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An Initial Hardware Implementation of a New Method for Phase Measurement of Sinewave Signals

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***Abstract*—In this paper, an innovative accurate phase measurement system for sinewave signals is described and a prototype implementation using an analog multiplier board as a sampler is presented. The first experimental results show that the proposed prototype exhibits lower standard deviation values for phase than the previously proposed proof of concept.**

***Keywords*—phase measurement, sinewave signal, analog multiplier, sampler, measurement uncertainty.**

I. Introduction

"The phase is the time (instant) for a given signal value on a waveform cycle", [1]. Usually, the phase is an expression of relative time difference between two corresponding features (peaks or zero crossings) of two waveforms having the same frequency [1]. The estimation of the phase of an electrical signal is used for measuring several indirect physical quantities, such as, displacement [2], strain, acceleration, power quality [3], and so on. Furthermore, phase measurements are needed for characterizing the frequency response of electrical or electronic circuitry and instrumentation. As reported in [4], there currently are three methods that have generally been used for measuring phase: (i) event-counting-based methods, (ii) modulation-based methods, and (iii) sampling-based methods. The event-counting-based methods provide phase delay measurements of two isofrequential electrical signals. The main disadvantages of such methods are: (i) the phase measurement is affected by the noise on the trigger circuit, (ii) the measurement accuracy is limited by the period of the reference internal clock, and (iii) the need of a reference signal at the same frequency as the signal under test. In this case, the phase measurement uncertainty is in the order of $0.1°$ at around frequency values of $100\,\mathrm{kHz}$ [4].

The modulation-based methods are based on the multiplication of a sinewave signal with a reference signal. The output of the multiplication is acquired by an Analog-to-Digital Converter (ADC). An example of an instrument based on this method is the Vector Network Analyzer (VNA), which is used for characterizing the frequency response of electrical and electronic circuits [5]. The main disadvantage of this method is that it is only useful for characterizing two-port circuits. If the reference signal and the sinewave signal are isofrequential, the samples acquired by the ADC are related to a dc signal. An instrument that implements this method is the Phase-to-Voltage Converter (PVC). The amplitude of the dc signal is proportional to the phase delay between the reference signal and the input one. The main limit of the PVC is that the reference and the signal under test must be isofrequential. As reported in [4], the measurement uncertainty of this method is around $0.01°$ from $1\,\mathrm{kHz}$ up to $100\,\mathrm{GHz}$.

The sampling-based methods consist on the direct sampling and digitizing of the signal under test. An example of an instrument based on sampling is the Phase Measurement Unit (PMU) [3]. In this case for measuring the phase of a signal, the signal has to be acquired by an ADC having a clock synchronized with the other PMUs distributed on the network grid via a Global Positioning System (GPS) signal. The main disadvantages are: (i) within the same unit, the phase measurement is provided for a limited frequency range (usually from $50\,\mathrm{Hz}$ up to $10\,\mathrm{kHz}$), and (ii) a huge number of samples has to be acquired to provide accurate phase measurements. As reported in [4], the measurement uncertainty of the PMUs is on the order of $0.0001°$ at $50\,\mathrm{Hz}$.

In [4] and [6], a sampling-based method for accurate phase measurements of sinewave signals is proposed to overcome the above mentioned disadvantages of the instrumentation currently available on the market. The method is suitable for accurately measuring the phase of sinewave signals from $100\,\mathrm{mHz}$ up to $10\,\mathrm{GHz}$. This sampling-based method consists of eight functional blocks, as depicted in Figure 1: (i) an external clock source, (ii) the sinewave source, (iii) the pulse train source, (iv) the delay block, (v) the pulse selection block, (vi) the sampling block, (vii) the average measurement, and (viii) the 3-parameters sine-fit. From the simulation results obtained in [4], the authors estimated the lowest achievable phase measurement uncertainty to be around $0.1°$ at $10\,\mathrm{GHz}$. Furthermore, they proposed a first proof of concept of the method based on an oscilloscope and an arbitrary waveform generator, which works in the frequency range from about $100\,\mathrm{Hz}$ to about $1\,\mathrm{MHz}$, with a standard deviation on the phase

