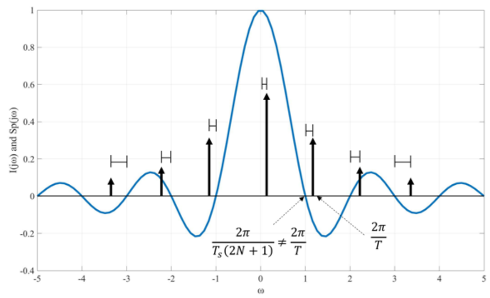

Fig. 1 $I(j\omega)$ and $S_p(j\omega)$ when the synchronous sampling condition is not met

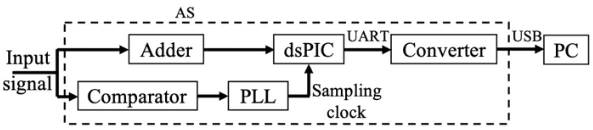

Fig. 2 Schematic representation of the Acquisition System proposed

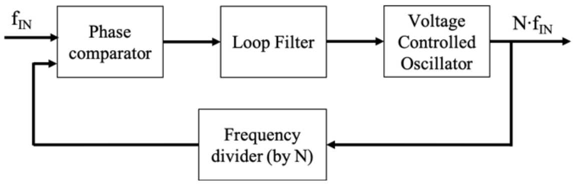

Fig. 3 Typical block-diagram of a PLL structure

V all their results are presented and discussed in detail. Finally, comments and conclusions are reported in Section VI.

II. Spectral Leakage

As already introduced in the previous Section, spectral leakage phenomenon becomes an issue during a signal sampling. Therefore, let us briefly recall this critical concept [21].

A. Definition

Be $s_p(t)$ a periodic signal of period T limited by the N^{th} harmonic and sampled with a train of pulses $i(t)$ of period T_s, thus collecting *2N+1* samples over *T*. Hence, the sampled signal p in the time and in the frequency domain results:

$$p(t) = s_p(t) \cdot i(t) \tag{1}$$

and

$$P(j\omega) = S_p(j\omega) * I(j\omega) \tag{2}$$

respectively. Being $S_p(j\omega)$ and $I(j\omega)$ the Fourier transform of $s_p(t)$ and $i(t)$, respectively. When the synchronous sampling condition is met, the observation window and the signal period correspond. The signal has been correctly acquired and the leakage phenomenon avoided. However, the sampling condition is not always verified, especially in in-field measurement campaigns, because:

- Typically, the signal period is unknown.
- When it is known, the sampling clock rarely has sufficient resolution.
- Finally, when there is a sufficient resolution, the signal period is not stable during all the measurement time-window.

Hence, the non-synchronous condition results in a discrepancy between the $I(j\omega)$ zeros and $P(j\omega)$ harmonics position quantified as:

$$\Delta\omega = 2\pi\left[\frac{1}{T_s(2N+1)} - \frac{1}{T}\right] \tag{3}$$

and clarified with Fig. 1. This leads to $P\left(\frac{2\pi}{T_s(2N+1)}\right) \neq S_p\left(\frac{2\pi}{T}\right)$, usually referred to as leakage error.

B. Methods for leakage error reduction

Due to the effects of the leakage presence during a measurement campaign, some countermeasures need to be taken in advance. The main methods used to solve this issue, fully describe in the literature [22-24], are:

- Windowing.
- Time or frequency interpolation.
- PLL hardware synchronization.

Among the three, the third one has been adopted in [4] and further developed in this work. In addition, this work includes windowing tests to complete the overall comparison among acquisition systems.

III. Acquisition Board

The PLL-based acquisition board (Acquisition System, AS from here on out) essentially consists in the following main components: a comparator, a PLL, an adder, a microcontroller with integrated ADC and a personal computer. In Fig. 2, a schematic representation of the acquisition systems is shown. By starting from the input signal, two main branches can be noted. The bottom one is aimed to generate the sampling clock:

- A comparator transforms the input signal in a square-wave with a frequency f equal to the input signal one.
- A PLL, Texas Instruments CD4046, takes the f frequency signal as input and provides a sampling clock signal at a Nf frequency. It provides output for inputs up to 150 Hz, hence enough when considering the power frequency values (around 50 Hz) adopted in the tests. As for its conditioning circuits, it has been developed by following what suggested in the datasheet [25] to optimise the dynamic response of the PLL.
- Such output is given to the new microcontroller as described in the following. A general structure of the PLL is shown in Fig. 3 with the blocks commonly required for its implementation: the phase comparator for the input frequency detection and the voltage-controlled oscillator, that provides a new output frequency.

