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Accuracy Evaluation of an Equivalent Synchronization Method for Assessing the Time Reference in Power Networks

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***Abstract*— This paper deals with the evaluation of the accuracy performance of an approach for assessing the phase displacement between voltages at power network nodes. This task is accomplished by processing asynchronous measurements taken at each node. This turns into an equivalent synchronization, which is, therefore, obtained without exploiting any synchronization signals, such as the ones provided by means of wireless (i.e., global positioning system) or wired technologies. As a matter of fact, distribution system operators will gain the possibility of deploying, at more affordable costs, wide area measurement system (WAMS) over their power networks for enhancing their stability and reliability. Phasor measurement units (PMUs) are the most common examples of such WAMS, but, besides their high cost, there are circumstances where providing a time reference signal to remote PMUs often becomes a difficult task. This paper aims at recalling the basic theoretical principles of the method and at proving its applicability in power network through a deep analysis of its metrological performance.**

***Index Terms*— Accuracy evaluation, asynchronous measurement, network impedance, phase angle measurement, phase difference, phasor measurement units (PMUs), time synchronization, uncertainty.**

I. Introduction

WITH the huge and fast development of smart grids and distributed generation, the need to perform measurements in many different nodes of the power networks has become a paramount importance for distribution system operators to allow an effective control of the network operation. Furthermore, the possibility to also synchronize measurements performed at different nodes of the power networks has allowed even to improve the control performance: better control of the operation frequency, fault detection and location, higher network stability, islanding detection and operation, improving the power flow in the network, etc.

As well known, the devices that allow to perform synchronized measurements in power networks are referred to as phasor measurements units (PMUs) [1]. They allow not only to perform the measurement of the rms value of the voltages and currents but also of their phases with respect to a global time reference. This way, according to the definition of phasor given by Steinmetz [2] in 1893, the phasor of a voltage or a current is given by its rms value and by its phase difference with respect to a defined time reference. The comparison between the phases of all voltages in a power network allows to evaluate the state estimation of the network, which, in turn, represents the gate for getting the observability of the whole network. So, the added value of a PMU with respect to a typical power meter is given by the possibility to evaluate the phase difference of all voltages in a network, which is accomplished by means of a global time reference.

The use of PMUs in transmission lines started around 1988 and its usefulness for a better network control and monitoring is today well recognized. In transmission lines, the errors allowed in the evaluation of phase displacement between voltages are not a critical parameter due to the very long distances and then to the large difference of the voltage phases (in the order of tens of mrad/km). So, traditional voltage transformers (VTs) with 0.2 accuracy class, used for billing purposes, result well suitable for such an application.

However, in distribution networks this is not likely to happen. The use of PMUs in such kind of networks has been widely investigated in the scientific literature also from the measurement point of view (see [3]–[5]). But distribution lines are far shorter than transmission ones and the difference between the node voltage phases results often very small, in the order of very few milliradian per kilometer. Hence, VTs with typical 0.5 accuracy class already installed for billing purposes and measurement in general are no longer suitable for PMU usage. In conclusion, besides the need to have an accurate time reference (with standard deviation in the order of 1 μs or lower) also very accurate VTs are required for assuring a properly accurate evaluation of the voltage phasors. Of course, noticeable contribution to the study of how the uncertainty in the measurement hardware affects the results provided by the PMU-based system has been given by the measurement community, as proved in [6]–[8].

Nowadays the global time reference can be provided to all PMUs deployed in the network by means of wireless or wired communication protocols. The pulse-per-second information included in the global positioning system (GPS) signals represents the worldwide most used time reference information. It can be easily and freely read by means of antennas and receivers for triggering all PMUs to a unique reference.

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Among many advantages in using such a technique, it shows, on the contrary, some criticalities: the most important one is represented by the need to install the antenna such that to be able to receive satellite signals. But this is not always occurring in many circumstances, like, for instance, in urban areas, where many obstacles can make it difficult: trees, buildings, skyscrapers, underground secondary substations, roads, and others. In such situations, there is a need of a periodical calibration of the PMUs internal clock, by means, for example, of a traveling standard [9].

