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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, 5 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 10 system (WAMS) over their power networks for enhancing their 11 stability and reliability. Phasor measurement units (PMUs) are 12 the most common examples of such WAMS, but, besides their 13 high cost, there are circumstances where providing a time 14 reference signal to remote PMUs often becomes a difficult task. 15 This paper aims at recalling the basic theoretical principles of 16 the method and at proving its applicability in power network 17 through a deep analysis of its metrological performance. 18

Index Terms-Accuracy evaluation, asynchronous mea-19 surement, network impedance, phase angle measurement, 20 21 phase difference, phasor measurement units (PMUs), time 22 synchronization, uncertainty.

#### I. INTRODUCTION

23

WITH the huge and fast development of smart grids 24 and distributed generation, the need to perform mea-25 surements in many different nodes of the power networks 26 has become a paramount importance for distribution system 27 operators to allow an effective control of the network oper-28 ation. Furthermore, the possibility to also synchronize mea-29 surements performed at different nodes of the power networks 30 has allowed even to improve the control performance: better 31 32 control of the operation frequency, fault detection and location, 33 higher network stability, islanding detection and operation, improving the power flow in the network, etc. 34

As well known, the devices that allow to perform 35 synchronized measurements in power networks are referred 36 to as phasor measurements units (PMUs) [1]. They allow not 37 only to perform the measurement of the rms value of the voltages and currents but also of their phases with respect to

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a global time reference. This way, according to the definition 40 of phasor given by Steinmetz [2] in 1893, the phasor of a 41 voltage or a current is given by its rms value and by its 42 phase difference with respect to a defined time reference. The 43 comparison between the phases of all voltages in a power 44 network allows to evaluate the state estimation of the network, 45 which, in turn, represents the gate for getting the observability 46 of the whole network. So, the added value of a PMU with 47 respect to a typical power meter is given by the possibility 48 to evaluate the phase difference of all voltages in a network, 49 which is accomplished by means of a global time reference. 50

The use of PMUs in transmission lines started around 51 1988 and its usefulness for a better network control and 52 monitoring is today well recognized. In transmission lines, 53 the errors allowed in the evaluation of phase displacement 54 between voltages are not a critical parameter due to the 55 very long distances and then to the large difference of the 56 voltage phases (in the order of tens of mrad/km). So, tra-57 ditional voltage transformers (VTs) with 0.2 accuracy class, 58 used for billing purposes, result well suitable for such an 59 application. 60

However, in distribution networks this is not likely to 61 happen. The use of PMUs in such kind of networks has 62 been widely investigated in the scientific literature also from 63 the measurement point of view (see [3]–[5]). But distribution 64 lines are far shorter than transmission ones and the difference 65 between the node voltage phases results often very small, 66 in the order of very few milliradian per kilometer. Hence, VTs 67 with typical 0.5 accuracy class already installed for billing 68 purposes and measurement in general are no longer suitable 69 for PMU usage. In conclusion, besides the need to have an 70 accurate time reference (with standard deviation in the order 71 of 1  $\mu$ s or lower) also very accurate VTs are required for 72 assuring a properly accurate evaluation of the voltage phasors. 73 Of course, noticeable contribution to the study of how the 74 uncertainty in the measurement hardware affects the results 75 provided by the PMU-based system has been given by the 76 measurement community, as proved in [6]-[8]. 77

Nowadays the global time reference can be provided to all 78 PMUs deployed in the network by means of wireless or wired 79 communication protocols. The pulse-per-second information 80 included in the global positioning system (GPS) signals rep-81 resents the worldwide most used time reference information. 82 It can be easily and freely read by means of antennas and 83 receivers for triggering all PMUs to a unique reference. 84

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Among many advantages in using such a technique, it shows, 85 on the contrary, some criticalities: the most important one is 86 represented by the need to install the antenna such that to be 87 able to receive satellite signals. But this is not always occurring 88 in many circumstances, like, for instance, in urban areas, 89 where many obstacles can make it difficult: trees, buildings, 90 skyscrapers, underground secondary substations, roads, and 91 others. In such situations, there is a need of a periodical 92 93 calibration of the PMUs internal clock, by means, for example, 94 of a traveling standard [9].