The upper branch of Fig. 2 instead, contains:

TABLE I. MAIN CHARACTERISTICS OF THE NEW MICROCONTROLLER STM32L452

Architecture	32-bit	**Max CPU speed**	60 MHz
Memory	512 kB	**SRAM**	52 kB
Temperature Range	-40 to 125 °C	**Operating and Input Voltage**	3 to 3.6 V_{PP}
ADC resolution		12 bits	

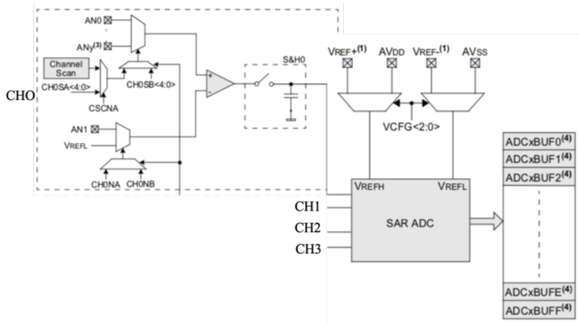

Fig. 4 Block diagram of the microcontroller acquisition stage

TABLE II. MAIN CHARACTERISTICS OF THE NI 9215

Architecture	16-bit	**Max input signal**	±10 V
Sample rate	100 kS/s/ch	**Simultaneous channels**	YES
ADC	SAR	**Temperature range**	-40 to 70 °C
Gain Error	0.02 %	**Offset Error**	0.014 %

TABLE III. MAIN CHARACTERISTICS OF THE NI 9239

Architecture	24-bit	**Max input signal**	±10 V
Sample rate	50 kS/s/ch	**Simultaneous channels**	YES
ADC	Delta Sigma	**Temperature range**	-40 to 70 °C
Gain Error	0.03 %	**Offset Error**	0.008 %

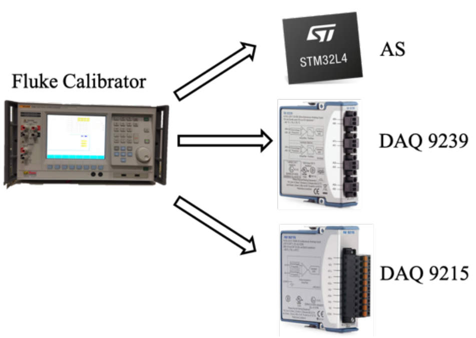

Fig. 5 Automatic measurement setup for the tests performed with the 3 Device Under Test (DUT)

- An adder block to obtain a completely positive output, by summing a constant value to the input signal.
- The new microcontroller STM32L452, whose characteristics are listed in Table I. It has been chosen due to its cheapness compared to the one in [4], maintaining the same technical specification (except for the architecture which is 32 bits instead of 16). Moreover, the choice has been supported to extend the range of off-the-shelf tested products. A feature of the new adopted microcontroller is the oversampling. It allows to increase the measurement accuracy by acquiring 1 sample each X values (averaging them). However, by considering the results described in the following and the increase of the measurement time window (not always possible in in-field application), such a technique has not been used. The micro samples the positive input signal with a sampling frequency provided by the PLL output: $f_s = Nf$. The sampled signal, can be either stored in the microcontroller memory and then processed, for example, through the Discrete Fourier Transform (DFT), or simply sent as output and processed successively. In this case the latter applies: the output of the STM32 is then transmitted via UART communication interface and then converted to an USB one to store data on a personal computer (PC). For the sake of clarity, in Fig. 4 a block diagram of the acquisition stage of the microcontroller is presented. In the picture, just one channel has been detailed (4 identical channels). Each of them has its dedicated sample&hold circuit, allowing the simultaneous acquisitions.