In the last decade also wired time reference infrastructures have been developed. Today their performance (in terms of delays and accuracy of the time reference) is getting more and more close to the GPS one. In particular, the IEEE 1588 [10] and IEC 61850-5 [11] Standards are by far the most used recommend practices for the transmission of reference times over wired communication infrastructures [12]. However, also such a technology shows some limitations. In particular, they are cost effective in case of a lack of a suitable communication network. Moreover, in rural areas the deployment of a wiring infrastructure can result almost impossible.

At the light of all the aforementioned issues, a novel analytical method for assessing the phase difference between voltages at different nodes of a distribution power network has been proposed in [13], of which this paper is a technical extension. The main feature of such a method is that no global time reference is required for triggering the measurement units deployed in the field. Measurements at different nodes are performed asynchronously. It only requires that voltages and currents in each node of the networks are simultaneously acquired. This task is generally accomplished by commercial power meters.

The implementation of such a method is beneficial in all situations where synchronization signals are not available or (and) a less expensive measurement architecture is required.

In the scientific literature, only one application of unsynchronized measurement of phasors in power networks can be found, i.e., in [14]. In [14], Janssen *et al.* iteratively determine the state of the network formulated by means of the so-called augmented matrix approach. On the contrary, several papers (see [15]–[22]) exploit unsynchronized measurements to tackle fault location issues.

In [13], the performance of the proposed method has been evaluated by comparing the phase displacements provided by the method with actual ones in different simulated power network conditions. The obtained results look satisfactory, but in order to asses if the proposed approach can be an effective alternative to conventional synchronization methods (like GPS-based solutions), further investigations are required. To this purpose, in this paper a typical configuration of the measurement system, which allows getting the information required for applying the proposed equivalent synchronization method, is considered. Different scenarios, each of them characterized by different accuracies of the measurement devices, are analyzed to evaluate the overall accuracy of the proposed approach under actual conditions.

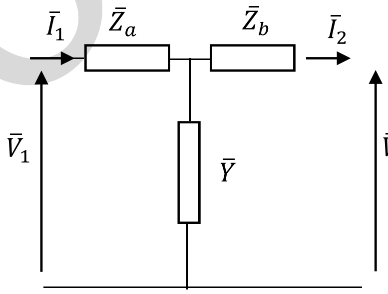

Fig. 1. T-circuit representation of single-wire line.

This paper is structured as follows. In Section II, the method presented in [13] is recalled, whereas in Section III the configuration of the measurement system is described.

A brief summary of uncertainty evaluation methods designed for this purpose is presented in Section IV. Numerical results of different scenarios are shown and discussed in Section V. Finally, conclusions are drawn in Section VI.

II. Proposed Approach

A. Theoretical Background: Electric Line Modeling

Let us briefly recall how an electric line is modeled. As is well known, it can be represented by the equivalent circuit in Fig. 1, where the following notations are used.

1) $\bar{V}_1$ and $\bar{V}_2$ are the voltage phasors at the beginning (node 1) and the end (node 2), respectively.
2) $\bar{I}_1$ and $\bar{I}_2$ are the current phasors getting out the node 1 and getting in the node 2, respectively.
3) $\bar{Z}_a$, $\bar{Z}_b$, and $\bar{Y}$ are the equivalent parameters of the above obtained T-circuit, as briefly described in the following, from the two-port model matrix.

Such a matrix relates $\bar{V}_1$ and $\bar{I}_1$ with $\bar{V}_2$ and $\bar{I}_2$

$$\begin{bmatrix} \bar{V}_2 \\ \bar{I}_2 \end{bmatrix} = \begin{bmatrix} \bar{A} & -\bar{B} \\ -\bar{C} & \bar{A} \end{bmatrix} \begin{bmatrix} \bar{V}_1 \\ \bar{I}_1 \end{bmatrix}. \tag{1}$$

In (1)

$$\bar{A} = \cosh(\bar{\gamma} l) \tag{2}$$
$$\bar{B} = \bar{Z}_c \sinh(\bar{\gamma} l) \tag{3}$$
$$\bar{C} = \bar{Y}_c \sinh(\bar{\gamma} l) \tag{4}$$

with l the length of the line and $\bar{\gamma}$ the propagation constant which depends on the per unit length parameters r, l, c, and g (usually g is neglected in medium voltage cables).