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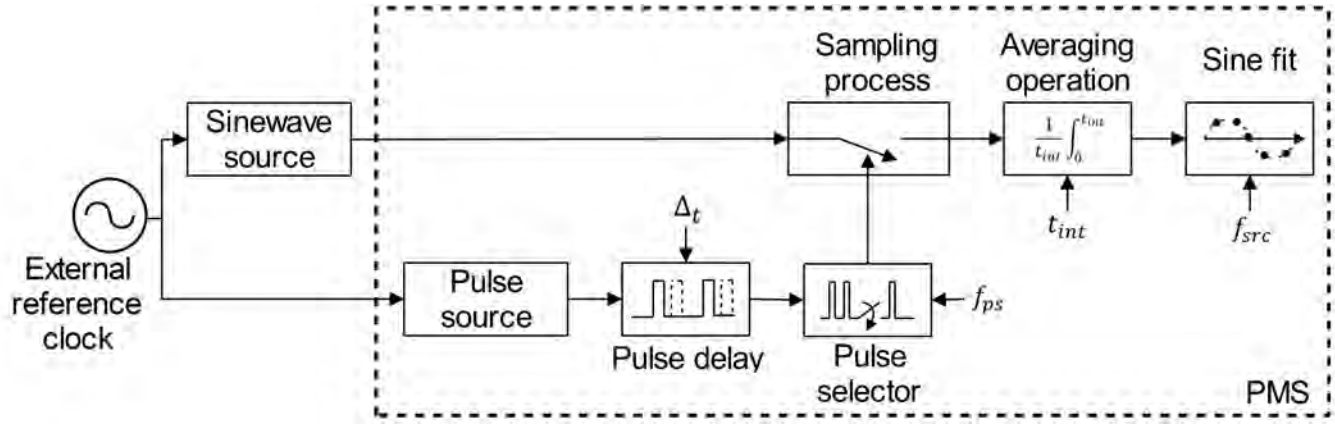

Fig. 1. The phase measurement method proposed in [4].

measurements of approximately $0.01°$.

The proof of concept prototype proposed in [4] does not implement completely the proposed method: (i) it cannot be used for measuring the phase of a sinewave coming from any generator because the pulse signal and the sinewave signal under test are generated by the same instrument, (ii) the sampling process is implemented on the oscilloscope, thus it is affected by the oscilloscope trigger noise, and (iii) an external reference clock cannot be used for the phase measurement.

In this paper, with the aim of designing an instrument that implements the method proposed in [4], a first hardware version of the sampling block is presented and the first experimental results are reported.

The paper is organized as follows. The Section II describes the sampling-based method proposed in [4]. The hardware and the software description of the prototype proposed in this paper are reported in Section III. The first results obtained from the proposed prototype are discussed in Section IV. The last section describes the next steps of the research and concludes the paper.

II. The Sampling-Based Method for Accurate Phase Measurements

In this section, a brief description of the method proposed in [4] is reported.

The external reference clock provides a reference signal to both the pulse and the sinewave sources. The sinewave source provides the sinewave signal under test, having a frequency value, f_{src}, synchronized with the input reference clock. The pulse source generates a pulse train signal synchronized with the reference clock. The pulse train signal is delayed by means of the pulse delay block, which is capable of imposing delays with a time resolution, Δ_t, much less than the sinewave period. The delayed pulse train signal is input into the pulse selection block, which sets the number of pulses that will be used to sample the input sinewave. This sampling pulse has a frequency, f_{ps}, that is a sub-multiple of f_{src}. The sampling pulses define the time instants when the sinewave signal is sampled. An average of the samples are taken over the time duration, t_{int}. This average value is digitized and stored in a vector. By varying the time delay of the pulse train, it is possible to sample the sinewave signal at several instants of a sinewave period. The resultant measurements are used as input of the 3-parameters sine-fit block. By knowing the frequency of the sinewave signal under test, this block provides the phase estimation.

This method overcomes the disadvantages of the other methods described in the introduction because: (i) it can be adapted for measuring the phases of high frequency signals by using the low-frequency sampling of the output of the pulse selector f_{ps}, (ii) at low frequencies, the phase measurements does not suffer from the effect of additive noise on the sinewave signal because the method does not require the use of a trigger circuitry, and (iii) it is not needed to acquire a huge number of samples, due to the fact that the averaging operation can be performed before or during the acquisition.