IV. SYSTEM EVALUATION TESTS

Several tests have been developed and performed to assess the AS performance and compare them with off-the-shelf systems. Before detailing them, the instrumentation of the different setups is described.

A. Setup

The instrumentation adopted consists of:

- Fluke Calibrator 6105A (max values 1000 V, 120 A) provides the supply voltage either with a 50 Hz sinusoid or with non-sinusoidal inputs. The latter includes possible frequency variations or harmonic superimposition. It features a 42 ppm accuracy in the voltage range tests (1 - 23 V) described in the following. Moreover, it has been used for testing all the DUTs, hence its uncertainty does not contribute to assess variations among them.
- NI 9215 and NI 9239 (cDAQ controlled), these 2 common acquisition board have been chosen to compare the AS results with. Their specifications are listed in Table II and III, respectively.
- HP 3458a 8 ½ digits Digital Multimeter, used in [4] to characterized the AS both in amplitude and frequency.

In light of the aforementioned, four tests have been run:

- an amplitude characterization;
- an amplitude vs. frequency characterisation;

TABLE IV. AMPLITUDE CHARACTERIZATION RESULTS, WITH OR WITHOUT THE PLL

Reference	*With PLL*		*Without PLL*	
V_{Cal} *[V]*	V_{Ma} *[V]*	σ_{Ma} *[V]*	V_{Mb} *[V]*	σ_{Mb} *[V]*
0.1	0.10028	$4 \cdot 10^{-5}$	0.09975	$3 \cdot 10^{-5}$
0.15	0.15006	$2 \cdot 10^{-5}$	0.14994	$4 \cdot 10^{-5}$
0.2	0.19997	$3 \cdot 10^{-5}$	0.20007	$3 \cdot 10^{-5}$
0.25	0.24997	$4 \cdot 10^{-5}$	0.25016	$4 \cdot 10^{-5}$
0.3	0.300010	$9 \cdot 10^{-6}$	0.30027	$4 \cdot 10^{-5}$
0.35	0.35007	$1 \cdot 10^{-5}$	0.35003	$3 \cdot 10^{-5}$
0.4	0.400111	$9 \cdot 10^{-6}$	0.40033	$4 \cdot 10^{-5}$
0.45	0.450142	$9 \cdot 10^{-6}$	0.45008	$5 \cdot 10^{-5}$
0.5	0.500184	$8 \cdot 10^{-6}$	0.50014	$4 \cdot 10^{-5}$
0.55	0.55002	$9 \cdot 10^{-5}$	0.55016	$4 \cdot 10^{-5}$
0.6	0.600141	$9 \cdot 10^{-6}$	0.60015	$4 \cdot 10^{-5}$
0.65	0.650123	$8 \cdot 10^{-6}$	0.65025	$6 \cdot 10^{-5}$
0.7	0.700071	$8 \cdot 10^{-6}$	0.70021	$6 \cdot 10^{-5}$
0.75	0.750069	$9 \cdot 10^{-6}$	0.75016	$6 \cdot 10^{-5}$
0.8	0.800090	$6 \cdot 10^{-6}$	0.80014	$5 \cdot 10^{-5}$
0.85	0.850065	$7 \cdot 10^{-6}$	0.85004	$7 \cdot 10^{-5}$
0.9	0.899986	$9 \cdot 10^{-6}$	0.90014	$5 \cdot 10^{-5}$
0.95	0.950005	$8 \cdot 10^{-6}$	0.95004	$6 \cdot 10^{-5}$
1	1.00007	$1 \cdot 10^{-5}$	1.00008	$6 \cdot 10^{-5}$

- an amplitude vs. harmonics components characterization.
- windowing test

Tests have been performed on all the devices under test: the AS and the two NI DAQs, with the setup shown in Fig. 5, valid for the four tests.

B. Amplitude Characterization

It consists in the Fluke Calibrator feeding each device under test (DUT) with a 50-Hz sinusoidal signal. The AS measured the rms value of the waveforms acquired in a range of 0.1 – 1 V rms (i.e. max 2.83 V_{PP}) with a 0.05 V step. As for the two DAQs, a 0.7 – 7 V range has been used with 0.3 V steps. This, to guarantee the same full-scale working condition of the three DUTs. For all the devices, in each step, mean value and standard deviation of the mean of the rms values acquired have been computed. To equalize the results, aside of the capabilities of each device, DUTs only stored the waveforms leaving all the computations to a common software (LabView 2016).