In the last decade also wired time reference infrastructures 95 have been developed. Today their performance (in terms of 96 delays and accuracy of the time reference) is getting more and 97 more close to the GPS one. In particular, the IEEE 1588 [10] 98 and IEC 61850-5 [11] Standards are by far the most used 99 recommend practices for the transmission of reference times 100 over wired communication infrastructures [12]. However, also 101 such a technology shows some limitations. In particular, they 102 are cost effective in case of a lack of a suitable communication 103 network. Moreover, in rural areas the deployment of a wiring 104 infrastructure can result almost impossible. 105

At the light of all the aforementioned issues, a novel 106 analytical method for assessing the phase difference between 107 voltages at different nodes of a distribution power network 108 has been proposed in [13], of which this paper is a technical 109 extension. The main feature of such a method is that no global 110 time reference is required for triggering the measurement units 111 deployed in the field. Measurements at different nodes are 112 performed asynchronously. It only requires that voltages and 113 currents in each node of the networks are simultaneously 114 acquired. This task is generally accomplished by commercial 115 power meters. 116

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 socalled 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 128 evaluated by comparing the phase displacements provided by 129 the method with actual ones in different simulated power 130 network conditions. The obtained results look satisfactory, 131 but in order to asses if the proposed approach can be an 132 effective alternative to conventional synchronization methods 133 (like GPS-based solutions), further investigations are required. 134 To this purpose, in this paper a typical configuration of the 135

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.

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

This paper is structured as follows. In Section II, the method 142 presented in [13] is recalled, whereas in Section III the 143 configuration of the measurement system is described. 144

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. 148

#### 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)  $\overline{V}_1$  and  $\overline{V}_2$  are the voltage phasors at the beginning (node 1) and the end (node 2), respectively. 155
- 2)  $\bar{I}_1$  and  $\bar{I}_2$  are the current phasors getting out the node 1 and getting in the node 2, respectively. 157
- 3)  $\overline{Z}_a, \overline{Z}_b$ , and  $\overline{Y}$  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  $\overline{V}_1$  and  $\overline{I}_1$  with  $\overline{V}_2$  and  $\overline{I}_2$ 

$$\begin{bmatrix} \bar{V}_2 \\ \bar{I}_2 \end{bmatrix} = \begin{bmatrix} \bar{A} & -\bar{B} \\ -\bar{C} & \bar{A} \end{bmatrix} \begin{bmatrix} \bar{V}_1 \\ \bar{I}_1 \end{bmatrix}.$$
(1) 162

In (1)

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 $\overline{A} = \cosh(\overline{\gamma} \, \mathbf{l}) \tag{2} \quad {}_{164}$  $\overline{B} = \overline{Z} \, \sinh(\overline{\gamma} \, \mathbf{l}) \tag{3} \quad {}_{165}$ 

$$B = Z_c \sinh(\overline{\gamma} \, \mathbf{l}) \tag{3}$$
 165

 $\bar{C} = \bar{Y}_c \sinh(\bar{\gamma} \, \mathbf{l}) \tag{4}$ 

with *l* the length of the line and  $\overline{\gamma}$  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  $\overline{A}$ ,  $\overline{B}$ , and  $\overline{C}$  are known, the parameters of the 170 equivalent circuit can be computed as follows: 171

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

$$\bar{Y} = \bar{C}.$$
 (6) 173

### B. Procedure

As mentioned in Section I, the main goal of this paper is the estimation of the phase displacement between voltage  $V_1$  at the beginning of the line, taken as reference, and voltage  $V_2$  at the end of the line without using synchronized measurements 178

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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 196 usually due to the combined effect of both the line (according 197 to its model shown in Fig. 1) and the equivalent impedance 198  $Z_L$  of the load connected at the end of line. The lack of 199 synchronization does not allow to write a sufficient number 200 of independent equations to determine all the three unknown 201 parameters ( $Z_L$ ,  $Z_a = Z_b$ , and Y) of such a circuit. Therefore, 202 the proposed method relies on the use of a different model, 203 shown in Fig. 3, where  $Z_e$  is an equivalent impedance of the 204 line computed in a such a way that line losses as well as the 205 active powers at nodes 1 and 2 are the same as the actual 206 ones. As a matter of fact, active power is an integral quantity 207 computed over one (or more) cycles and its value at such nodes 208 is independent from the synchronization of its measurements, 209 pending the power system is in steady-state conditions for just 210 one cycle in each node. 211

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  $\overline{V}_1$  and  $\overline{I}_1$ ,  $\overline{V}_2$  and  $\overline{I}_2$  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  $V_1$  and  $V_2$  is  $\Delta \varphi_a + \delta$ , where  $\delta$  is a random angle depending on the random time difference between the acquisition of the two couples of phasors. 224