Once $\bar{A}$, $\bar{B}$, and $\bar{C}$ are known, the parameters of the equivalent circuit can be computed as follows:

$$\bar{Z}_a = \bar{Z}_b = \frac{\bar{A}-1}{\bar{C}} \tag{5}$$
$$\bar{Y} = \bar{C}. \tag{6}$$

B. Procedure

As mentioned in Section I, the main goal of this paper is the estimation of the phase displacement between voltage $\bar{V}_1$ at the beginning of the line, taken as reference, and voltage $\bar{V}_2$ at the end of the line without using synchronized measurements

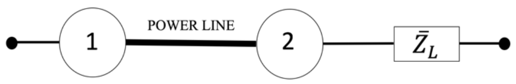

Fig. 2. Single-wire line topology.

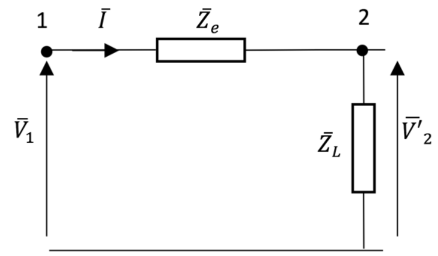

Fig. 3. Representation of a single-wire line and its load used in the proposed approach.

(Fig. 2). It must be underlined that as it will become more clear in the following, the proposed procedure can be applied (hence it is suitable) for state estimation of power networks under steady-state conditions, like for instance in all applications required by SCADA systems.

Besides the state estimation, the presented approach can be also successfully used for diagnostic purposes. For instance, it allows the evaluation of resistive and reactive losses of power lines. Nowadays, this knowledge represents one of the most important requirements that utilities are looking for in network monitoring systems for smart grids.

According to the proposed approach, measurements in every node are performed and transmitted asynchronously every few seconds, in compliance with SCADA specifications. On the contrary, the presented method is not suitable for network monitoring under transient conditions (hence for protection purposes).

The phase displacement between voltages in the network is usually due to the combined effect of both the line (according to its model shown in Fig. 1) and the equivalent impedance $\bar{Z}_L$ of the load connected at the end of line. The lack of synchronization does not allow to write a sufficient number of independent equations to determine all the three unknown parameters ($\bar{Z}_L$, $\bar{Z}_a = \bar{Z}_b$, and $\bar{Y}$) of such a circuit. Therefore, the proposed method relies on the use of a different model, shown in Fig. 3, where $\bar{Z}_e$ is an equivalent impedance of the line computed in a such a way that line losses as well as the active powers at nodes 1 and 2 are the same as the actual ones. As a matter of fact, active power is an integral quantity computed over one (or more) cycles and its value at such nodes is independent from the synchronization of its measurements, pending the power system is in steady-state conditions for just one cycle in each node.

In the following, the procedure for estimating the searched phase difference is recalled. To this purpose, let us denote by $\Delta\varphi_a$ the actual value of such a phase difference and by $\Delta\varphi_e$ the corresponding estimate provided by the equivalent synchronization approach.

First of all, the couple of phasors $\bar{V}_1$ and $\bar{I}_1$, $\bar{V}_2$ and $\bar{I}_2$ must be measured. In each measurement node, voltage and current are simultaneously acquired, so that the relationship between the phasors of each couple is correct. Of course, due to the lack of synchronization, the phase displacement between $\bar{V}_1$ and $\bar{V}_2$ is $\Delta\varphi_a + \delta$, where δ is a random angle depending on the random time difference between the acquisition of the two couples of phasors.

With reference to the circuit in Fig. 3, the following system of equations can be written:

$$\begin{cases} P'_2 = \mathrm{Re}\left(\dfrac{\left|\bar{V}'_2\right|^2}{\bar{Z}^*_L}\right) \\ \bar{V}'_2 = \bar{V}_1 \dfrac{\bar{Z}_L}{\bar{Z}_L + \bar{Z}_e} = \bar{V}_1 \dfrac{\bar{Z}_L}{\bar{Z}_L + R_e + jX_e} \end{cases} \tag{7}$$

where P'_2 is the active power at node 2 of such a circuit and R_e and X_e are the resistance and reactance of the equivalent impedance $\bar{Z}_e$. Given that, as stated above, $P'_2 = P_2$ and measurements of $\bar{V}_2$ and $\bar{I}_2$ allow the determination of the actual value of $\bar{Z}_L$