C. Amplitude vs. Frequency Characterization

The frequency characterization test setup is the same of Fig. 4. The Calibrator feeds the DUT with a sinusoidal signal with an amplitude of 1 V rms. The frequency varies in the range 48.5 to 51.5 Hz with steps of 0.05 Hz. Such interval, according to [1], contains the thresholds within systems with synchronous connection to an interconnected system have to being fed with for the 99.5 % of the time. One hundred sequences of 10 periods for the AS and 200 ms for the DAQ have been acquired as suggested in [26]. All the instruments are connected to a PC which sets the Calibrator and stores the acquired waveforms. The rms values of the components, at tested frequencies, are then computed by applying the same Discrete Fourier Transform algorithm to all the sequences of samples.

D. Amplitude vs. Harmonic Components Characterization

This third test aimed at completing the power quality tests started with the previous one. To this purpose, according to [1], DUTs have been fed with a signal consisting of the fundamental signal (50 Hz) plus 1 odd harmonic in the range (3-25). Even harmonics have not been considered for the sake of brevity but also because not significant in most of the application concerning Distribution Networks. The amplitude of the superimposed harmonics has been chosen as the maximum value allowed by [1] and detailed in the results Section. Also for this test 100 sequences of 10 periods have been collected, using 1 V rms as amplitude value for the fundamental signal. Then, rms value of the composed signal has been calculated together with its standard deviation. By following the same measurement procedure two more tests have been done concerning harmonics.

First test consists of the same test above described but setting a 30 ° initial phase on the harmonics waveforms. Again, harmonics up to the 25th have been tested and 100 measurements acquired

Second test consists in the simultaneous application of the 3rd, 5th and 7th harmonic on the fundamental signals (7 V and 1 V, rms, for the DAQ and the AS, respectively). Their amplitudes have been selected according to [1], which limits the THD to 5 %. Hence 2.5 %, 3 % and 2.5 % of the applied voltage have been used as values for the 3rd, 5th and 7th harmonic, respectively. Then 100 measurements of the voltage amplitude have been acquired.

.

E. Windowing Test

This last test aimed at verifying a second method for the leakage phenomenon reduction, as mentioned above: the windowing. To this purpose, the 3 DUTs have been used to acquire the same number of samples of the previous tests. Then, trough LabView software, a digital cosine window of the second order, the Hanning, has been applied to the acquired samples.

V. TEST RESULTS

This Section contains all the tests results. Subsection A aims at evaluating the performance of the AS proposed. Subsection B instead presents a full comparison among the 3 DUTs analysed in this work.

A. AS Evaluation

1) Amplitude

Table IV lists the results of the amplitude characterization performed using the Calibrator. The Table contains the reference voltage value V_{Cal}, the mean value (100 measurements) of the rms voltages measured with or without the PLL block of the AS, V_{Ma} and V_{Mb}, respectively. Both quantities are provided along with their standard uncertainty evaluated with type A method, σ_{Ma} and σ_{Mb}, respectively. From the Table it can be noted that in the case of measurement without PLL, the uncertainty associated is at least one order of magnitude lower than the one of measurements performed with PLL. Furthermore, results in Table IV represents a calibration curve for the developed AS, which can be linearized by applying a regression technique that provides a straight line crossing the axes origin. Hence, it is possible to define the deviation of the calibration curve from the

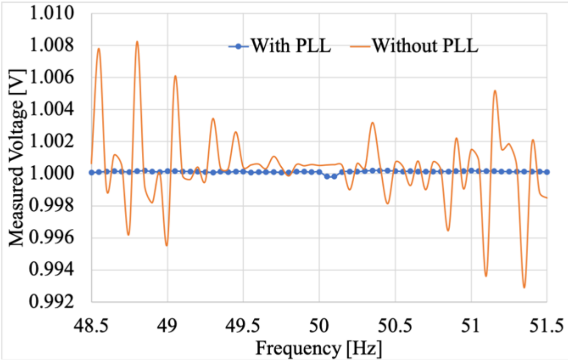

Fig. 6 AS Frequency characterization results either when the PLL feature is activated or not