With reference to the circuit in Fig. 3, the following system 225 of equations can be written: 226

$$\begin{cases} P_{2}' = \operatorname{Re}\left(\frac{|\bar{V}_{2}'|^{2}}{\bar{Z}_{L}^{*}}\right) \\ \bar{V}_{2}' = \bar{V}_{1}\frac{\bar{Z}_{L}}{\bar{Z}_{L} + \bar{Z}_{e}} = \bar{V}_{1}\frac{\bar{Z}_{L}}{\bar{Z}_{L} + R_{e} + jX_{e}} \end{cases}$$
(7) 227

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  $\bar{Z}_L$  230

$$\bar{Z}_L = \frac{V_2}{\bar{I}_2}.$$
 (8) 233

The only unknowns of (7) are  $\overline{V}'_2$  and  $\overline{Z}_e$ . As for  $\overline{Z}_e$ , 234 the resistive part  $R_e$  can be determined under the assumption of the same line losses in both circuits of Figs. 1 and 3 236

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

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. 240

By substituting the second equation of (7) into the first one, the reactive part  $X_e$  of  $\overline{Z}_e$  can be obtained by solving the following second-order equation [5]: 243

$$X_e^2 + 2X_e X_L + d = 0 (10) (12) (12)$$

245

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

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

One of the solutions of (10) is always negative if, as it is usual, the power factor of  $\overline{Z}_L$  is lagging. 249

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

### III. MEASUREMENT SYSTEM CONFIGURATION

The implementation of the proposed equivalent synchro-254 nization approach requires the use of a wide area measure-255 ment system which, conversely to those based on PMUs, 256 does not require any kind of synchronization among different 257 remote units. In the scientific literature, several applications 258 of distributed measurement systems can be found for two 259 main purposes: 1) for monitoring periodic disturbances and 260 try to determine their sources [23], [24] and 2) for locating 261 the faults caused by internal (i.e., line fault [25], [26]) and 262



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

external (i.e., lighting [27]) sources. Both situations require 263 synchronization between the different remote units. The lack 264 of such a requirement has to be investigated [28] as well as 265 the overall metrological performance of the system [29]. The 266 proposed system consists of a main unit and many remote units 267 as the number of the monitored nodes (two in the considered 268 examples). Each remote unit consists of three VTs, three 269 current transformers (CTs), an acquisition system, a processing 270 unit, and a transmission device, as shown in Fig. 4. VT and CT 271 272 may be inductive instrument transformers (ITs) [30] or lowpower ITs [31] and can be considered as the main sources 273 of uncertainty. As for the acquisition system, it must feature 274 simultaneous sampling of its inputs in order to avoid any addi-275 tional phase errors. Commercial devices can easily ensure time 276 delay on the order of very few microseconds (about 0.3 mrad 277 at 50 Hz). Moreover, the use of a phase-locked loop results 278 in negligible effects of leakage errors. This solution is already 279 implemented in many instrument used in power system, such 280 as, for example, several commercial digital energy meters. The 281 processing unit computes voltage and current phasors from the 282 sequence representing voltage and current waveforms. Finally, 283 the transmission device sends the above phasors to the main 284 unit by exploiting some kind of communication technology 285 and protocol. The way the information is sent is outside the 286 purpose of this paper. 287

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 292 Measurements" and its Supplement 1 [32], [33], the result Y of 293 a measurement is a random variable. Y is a function f of the 294 input quantities  $X_i$ . As it is well known, random variables can 295 be used to represent both random and systematic effects. The 296 first one is caused by unpredictable changes in the experiment, 297 while the second originates from the measuring instruments. 298 According to [32] and [33], the pdf associated with Y 299 is determined by a combination of the pdfs associated with 300 each  $X_i$ . However, if the operation between the pdfs is 301 different from the sum of two pdfs, which turns into the 302 convolution of them, there is not any mathematical approach to 303 deal with such pdfs. In order to solve this issue, [32] and [33] 304

<sup>305</sup> propose two different solutions.