$$\bar{Z}_L = \frac{\bar{V}_2}{\bar{I}_2}. \tag{8}$$

The only unknowns of (7) are $\bar{V}'_2$ and $\bar{Z}_e$. As for $\bar{Z}_e$, the resistive part R_e can be determined under the assumption of the same line losses in both circuits of Figs. 1 and 3

$$R_e = 2\frac{P_1 - P_2}{I_1^2 + I_2^2} \tag{9}$$

where P_1 and P_2 are the active powers measured at nodes 1 and 2, respectively, and I_1 and I_2 are the rms values of the above-defined current phasors.

By substituting the second equation of (7) into the first one, the reactive part X_e of $\bar{Z}_e$ can be obtained by solving the following second-order equation [5]:

$$X_e^2 + 2X_eX_L + d = 0 \tag{10}$$

where X_L is the reactive part of $\bar{Z}_L$ and

$$d = |\bar{Z}_L|^2 - \frac{|\bar{V}_1|^2|\bar{Z}_L|^2}{P_2}\mathrm{Re}\left\{\frac{1}{\bar{Z}^*_L}\right\} + R_e\bar{Z}^*_L + R_e\bar{Z}_L + R_e^2. \tag{11}$$

One of the solutions of (10) is always negative if, as it is usual, the power factor of $\bar{Z}_L$ is lagging.

Finally, $\bar{V}'_2$ can be determined along with its phase displacement $\Delta\varphi_e$, with respect to $\bar{V}_1$ by means of the second equation of (7).

III. Measurement System Configuration

The implementation of the proposed equivalent synchronization approach requires the use of a wide area measurement system which, conversely to those based on PMUs, does not require any kind of synchronization among different remote units. In the scientific literature, several applications of distributed measurement systems can be found for two main purposes: 1) for monitoring periodic disturbances and try to determine their sources [23], [24] and 2) for locating the faults caused by internal (i.e., line fault [25], [26]) and

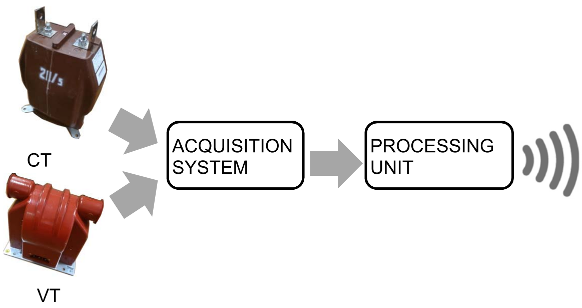

Fig. 4. Schematic representation of the measurement system configuration.

TABLE I

ACTUAL AND ESTIMATED VOLTAGE PHASE DIFFERENCE FOR A 500-KVA LOAD, 10-km LENGTH CABLE

S (mm^2)	$\Delta\varphi_a$ (mrad)	$\Delta\varphi_e$ (mrad)	$\Delta\varphi_e$ - $\Delta\varphi_a$ (mrad)
50	3.47	5.31	1.84
95	0.69	1.485	1.415

TABLE II

PER UNIT LENGTH PARAMETERS FOR THE TWO TYPES OF CABLES

S (mm^2)	r (mΩ/m)	l (uH/m)	c (nF/m)
50	0.587	0.4138	0.21
95	0.193	0.3694	0.26

external (i.e., lighting [27]) sources. Both situations require synchronization between the different remote units. The lack of such a requirement has to be investigated [28] as well as the overall metrological performance of the system [29]. The proposed system consists of a main unit and many remote units as the number of the monitored nodes (two in the considered examples). Each remote unit consists of three VTs, three current transformers (CTs), an acquisition system, a processing unit, and a transmission device, as shown in Fig. 4. VT and CT may be inductive instrument transformers (ITs) [30] or low-power ITs [31] and can be considered as the main sources of uncertainty. As for the acquisition system, it must feature simultaneous sampling of its inputs in order to avoid any additional phase errors. Commercial devices can easily ensure time delay on the order of very few microseconds (about 0.3 mrad at 50 Hz). Moreover, the use of a phase-locked loop results in negligible effects of leakage errors. This solution is already implemented in many instrument used in power system, such as, for example, several commercial digital energy meters. The processing unit computes voltage and current phasors from the sequence representing voltage and current waveforms. Finally, the transmission device sends the above phasors to the main unit by exploiting some kind of communication technology and protocol. The way the information is sent is outside the purpose of this paper.