TABLE V. LIST OF THE HARMONICS SUPERIMPOSED TO THE FUNDAMENTAL ALONG WITH THEIR WEIGHTS (%)

Harmonics Superimposition		
Harmonic order [-]	***p [%]***	***V_T [V]***
3	5.0	1.00124922
5	6.0	1.00179838
7	5.0	1.00124922
9	1.5	1.00011249
11	3.5	1.00061231
13	3.0	1.0004499
15	0.5	1.0000125
17	2.0	1.00019998
19	1.5	1.00011249
21	0.5	1.0000125
23	1.5	1.00011249
25	1.5	1.00011249

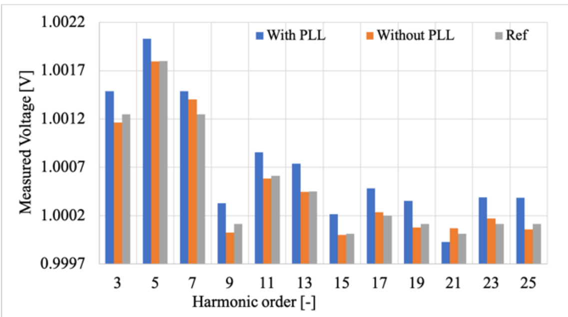

Fig. 7 AS Harmonic characterization results either when the PLL feature is activated or not

TABLE VI. DUTS COMPARISON OF THE AMPLITUDE CHARACTERISATION RESULTS

Parameter	AS	NI 9239	NI9215
***k* [%]**	0.010009	-0.015130	-0.003350
δ [%]	0.026829	0.005568	0.015278

ideal one by means of the gain error k and the non-linearity error δ:

$$k = \frac{g - g_n}{g} \quad (4)$$

$$\delta = \frac{max\{|V_{M,i} - gV_{Cal,i}|\}}{max\{V_{M,i}\}} \quad (5)$$

In (4), g is the angular coefficient of the line which linearizes the calibration curve, whereas g_n is the slope (which is unity in suitable coordinates) of the ideal characteristic. As for V_M it refers to both the voltages measured by the AS, V_{Ma} and V_{Mb}. The application of the above method provides $k = 0.010009$ % and $\delta = 0.026829$ % for V_{Ma} and $k = 0.018726$ % and $\delta = 0.027047$ % for V_{Mb}. The 2 parameters highlight that the developed AS features a remarkable linearity over the whole working range, with or without PLL, when the signal is a 50 Hz frequency stable signal.

2) Frequency

Frequency test results are reported in Fig. 6. They confirm the choice of using an architecture PLL-based. In fact, in the graph, the dotted line represents the 1 V rms acquisition when the PLL is activated, while the other line represents the case when it is not. Close to the frequency of interest (50 Hz) also the latter solution presents good results, but as soon as the frequency changes the measurement goodness drops. Moreover, comparing the standard deviation of the mean between the two cases, it results that with PLL it is 100 times lower than of the second case (10^{-6} vs. 10^{-4}). This is already an effect of the leakage error that, for the same length of the sequence and for the same frequency, leads to different RMS values depending on the sampling starting instant. For sure, this further effect could be reduced if the acquisitions are triggered.

As a final comment on Fig. 6, around 50.05 it could seem that there is a drop in the quantity measured by the AS. However, such values, considered the full scale of the picture, have the same variation from 1 V rms as the other ones but with an opposite sign.

3) Harmonics

As mentioned above, different harmonics have been superimposed (one at the time) to the fundamental signal at 50 Hz. The amplitudes *p (%)* of the harmonics, with respect to the fundamental signal (1 V rms), are listed in Table V. To improve the readability of the results, the Table contains also the total rms value of the voltage V_T (not the single harmonic component) that the Calibrator is providing at its terminals. Such quantity (the reference value) and the results from the acquisitions, with or without PLL, are reported in the histogram of Fig. 7. It is interesting to highlight the higher discrepancy between the results with PLL and the reference value than of the one without PLL (although the absolute value of the difference is limited in amplitude).