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TABLE I Actual and Estimated Voltage Phase Difference for a 500-kVA Load, 10-km Length Cable

S (mm <sup>2</sup> )	$\Delta \phi_a$ (mrad)	$\Delta \phi_e$ (mrad)	$\Delta \phi_e - \Delta \phi_a \text{ (mrad)}$
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 <sup>2</sup> )	r (mΩ/m)	l (uH/m)	c (nF/m)
50	0.587	0.4138	0.21
95	0.193	0.3694	0.26

- 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.
- 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. 319

#### V. NUMERICAL EXAMPLES

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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<sup>2</sup>). 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 general-339 ity, a single-phase configuration is considered, so that the 340 contribution to uncertainty of only a VT, CT, and of the 341 acquisition system must be taken into account. As for ITs, 342 their accuracy performances are expressed by their accuracy 343 classes as defined in [34] and [35] for inductive current and 344 VTs, respectively. Accuracy classes provide limits for ratio 345 and phase errors. Table III shows, for each accuracy class, 346

Accuracy Class	ε <sub>ct</sub> (%)	ε <sub>vt</sub> (%)	Δφ <sub>CT</sub> (crad)	Δφ <sub>vt</sub> (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

TABLE III

RATIO ERRORS AND PHASE ERRORS FOR CT AND VT

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

As far as the acquisition system is concerned, the delay due 350 to the noncomplete simultaneous sampling is neglected given 351 that, as mentioned above, it turns into a phase error quite lower 352 than the ones due to the ITs. Contributions due offset errors 353 are not considered given that, as it is well known, they do 354 not affect the phasors  $V_1$ ,  $V_2$ ,  $I_1$ , and  $I_2$ , when computed by 355 means of the discrete Fourier transform algorithm. Therefore, 356 only an overall contribution due to nonlinearity, gain, noise, 357 and quantization, which is chosen equal to  $\pm 0.05\%$ , is taken 358 into account. Such a value is consistent with that required 359 by the largest Italian utility for its fault detection and power 360 meters (see [36]). 361 For both the cable cross sections considered, different 362

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);

375 3) only phase error of the VT is considered (case #4);

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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 379 Monte Carlo simulation with 100000 iterations. According 380 to [33], in the lack of any further information, each random 381 variable, representing a contribution to uncertainty, is assumed 382 to be uniformly distributed with zero mean and limits equal to 383 the rated values of the considered contributions. A unimodal 384 random variable (like all random variables considered in 385 this paper), with uniform distribution, features the highest 386 dispersion hence, according to the maximum entropy principle, 387 in case of lack of information regarding the pdf of a random 388 variable, uniform distribution has to be assumed. 380

Table IV lists, for the 50-mm<sup>2</sup> 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<sup>2</sup> 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<sup>2</sup> 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  $\Delta \varphi_{\ell}$ , in the Case of a 95-mm<sup>2</sup> 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 396 from 0.1 to 0.5. Moreover, it seems to be not significantly 397 dependent on the cross section. By comparing case #2 with 398 case #3 it can be stated that the contribution to uncertainty of 399 the CT is greater than that of VT: in fact, the amplitude of 400 the confidence interval of  $\Delta \varphi_e - \Delta \varphi_a$  obtained by considering 401 only ratio and phase errors of the CT is about 1.5 times larger 402 than the one obtained when only the VT accuracy is taken 403 into account. This is justified by the fact that the quantity 404 measured by the CTs (current phasor), on the contrary to the 405 quantity (voltage phasor) measured by the VTs, appears also 406 in terms of rms value in the evaluation of  $R_e$  [see (9)]. Such an 407 explanation is confirmed by noticing that (see cases #3 and #4) 408 the contribution to uncertainty due to the ratio error of the CTs 409 is greater than that of VTs. As for cases #6 and #7, which 410 represent the contribution of the phase errors, no significant 411 dissimilarities between CT and VT can be appreciated, except 412 for the 0.5 accuracy class where, according to Table III, 413 the limits of the phase error are different for CT and VT. 414

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 425 example, with reference to the case #1 of Table IV, the limits 426 427 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 428 evaluated according to (10). Such limits are 0.17; 3.5 when 429 430  $X_e$  is assumed to be known within  $\pm 10\%$  and  $R_e$  computed 431 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 432  $\pm 10\%$  accuracy. 433

Figs. 5 and 6 show the estimated probability density func-434 tion (pdf) for cases #1 and #2, respectively, when the accuracy 435 class is 0.1 for both the ITs and the cross section is  $50 \text{ mm}^2$ . 436 It can be observed that the pdf in Fig. 5 is approximatively 437 normal, whereas the one in Fig. 6 is almost trapezoidal. 438 Of course, this is in accordance with the central limit theorem, 439 given that the pdf in Fig. 5 refers to a random variable, 440 which is obtained by the combination of more contributions 441 to uncertainty. 442