The main unit collects the voltage and current phasors coming from all the nodes and determines $\Delta\varphi_e$ by applying the procedure described in Section II-B.

IV. UNCERTAINTY EVALUATION METHODS

According to the "Guide to the expression of Uncertainty in Measurements" and its Supplement 1 [32], [33], the result Y of a measurement is a random variable. Y is a function f of the input quantities X_i. As it is well known, random variables can be used to represent both random and systematic effects. The first one is caused by unpredictable changes in the experiment, while the second originates from the measuring instruments.

According to [32] and [33], the pdf associated with Y is determined by a combination of the pdfs associated with each X_i. However, if the operation between the pdfs is different from the sum of two pdfs, which turns into the convolution of them, there is not any mathematical approach to deal with such pdfs. In order to solve this issue, [32] and [33] propose two different solutions.

1) GUM [32] presents an analytical approach, which provides exact results only in a restricted number of situations. It consists in the propagation of the mean and standard deviation of the pdfs along the measurement function, by means of a first-order Taylor series.
2) Supplement 1 [33] deals with a numerical simulation, the Monte Carlo method (MCM). Conversely to the previous approach, the MCM can be applied to a huge number of situations and, if well implemented, it features very accurate estimations.

Due to this fact, for the approach presented in this paper, f cannot be easily expressed, the MCM is the most suitable approach for tackling the uncertainty evaluation and propagation.

V. NUMERICAL EXAMPLES

In [13], the performance of the proposed approach has been tested in several conditions characterized by different cable cross sections, cable lengths, and apparent powers of the load. The results have been generally satisfactory (with an error ranging from 0.3 to 1.84 mrad) and it has been highlighted that the difference $\Delta\varphi_e - \Delta\varphi_a$ (which represents the error of the method):

1) increases as the length of the line increases;
2) decreases as the cable cross section increases;
3) slightly decreases as the apparent power of the load increases.

At the light of the above outcomes, the uncertainty evaluation is focused on the worst of the previous studied cases: the longest line (10 km), the lowest apparent power (500 kVA), and the smallest cross sections (50 and 95 mm^2). The errors $\Delta\varphi_e - \Delta\varphi_a$ obtained in [13] for the above configurations are recalled in Table I, whereas Table II shows the per unit length parameters of the two cable cross sections considered.

For the sake of simplicity but without loss of generality, a single-phase configuration is considered, so that the contribution to uncertainty of only a VT, CT, and of the acquisition system must be taken into account. As for ITs, their accuracy performances are expressed by their accuracy classes as defined in [34] and [35] for inductive current and VTs, respectively. Accuracy classes provide limits for ratio and phase errors. Table III shows, for each accuracy class,

TABLE III
RATIO ERRORS AND PHASE ERRORS FOR CT AND VT

Accuracy Class	ε_{CT} (%)	ε_{VT} (%)	$\Delta\varphi_{CT}$ (crad)	$\Delta\varphi_{VT}$ (crad)
0.1	0.1	0.1	0.15	0.15
0.2	0.2	0.2	0.3	0.3
0.5	0.5	0.5	0.9	0.6

ratio error $\boldsymbol{\varepsilon}_{\mathbf{VT}}$, phase error $\Delta\varphi_{\mathrm{VT}}$ and ratio error $\boldsymbol{\varepsilon}_{\mathbf{CT}}$, phase error $\Delta\varphi_{\mathrm{CT}}$ for VT and CT, as reported in [34] and [35], respectively.

As far as the acquisition system is concerned, the delay due to the noncomplete simultaneous sampling is neglected given that, as mentioned above, it turns into a phase error quite lower than the ones due to the ITs. Contributions due offset errors are not considered given that, as it is well known, they do not affect the phasors $\bar{V}_1$, $\bar{V}_2$, $\bar{I}_1$, and $\bar{I}_2$, when computed by means of the discrete Fourier transform algorithm. Therefore, only an overall contribution due to nonlinearity, gain, noise, and quantization, which is chosen equal to $\pm 0.05\%$, is taken into account. Such a value is consistent with that required by the largest Italian utility for its fault detection and power meters (see [36]).