As reported in [4], for achieving the best performance in terms of phase measurement uncertainty, the following system parameters have to be considered (see Table I): (i) for sinewave frequencies lower than $10\,\mathrm{Hz}$, the frequency of the pulse train is equal to that of the sinewave being measured, the pulse duration is one-tenth of the sinewave period, we have limited the time duration of the averaging operation to $100\,\mathrm{s}$, the number of average measurements is equal to 10, (ii) for sinewave frequencies between $10\,\mathrm{Hz}$ and $10\,\mathrm{MHz}$, the frequency of the pulse train is equal to that of the sinewave being measured, the pulse duration is one-tenth of the sinewave period, the time duration of the averaging operation is a thousand times the period of the sinewave signal, the number of average measurements for implementing the sine-fit is equal to 10, and (iii) for sinewave signals higher than $10\,\mathrm{MHz}$, the frequency of the pulse train is fixed to $10\,\mathrm{MHz}$, the pulse duration is fixed to $10\,\mathrm{ps}$, the number of average measurements is 10.

In this paper, a prototype implementation of the method for the frequencies between $100\,\mathrm{Hz}$ and $1\,\mathrm{MHz}$ is proposed, and the first experimental results, in terms of standard deviation values of the phase measurements, are reported.

III. Prototype Implementation

To advance the design of a measurement instrument to implement this new phase measurement method, a new simplified prototype has been realized. The general architecture of the implemented prototype is reported in Figure 2. It consists of: (i) an Arbitrary Waveform Generator (AWG), which provides both the pulse train and the sinewave signal on both its output

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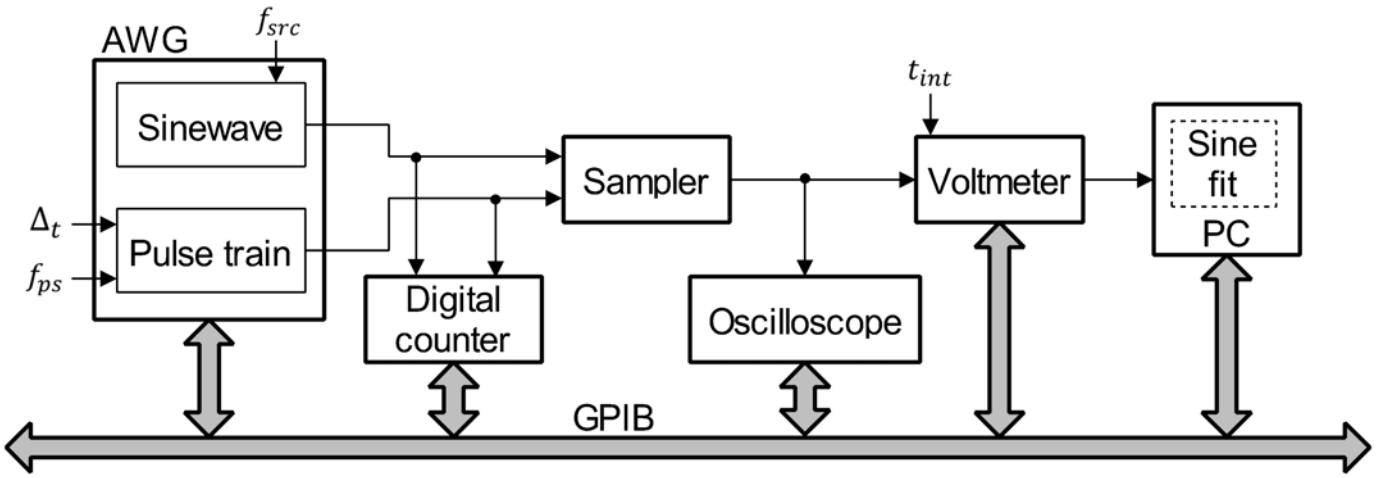

Fig. 2. General architecture of the implemented prototype.

TABLE I
SYSTEM PARAMETERS ACHIEVING THE LOW PHASE UNCERTAINTY VALUES AS REPORTED IN [4].