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

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In this paper, an approach for assessing the phase displace-449 ment between voltages at power network nodes by processing 450 asynchronous measurements in each node has been recalled. 451 Starting from the description of the distributed measurement 452 system that can be used to implement the recalled method, 453 uncertainty affecting the errors in the estimate of the volt-454 age phase displacements has been investigated in different 455 operating conditions. Moreover, the contribution to the above 456 uncertainty, due to each uncertainty source arising in the 457

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 the power cable are assumed to be known with an accuracy of  $\pm 10\%$ , the amplitude of the confidence timerval on the error in the phase displacement measurement is significantly reduced. This is not an unrealistic assumption that will be subjected to future investigations. 468

#### REFERENCES

- A. Monti, C. Muscas, and F. Ponci, *Phasor Measurement Units and wide area Monitoring Systems: From the Sensors to the System*. New York, NY, USA: Elsevier, 2016.
   C. P. Steinmetz, "Complex quantities and their use in electrical engi-473
- neering," in *Proc. Int. Elect. Congr. (AIEE)*, 1893, pp. 33–74.
- [3] P. Castello, J. Liu, C. Muscas, P. A. Pegoraro, F. Ponci, and A. Monti, "A fast and accurate PMU algorithm for P+M class measurement of synchrophasor and frequency," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 12, pp. 2837–2845, Dec. 2014.
- [4] A. Carta, N. Locci, and C. Muscas, "A PMU for the measurement of synchronized harmonic phasors in three-phase distribution networks," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 10, pp. 3723–3730, Oct. 2009.
   [5] P. A. Pegoraro, A. Meloni, L. Atzori, S. Sulis, and P. Castello, 482
- [5] P. A. Pegoraro, A. Meloni, L. Atzori, S. Sulis, and P. Castello, "PMU-based distribution system state estimation with adaptive accuracy exploiting local decision metrics and IoT paradigm," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 4, pp. 704–714, Apr. 2017.
- [6] J. Tang, J. Liu, F. Ponci, C. Muscas, and S. Sulis, "Effects of PMU's uncertainty on voltage stability assessment in power systems," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, May 2011, pp. 1–5.
- [7] C. Muscas, M. Pau, P. A. Pegoraro, and S. Sulis, "Uncertainty of voltage profile in PMU-based distribution system state estimation," *IEEE Trans. Instrum. Meas.*, vol. 65, no. 5, pp. 988–998, May 2016.
- [8] M. Asprou, E. Kyriakides, and M. Albu, "The effect of PMU measurement chain quality on line parameter calculation," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, May 2017, pp. 1–6.
- [9] A. Carullo, M. Parvis, and A. Vallan, "A GPS-synchronized traveling standard for the calibration of distributed measuring systems," in *Proc. IEEE Instrum. Meas. Technol. Conf.*, vol. 3. May 2005, pp. 2148–2152.
- [10] IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, 499 IEEE Standard 1588-2008 (Revision of IEEE Std 1588-2002), Jul. 2008. 500
- [11] Communication Networks and Systems for Power Utility Automation— Part 5: Communication Requirements for Functions and Device Models, Standard IEC 61850-5:2013, 2013.
- P. Ferrari, A. Flammini, S. Rinaldi, and G. Prytz, "Evaluation of time gateways for synchronization of substation automation systems," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 10, pp. 2612–2621, Oct. 2012.
- [13] A. Mingotti, L. Peretto, and R. Tinarelli, "A novel equivalent power network impedance approach for assessing the time reference in asynchronous measurements," in *Proc. IEEE 12MTC*, May 2017, Turin, Italy, pp. 624–629.
- [14] P. Janssen, T. Sezi, and J.-C. Maun, "Distribution system state estimation using unsynchronized phasor measurements," in *Proc. IEEE ISGT Europe*, Oct. 2012, pp. 1–6.
- [15] A. L. Dalcastagne, S. N. Filho, H. H. Zurn, and R. Seara, "An iterative two-terminal fault-location method based on unsynchronized phasors," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2318–2329, Oct. 2008.
- [16] D. Novosel, D. G. Hart, E. Udren, and J. Garitty, "Unsynchronized twoterminal fault location estimation," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 130–138, Jan. 1996.
- 17] C.-S. Yu, L.-R. Chang, and J.-R. Cho, "New fault impedance computations for unsynchronized two-terminal fault-location computations," *IEEE Trans. Power Del.*, vol. 26, no. 4, pp. 2879–2881, Oct. 2011.
- [18] J. Izykowski, R. Molag, E. Rosolowski, and M. M. Saha, "Accurate location of faults on power transmission lines with use of two-end unsynchronized measurements," *IEEE Trans. Power Del.*, vol. 21, no. 2, pp. 627–633, Apr. 2006. 526