B. Data Acquisition Systems Comparison

In this final subsection, the 3 different DUTs are compared to determine their performance.

1) Amplitude

For the sake of brevity, the amplitude comparison is provided through the use of the two parameters defined above: the gain and non-linearity error (k and δ). All the values are reported in Table VI. As it appears from the Table, both AS parameters are definitely consistent with the ones of the NI DAQs. Moreover, all the 3 devices present a remarkable behaviour on the full range considered.

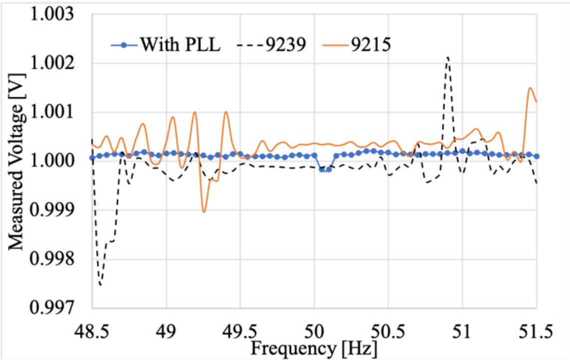

Fig. 8 AS Frequency characterization results comparison among the DUTs

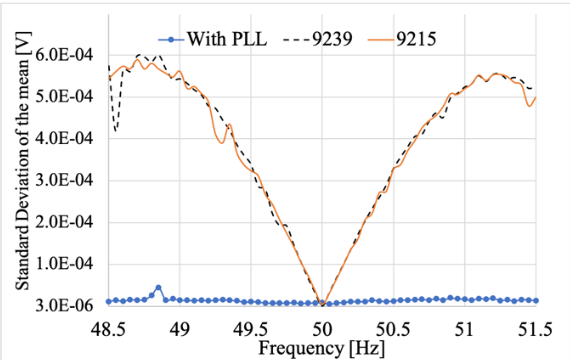

Fig. 9 Comparison of the standard deviation obtained from the frequency characterisation, for the 3 DUTs

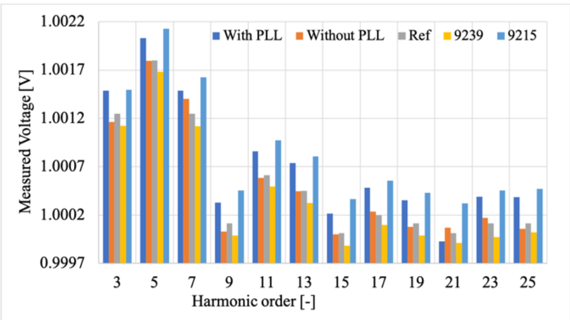

Fig. 10 Harmonic characterization results comparison among the DUTs at 50 Hz fundamental frequency

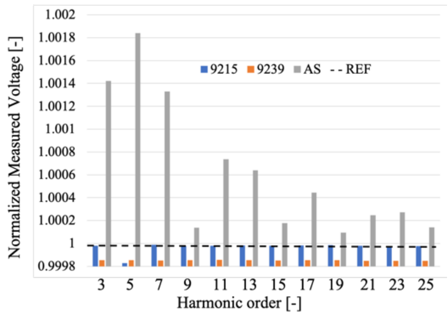

Fig. 11 Harmonic characterization (with 30 ° phase shift) results comparison among the DUTs at 50 Hz fundamental frequency

TABLE VII. DUTS COMPARISON OF THE MULTIPLE HARMONICS PRESENCE TEST RESULTS

Reference voltage 1 V		
DUT	**Measured Voltage [V]**	**Std. Deviation of the mean[V]**
AS	1.00124	$8 \cdot 10^{-5}$
NI9239	0.9998367	$3 \cdot 10^{-7}$
NI9215	0.999981	$3 \cdot 10^{-6}$