For both the cable cross sections considered, different scenarios are analyzed. Each scenario is characterized by a CT and a VT featuring the same accuracy class, as usual in actual situations. Hence, according to Table III, three scenarios arise, in which, first the limits of the 95% confidence interval of $\Delta\varphi_e - \Delta\varphi_a$ is evaluated (case #1). Then, it is studied how the different uncertainty sources located in the ITs contribute to the above interval. To this purpose, the following cases are analyzed:

1) only the sources located in the VT are considered (case #2);
2) only the sources located in the CT are considered (case #3);
3) only phase error of the VT is considered (case #4);
4) only ratio error of the VT is considered (case #5);
5) only phase error of the CT is considered (case #6);
6) only ratio error of the CT is considered (case #7).

All the uncertainty evaluation is performed by running a Monte Carlo simulation with 100 000 iterations. According to [33], in the lack of any further information, each random variable, representing a contribution to uncertainty, is assumed to be uniformly distributed with zero mean and limits equal to the rated values of the considered contributions. A unimodal random variable (like all random variables considered in this paper), with uniform distribution, features the highest dispersion hence, according to the maximum entropy principle, in case of lack of information regarding the pdf of a random variable, uniform distribution has to be assumed.

Table IV lists, for the 50-mm^2 cable, the limits of the 95% confidence interval for the aforementioned seven cases of each of the three scenarios. The same quantities are shown in Table V for the 95-mm^2 cable. The first comment is that, as it is expected, uncertainty on $\Delta\varphi_e - \Delta\varphi_a$, which is reported in row named #1 of Tables IV and V in terms of limits of the

TABLE IV
LIMITS (mrad) OF THE 95% CONFIDENCE INTERVAL OF PHASE DISPLACEMENT $\Delta\varphi_e$, IN THE CASE OF A 50-mm^2 CABLE, FOR DIFFERENT ACCURACY CLASSES

CASE	0.1	0.2	0.5
#1	-2.10; 5.80	-6.10; 9.80	-18.1; 21.9
#2	-0.36; 4.00	-2.60; 6.30	-7.00; 10.7
#3	-1.40; 5.10	-4.60; 8.30	-15.9; 19.6
#4	-0.34; 4.00	-2.50; 6.20	-6.90; 10.6
#5	1.60; 2.00	1.40; 2.30	0.82; 2.90
#6	-0.35; 4.00	-2.50; 6.20	-11.3; 15.0
#7	-0.41; 4.10	-2.7; 6.40	-9.40; 13.2

TABLE V
LIMITS (mrad) OF THE 95% CONFIDENCE INTERVAL OF PHASE DISPLACEMENT $\Delta\varphi_e$, IN THE CASE OF A 95-mm^2 CABLE, FOR DIFFERENT ACCURACY CLASSES

CASE	0.1	0.2	0.5
#1	-2.50; 5.40	-6.50; 9.30	-18.6; 21.4
#2	-0.74; 3.60	-2.90; 5.70	-7.30; 10.1
#3	-1.80; 4.70	-5.00; 7.90	-16.4; 19.2
#4	-0.73; 3.60	-2.90; 5.70	-7.20; 10.0
#5	1.20; 1.70	0.92; 1.90	0.18; 2.70
#6	-0.74; 3.60	-2.90; 5.70	-11.5; 14.3
#7	-0.89; 3.70	-3.20; 6.00	-10.1; 13.0

95% confidence interval, increases as the accuracy class moves from 0.1 to 0.5. Moreover, it seems to be not significantly dependent on the cross section. By comparing case #2 with case #3 it can be stated that the contribution to uncertainty of the CT is greater than that of VT: in fact, the amplitude of the confidence interval of $\Delta\varphi_e - \Delta\varphi_a$ obtained by considering only ratio and phase errors of the CT is about 1.5 times larger than the one obtained when only the VT accuracy is taken into account. This is justified by the fact that the quantity measured by the CTs (current phasor), on the contrary to the quantity (voltage phasor) measured by the VTs, appears also in terms of rms value in the evaluation of R_e [see (9)]. Such an explanation is confirmed by noticing that (see cases #3 and #4) the contribution to uncertainty due to the ratio error of the CTs is greater than that of VTs. As for cases #6 and #7, which represent the contribution of the phase errors, no significant dissimilarities between CT and VT can be appreciated, except for the 0.5 accuracy class where, according to Table III, the limits of the phase error are different for CT and VT.