Sinewave frequency	Pulse train frequency	Pulse duration	Integration time	N
$f_{src} \leq 10\,\mathrm{Hz}$	f_{src}	$1/(10 \cdot f_{src})$	$100\,\mathrm{s}$	10
$10\,\mathrm{Hz} < f_{src} \leq 10\,\mathrm{MHz}$	f_{src}	$1/(10 \cdot f_{src})$	$1000/f_{src}$	10
$f_{src} > 10\,\mathrm{MHz}$	$10\,\mathrm{MHz}$	$10\,\mathrm{ps}$	$1000/f_{src}$	10

channels, (ii) a sampler based on an analog multiplier, (iii) the voltmeter, which performs the averaging operation on the sampler output according to an imposed integration time, (iv) the oscilloscope, which estimates the sign of the sampler output, (v) the digital counter that performs the measurement of the sinewave frequency and the reference phase, and (vi) the sine fit algorithm, which operates on the measurements provided by the voltmeter for several values of pulse delays. The pulse generator has been implemented using a commercially-available arbitrary waveform generator (AWG). In particular, the pulse train signal is generated by using the second channel of the AWG, while the sinewave signal is generated on its first channel. Because both channels are synchronized, the timing of the sampling pulse can be relative to the sinewave under test with a time resolution of $5\,\mathrm{ns}$. According to the AWG specifications, it is possible to generate pulse train signals from $100\,\mathrm{mHz}$ up to $10\,\mathrm{MHz}$ with a pulse duration and a pulse delay resolution from $5\,\mathrm{ns}$ up to $500\,\mathrm{ms}$.

The sampling circuitry has been designed and realized using a commercially-available analog multiplier integrated circuit (IC). The used analog multiplier IC is a four-quadrant analog multiplier which exhibits a working bandwidth of $500\,\mathrm{MHz}$, thus, it can be suitable for multiplying a sinewave signal up to $10\,\mathrm{MHz}$ with a pulse train having a pulse duration of $10\,\mathrm{ns}$. The output of the sampler is a pulse train, where the pulse amplitudes are modulated according to the sinewave signal values at the time instants defined by the pulse delay. Thus, the output is a signal having an energy that is proportional to the amplitude of the sinewave signal sampled at the time instants defined by the pulse train. Thus, to quantify this energy, a voltmeter which performs true-root mean square (true-rms) measurements is used. The commercially-available voltmeter has an accuracy of eight-and-half digits for input frequencies greater than $10\,\mathrm{kHz}$. Due to the fact that the voltmeter provides rms measurements, it is necessary to recognize the sign of the output signal provided by the sampler. This operation has been performed by using an oscilloscope that acquires the output signal of the analog multiplier.

A. Hardware

The sampler is based on a commercially-available analog multiplier IC. This analog multiplier is a three-port device: (i) two input differential ports are driven by the voltage signals that must be multiplied, and (ii) a differential output port, which consists of differential currents provided by two open collector circuits. In the linear operating region of the multiplier and by considering a signal having a frequency much lower than $500\,\mathrm{MHz}$, the transfer function of the analog

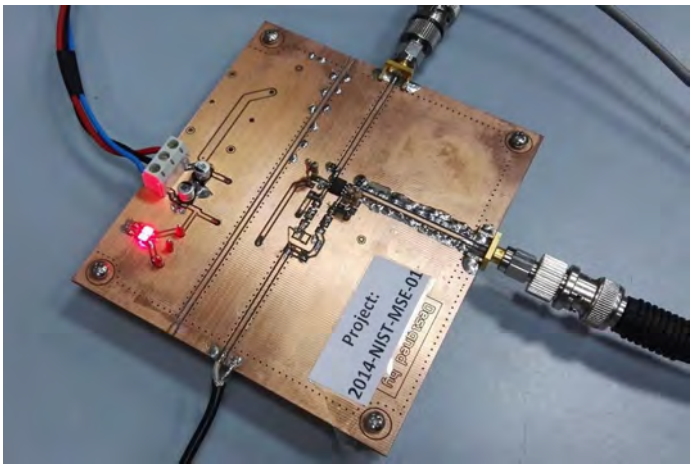

Fig. 3. The realized PCB prototype of the sampler block.