2) *Frequency*

Moving to frequency comparison, the results of the test are shown in Fig. 8. These results do not include anymore the solution of AS without PLL because it has already been demonstrated its inefficiency with respect to the PLL solution. In the figure, the solid line represents the 9215, the dashed one the 9239, while the proposed solution is represented by dotted line. From the results it is evident the stability vs. frequency of the proposed acquisition board in all the considered range. The differences among the 3 DUTs, considering their overall little variation in the *y* axis, can be further highlighted from Fig. 9. It contains the standard deviation of the mean for the 3 DUTs in all the frequencies range. The AS provide figures two order of magnitude lower than the other two DAQs (10^{-6} vs. 10^{-4}). A further comment can be made focusing on the two NI DAQs. Both present a quite stable behaviour, the 9215 less than the 9239, on the overall range of frequency expect for some points. In particular, 48.55 Hz for the 9239 and 51.45 for the 9215. These two critical points deserved a particular attention and have been tackled in the next subsection.

3) *Harmonics*

Last comparison concerns the harmonic superimposition on the fundamental signal (50 Hz). Referring to the harmonics' values of Table V, the full comparison among the DUTs is presented in Fig. 10. For this analysis the test results of the AS without PLL has been maintained, as explained above, for its consistence with the other results. In fact, it can be seen from the figure that the PLL solution and the 9215 DAQ suffer the most by the harmonics presence, with respect of the 9239 one. In Fig. 11, the results of the same test, but with a 30° phase shift of the harmonic waveform, are presented. From the graph it can be noted that the PLL-based proposed solution suffers more than the DAQ from the phase shift. This is confirmed also by comparing Fig. 10 with Fig. 11. In fact, the variation of the AS measurement is higher compared to the reference one. However, the absolute variation of the results from the reference is limited and still acceptable for the DUTs (max two per thousand), but in particular for the AS. This is due to its limited cost and particular field of application, where inexpensiveness and accuracy have almost the same weight.

As for the multiple harmonics test, results are listed in Table VII. At a glance, it emerges that the AS results are 1 order of magnitude worse than the DAQs ones. However, the variation is in the order of 1 per thousand of the reference value (1 V rms), hence a satisfactory results.

To complete the harmonics analysis, the two critical frequencies aforementioned have been used to run another harmonic test. Such test is identical to the one performed at 50 Hz, and it is aimed at discovering if 48.55 and 51.45 Hz are

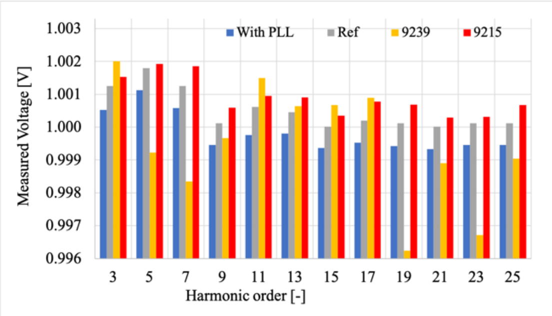

Fig. 12 Harmonic characterization results comparison among the DUTs at 48.55 Hz fundamental frequency

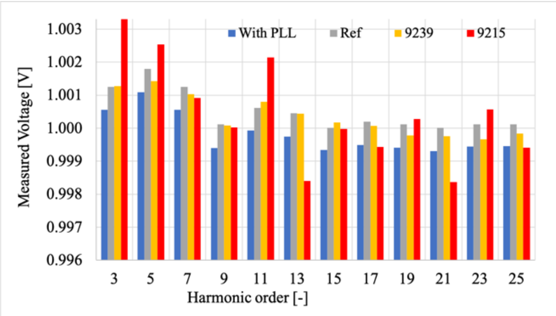

Fig. 13 Harmonic characterization results comparison among the DUTs at 51.45 Hz fundamental frequency

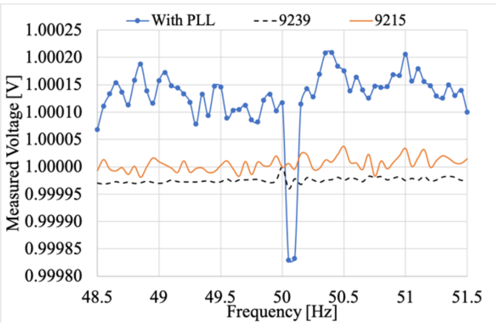

Fig. 14 Results of the windowing application results comparison among the DUTs

really critical points for the 9239 and 9215 DAQs, respectively. Fig. 12 and 13 show the results of this tests. The yellow column in Fig. 12 represents the measured voltage by the 9239 DAQ when the fundamental frequency is 48.55 Hz. The behaviour confirms what preannounced: at that frequency the DAQ cannot follow the reference value shown in grey. For the other DUTs instead, the selected frequency does not cause any change in their behaviour.