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519

- M. Fulczyk, P. Balcerek, J. Izykowski, E. Rosolowski, and M. M. Saha,
   "Two-end unsynchronized fault location algorithm for double-circuit series compensated lines," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2008, pp. 1–9.
- [20] B. Mahamedi and J. G. Zhu, "Unsynchronized fault location based on
   the negative-sequence voltage magnitude for double-circuit transmission lines," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1901–1908,
   Aug. 2014.
- L. Yuansheng, W. Gang, and L. Haifeng, "Time-domain fault-location method on HVDC transmission lines under unsynchronized two-end measurement and uncertain line parameters," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1031–1038, Jun. 2015.
- [22] Voltage Characteristics of Electricity Supplied by Public Distribution
   Systems, Standard IEC EN 50160:1999, 2003.
- [23] C. Muscas, L. Peretto, S. Sulis, and R. Tinarelli, "Investigation on Multipoint Measurement Techniques for PQ Monitoring," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 5, pp. 1684–1690, Oct. 2006.
- [24] C. Muscas, "Power quality monitoring in modern electric distribution systems," *IEEE Instrum. Meas. Mag.*, vol. 13, no. 5, pp. 19–27, Oct. 2010.
- L. Peretto, R. Sasdelli, E. Scala, and R. Tinarelli, "Performance characterization of a measurement system for locating transient voltage sources in power distribution networks," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 2, pp. 450–456, Feb. 2009.
- L. Peretto, R. Sasdelli, E. Scala, and R. Tinarelli, "Metrological characterization of a distributed measurement system to locate faults in power networks," in *Proc. IEEE Instrum. Meas. Technol. Conf.*, May 2008, pp. 95–100.
- M. Paolone, L. Peretto, R. Sasdelli, R. Tinarelli, M. Bernardi, and
   C. A. Nucci, "On the use of data from distributed measurement systems for correlating voltage transients to lightning," *IEEE Trans. Instrum. Meas.*, vol. 53, no. 4, pp. 1202–1208, Aug. 2004.
- L. Cristaldi, A. Ferrero, C. Muscas, S. Salicone, and R. Tinarelli, "The impact of Internet transmission on the uncertainty in the electric power quality estimation by means of a distributed measurement system," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 4, pp. 1073–1078, Aug. 2003.
- [29] A. Carullo, "Metrological management of large-scale measuring systems," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 2, pp. 471–476, Apr. 2006.
- Instrument Transformers—Part 1: General Requirements,
   Standard IEC 61869-1:2016, International Standardization Organization,
   Geneva, Switzerland, 2016.
- [31] Instrument Transformers—Part 6: Additional General Requirements for Low-Power Instrument Transformers, Standard IEC 61869-6:2016, International Standardization Organization, Geneva, Switzerland, 2016.
- Incertainty of Measurement—Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995), Standard ISO/IEC Guide 98-3:2008, International Standardization
- Organization, Geneva, Switzerland, 2008.
   Station, Geneva, Switzerland, 2008.
   Evaluation of Measurement Data—Supplement 1 to the Guide to
- the Expression of Uncertainty in Measurement—Propagation of Dis tributions Using a Monte Carlo Method, Standard ISO/IEC Guide
   98-3/Suppl.1:2008, International Standardization Organization, Geneva,
- Switzerland, 2008.
   [34] Instrument Transformers—Part 2: Additional Requirements for Current Transformers, Standard IEC 61869-2:2012, International Standardization Organization, Geneva, Switzerland, 2011.
- [35] Instrument Transformers-Part 3: Additional Requirements for Inductive
   Voltage Transformers, Standard IEC 61869-3:2011, International Stan dardization Organization, Geneva, Switzerland, 2011.
- [36] Fault Detection and Power Meter—Specifications and Test Methods, (in Italian), document e-distribuzione DV7070, Nov. 2016.



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