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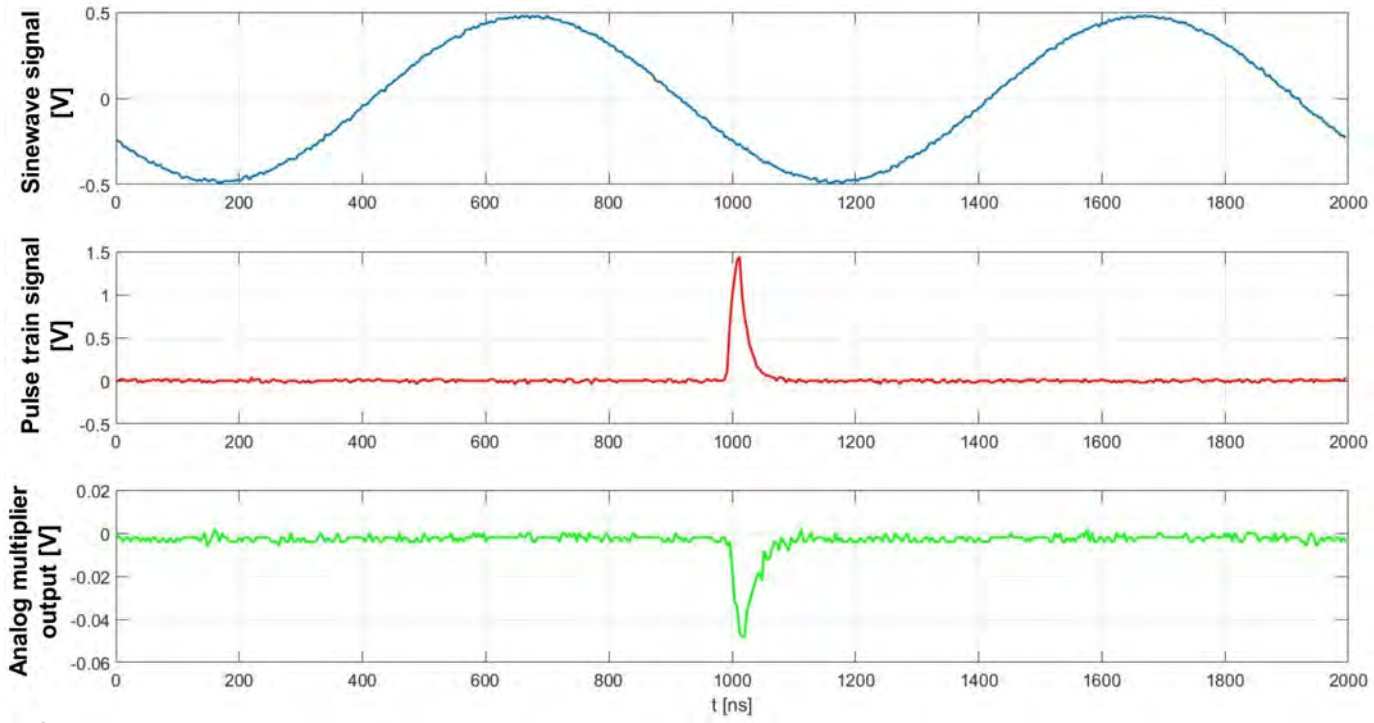

Fig. 4. Sinewave signal, pulse train and analog multiplier output acquired by the oscilloscope, during the functional tests at 1 MHz.

multiplier can be approximated as follows [7]:

$$i(t) = \frac{v_1(t) \cdot v_2(t)}{(1V)^2} \cdot 4mA \tag{1}$$

where, $v_1(t)$ and $v_2(t)$ are the differential input signals, and $i(t)$ is the output current for each open collector circuit. In order to convert the current in a voltage signal, two pull-up resistors of $50\,\Omega$ are placed between the output open collectors and the $5\,\mathrm{V}$, provided by the dc power supply. In this way, the output voltage signal, $v_o(t)$ is given by:

$$v_o(t) = \frac{v_1(t) \cdot v_2(t)}{2.5} \tag{2}$$

A printed circuit board (PCB) for the analog multiplier has been designed and realized on two layers. In Figure 3, a picture of the PCB prototype for implementing the sampler block is depicted. A functional validation of the board has been carried out for several sinewave frequency and pulse duration values. In Figure 4, the sinewave signal, the pulse train signal, and the analog multiplier output signal are depicted. The example shown in Figure 4 refers to a sinewave frequency of 1 MHz, a pulse train frequency of 10 kHz and a pulse duration of 20 ns. The pulse shape is not a rectangular one, since it exhibits non-symmetric rise and fall times, and their values are not negligible with respect to the pulse duration of the sampling pulse. Furthermore, the analog multiplier output is affected by additive noise.

B. Software

For managing the entire system, a software has been implemented allowing for: (i) the generation of the pulse train signal with selectable pulse amplitude, pulse train frequency and pulse duration, on the second channel of the AWG, (ii) the generation of the sinewave signal under test with selectable frequency and phase respect to the pulse train, on the first channel of the AWG, (iii) the acquisition of the analog multiplier output with the oscilloscope for detecting the sign of the signal, (iv) the acquisition of the rms measurements provided by the reference multimeter, according to a selectable integration time, (v) the measurement of the frequency of the sinewave signal with the digital counter, and (vi) the 3-parameters sine fit on the acquired rms measurements for estimating the phase of the sinewave signal. In particular, the phase measurement procedure can be summarized in the following steps:

1 - the sinewave signal at a given frequency and with user-defined phase and amplitude values is generated on the first channel of the AWG;
2 - the pulse train is configured in terms of pulse train frequency, amplitude and pulse duration, which is chosen according to the number of delays that will be adopted for sampling the sinewave in several time instants;
3 - the time delay, Δ_t, of the pulse train is imposed to $0\,\mathrm{s}$;
4 - the integration time of the voltmeter is configured and the rms measurement is acquired;
5 - the output of the analog multiplier is acquired with the oscilloscope and the sign of the signal is estimated according to the sign of the average value of the acquired samples;
6 - the time delay, Δ_t, is changed according to the set of selected delays;
7 - the vector pairs of the rms measurements with the sign and their associated time delays are built;
8 - the frequency of the sinewave signal is measured with the universal digital counter;
9 - using the frequency measurement, the 3-parameters sine fit is performed on the stored vectors and the sinewave

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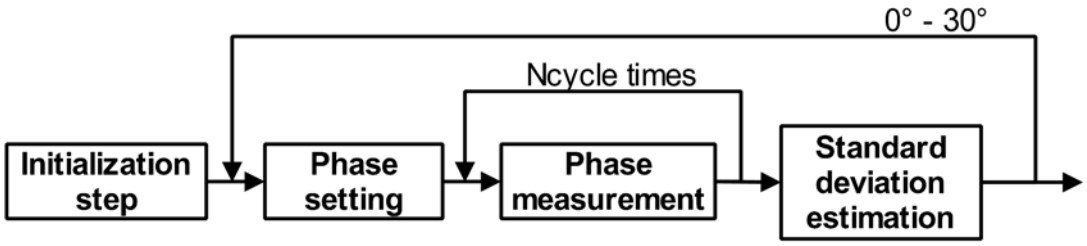

Fig. 5. Procedure for repeatability investigation of the phase measurements, implemented in MATLAB.

phase is obtained.

The 3-parameters sine fit has been implemented according to [8]. Let us consider the following expression for the sinewave signal under test:

$$y(t) = A \cdot cos(2\pi f_{src} t) + B \cdot sin(2\pi f_{src} t) + C \quad (3)$$

where A, B, and C are the coefficients that define the sinewave signal and have to be estimated by the 3-parameters sine fit.