The same conclusion can be made focusing on Fig. 13. In this case is the DAQ 9215 whose presenting some issues with the frequency 51.45 Hz. One more time, the rms values measured are completely different from the reference one, while for the other DUTs this is not happening. The main explanation of these critical behaviour at those frequency can be associated to the different internal architecture of the two DAQs.

Moving to the multiple harmonics presence effects on the measured voltage, results of this test are presented in Table VII. It contains the mean value (of 100 measurements) and the associated standard deviation of the mean for the 3 DUTs. Values have been normalized to 1 for the sake of comparison. As it can be seen from the Table, the harmonic presence is not significantly affecting the 3 DUTs. In addition, the AS result is fully comparable with the DAQs, hence implementable also in power quality applications.

4) *Windowing*

In this subsection the results of a Hanning window application on the acquired data is presented. The results are summarised in Fig. 14. From the graph it is clear that the window improved dramatically the results of the measurements performed with the two DAQs (9239 and 9215), which are now stable along the overall range of frequencies. Moreover, the standard deviation of the mean associated to the windowed measurements dropped from 10^{-4} to 10^{-6} for both the acquisition boards 9239 and 9215. The results of the proposed solution have been added to the graph to compare its performance in case of windowing. As it can be seen, the AS present high variation with respect of the DAQs, however, the absolute value of these variations is very limited and in the order of $1 \cdot 10^{-5}$. Such value, considering the price of the AS proposed, is very satisfactory and acceptable with respect to the expensive solutions.

C. *Economic Analysis*

To better detail the advantages of the proposed solution, in this subsection a brief economic analysis is provided. By starting from the NI-DAQ board, their average cost is around 1600 € (including board and chassis). Of course, the costs can be slightly reduced if lower accuracy and features are accepted by the user. As for the proposed AS, the evaluation board plus the ST has a single unit cost of 13 €. By adding the PLL and the electronic components added to run the board, an overall cost of 20-22 € is obtained.

In light of the aforementioned cost, some comments arise. The AS it is suitable for two different purposes:

- It is a convenient solution to be implemented inside a laboratory to extend the instrument portfolio of a research group. This without renouncing to the accuracy aspects, as shown in the previous sections.
- Low-cost applications. DSOs and electrical utilities require, for MV and in particular LV networks, inexpensive solutions. Hence, the AS has been completed with chassis and connectors to evaluate its cost impact on a complete measurement system installable in-field. The overall amount reached the 50 € for a single unit, hence by considering the economy of scale the cost can be halved.

Of course, the analysis might be extended to all kind of acquisition systems available on the market. For example, a compact RIO-based solution costs around 3000 € hence, even if with much higher performance, not comparable with the proposed solution. Furthermore, to the authors knowledge, one of the cheapest DAQ plus PLL solution available on the market costs 400 €. Therefore, in the overall, the presented comparison tackles a wide scenario of off-the-shelf, expensive or not products, leading to the conclusion that the AS proposed might be well-implemented in multifold applications.

VI. Conclusions

Different applications require different acquisition systems. In particular, in-field or low-cost measurements can be performed only with equipment fulfilling some basic requirements. With this purpose, the paper continues the work of a previous paper, of which this is a technical extension, presenting the improved low-cost PLL-based acquisition system solution stressed with all the power quality limits (frequency and harmonics) as defined in the EN 50160. Furthermore, a full comparison among off-the-shelf data Acquisition boards is provided to assess the performance and limitations of the proposed solution. The results, and the <40 € price, confirms its applicability in both laboratory and low-cost distributed network applications. In fact, the proposed system performances are always comparable with the one of common but expensive off-the-shelf systems. Future works will include the study on how interharmonics, although not standardized yet, affects the behaviour of this Data Acquisition systems, increasingly spread along the power networks.

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