As a final comment about the effect of the ITs accuracy, the analysis of the confidence interval widths, shown in Tables IV and V, highlights that only ITs featuring 0.1 or 0.2 accuracy class can be employed in actual application of the proposed approach.

On the basis of the procedure described in Section II-B, the evaluation of $\Delta\varphi_e$ relies on several quantities that are estimated by processing voltage and current phasors measured at the two nodes. Among such parameters, it can be observed that R_e and X_e can be derived in a different way if some

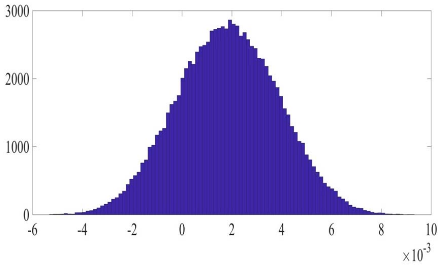

Fig. 5. Pdf of $\Delta\varphi_e - \Delta\varphi_a$ for case #1 with 0.1 accuracy class.

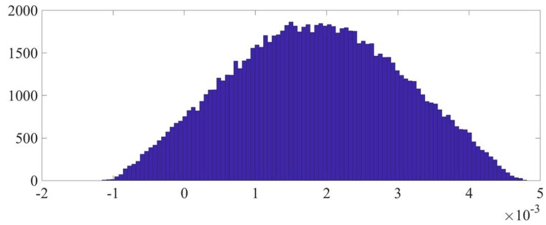

Fig. 6. Pdf of $\Delta\varphi_e - \Delta\varphi_a$ for case #2 with 0.1 accuracy class.

information about the cable characteristics are provided. For example, with reference to the case #1 of Table IV, the limits of the confidence interval of $\Delta\varphi_e - \Delta\varphi_a$ become -0.34; 4 if R_e is known with an accuracy of $\pm 10\%$ and X_e is evaluated according to (10). Such limits are 0.17; 3.5 when X_e is assumed to be known within $\pm 10\%$ and R_e computed as in (9). Finally, the confidence interval of $\Delta\varphi_e - \Delta\varphi_a$ is only 1.5; 2.3 when both the above parameters are provided with a $\pm 10\%$ accuracy.

Figs. 5 and 6 show the estimated probability density function (pdf) for cases #1 and #2, respectively, when the accuracy class is 0.1 for both the ITs and the cross section is 50 mm^2. It can be observed that the pdf in Fig. 5 is approximatively normal, whereas the one in Fig. 6 is almost trapezoidal. Of course, this is in accordance with the central limit theorem, given that the pdf in Fig. 5 refers to a random variable, which is obtained by the combination of more contributions to uncertainty.

All the uncertainty intervals associated with the phase displacement, have been obtained by assuming the worst case for the probability distribution of the random variables related to the uncertainty terms. This, according to the GUM, has to be considered the most likelihood confidence interval.

VI. Final Remarks and Future Work

In this paper, an approach for assessing the phase displacement between voltages at power network nodes by processing asynchronous measurements in each node has been recalled. Starting from the description of the distributed measurement system that can be used to implement the recalled method, uncertainty affecting the errors in the estimate of the voltage phase displacements has been investigated in different operating conditions. Moreover, the contribution to the above uncertainty, due to each uncertainty source arising in the measurement chain, has been evaluated. In the light of the obtained results concerning uncertainty evaluation, it can be concluded that the proposed approach can be assumed suitable for being extended to more complex power networks. In such cases, the proposed approach would be iteratively applied.

In the end, it has been highlighted that if the parameters characterizing the power cable are assumed to be known with an accuracy of $\pm 10\%$, the amplitude of the confidence interval on the error in the phase displacement measurement is significantly reduced. This is not an unrealistic assumption that will be subjected to future investigations.

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