By considering the M rms measurements provided by the voltmeter in the Δ_t instants, the following system of equations can be written:

$$\begin{cases} y_0 = A \cdot cos(2\pi f_{src}\Delta_{t0}) + B \cdot sin(2\pi f_{src}\Delta_{t0}) + C \\ y_1 = A \cdot cos(2\pi f_{src}\Delta_{t1}) + B \cdot sin(2\pi f_{src}\Delta_{t1}) + C \\ \vdots \\ y_M = A \cdot cos(2\pi f_{src}\Delta_{tM}) + B \cdot sin(2\pi f_{src}\Delta_{tM}) + C \end{cases} \quad (4)$$

where, $\mathbf{y} = [y_0, y_1, \ldots, y_M]^T$ is the vector containing the M rms measurements, and $[\Delta_{t0}, \Delta_{t1}, \ldots, \Delta_{tM}]^T$ is the vector of the imposed time delays. This system can be written in a matrix form as follows:

$$\mathbf{y} = \mathbf{D} \cdot \mathbf{p} \quad (5)$$

where, $\mathbf{p} = [A, B, C]^T$, and $\mathbf{D}$ is defined as follows:

$$\mathbf{D} = \begin{bmatrix} cos(2\pi f_{src}\Delta_{t0}) & sin(2\pi f_{src}\Delta_{t0}) & 1 \\ cos(2\pi f_{src}\Delta_{t1}) & sin(2\pi f_{src}\Delta_{t1}) & 1 \\ \vdots & \vdots & \vdots \\ cos(2\pi f_{src}\Delta_{tM}) & sin(2\pi f_{src}\Delta_{tM}) & 1 \end{bmatrix} \quad (6)$$

According to (5), an estimation of the the vector $\mathbf{p}$ is given by:

$$\hat{\mathbf{p}} = \mathbf{D}^+ \cdot \mathbf{y} \quad (7)$$

where, $\mathbf{D}^+$ is the pseudo-inverse of $\mathbf{D}$, and $\hat{\mathbf{p}}$ is the estimated vector. From the estimated vector $\hat{\mathbf{p}}$, the phase of the sinewave signal is given by:

$$\hat{\phi} = atan\left(\frac{\hat{B}}{\hat{A}}\right) \quad (8)$$

IV. First experimental results

A repeatability analysis has been performed for the sinewave frequency values of 100 Hz and 1 MHz. This analysis procedure is shown diagrammatically in Figure 5.

At the beginning, in the initialization step, the integration time of the voltmeter, t_{int}, the sinewave frequency, f_{src}, the pulse train frequency, f_{ps}, and the pulse duration, T_p are set. Then, the phase of the sinewave signal is imposed. The phase measurement is performed for $Ncycle = 40$ times. The standard deviation values on the obtained phases are evaluated. The phases of the sinewave signals under test are $0°$ and $30°$. The imposed phases between the pulse train signal, with imposed delay equals to 0 s, and the sinewave signals have been measured by means of the digital counter.

For both the test frequencies, the number of delays N is 10, and the pulse train frequency is equal to the sinewave frequency. For $f_{src} = 100$ Hz, $t_{int} = 2$ s and $T_p = 200$ µs; and for $f_{src} = 1$ MHz, $t_{int} = 200$ ms and $T_p = 100$ ns.

For each imposed phase, the standard deviation, σ_ϕ, on the estimated phases has been calculated. In Table II, the comparison between the maximum phase standard deviation values obtained with the proof of concept prototype proposed in [4] and the proposed analog multiplier-based prototype are reported. It is possible to note that for the frequency value of 1 MHz, the analog multiplier standard deviation value is lower than the ones obtained in [4]. At 100 Hz, the analog multiplier exhibits lower repeatability than the proof of concept.

TABLE II
Comparison between the experimental maximum standard deviation values obtained in [4], and the values obtained with the proposed analog multiplier prototype.

f_{src}	Proof of concept	Analog multiplier prototype
	σ_ϕ	σ_ϕ
100 Hz	0.009°	0.017°
1 MHz	0.007°	0.0022°

V. Conclusion

In this paper, a hardware implementation of a phase measurement prototype that used as a sampler an analog multiplier was proposed. The hardware and software aspects of the implemented phase measurement system were described. The first experimental results show that the proposed prototype exhibits a smaller standard deviation than the proof of concept proposed in [4] at 1 MHz.

Future work will be focused on: (i) the complete metrological characterization of the prototype in the frequency range of 100 Hz up to 10 MHz, (ii) the comparison in terms of standard deviation of the proposed prototype with the proof of concept from [4], and (iii) the implementation of a new prototype, where the generation of the pulse train and the sinewave signals are not performed by the same instrument.

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