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Development of an RTU for Synchrophasors Estimation in Active Distribution Networks

M. Paolone, A. Borghetti, C.A. Nucci

Abstract—**The centralized control of active distribution networks with large penetration of dispersed resources requires algorithms capable of providing network state estimation. Within this context, the measurement of bus voltage synchrophasors provides useful data that increase the observability of the network. The peculiar characteristics of distribution networks, such as feeder impedances, power flows and harmonic distortion, are different from those of transmission networks. Therefore, in order to obtain reasonably low uncertainty levels, Remote Terminal Units (RTU) with specific characteristics need to be developed. The paper presents an algorithm developed for the synchrophasor measurement in active distribution networks together with its implementation into a specific hardware based on a real-time microcontroller. The paper also presents the experimental characterization of the developed RTU by making reference to both single-tone and distorted signals.**

Index Terms—**Synchrophasors, Remote Terminal Units, Real-Time Monitoring, Distribution Networks.**

I. INTRODUCTION

ACTIVE distribution networks operation requires accurate control of the available distributed energy resources (DERs) in order to optimally dispatch power flows, keep bus voltages within specified limits and, particularly in islanding condition, maintain the network frequency. These requirements call for the development of specific centralized or decentralized control systems [1-5]. Control systems require, in general, suitable information on the state of the network [6,7]. For such a purpose, the tasks that monitoring systems are called to provide are similar to those of large transmission networks; the concept of WAMS (Wide Area Monitoring Systems) can be adopted with suitable adaptations too.

As known, WAMS are based on the measurements of bus voltages synchrophasors realized by means of RTUs (Remote Terminal Units) typically synchronized by means of the UTC-GPS time code. However, the peculiar characteristics of distribution systems, in terms of feeder impedances, power flows and harmonic distortion, calls for improved accuracy in synchrophasors measurements so to be useful for the system state estimation. The paper deals with this issue.

In particular, the paper presents an algorithm specifically developed to measure bus voltage synchrophasors in active distribution networks. The algorithm, implemented into a real-time microcontroller, incorporates signal processing techniques that allow the extraction of the fundamental frequency waveform and provide the synchrophasors measurement also in presence of high levels of harmonic distortion of the network bus voltages waveform.

The structure of the full paper is the following. Section II discusses the synchrophasor accuracy limits required by IEEE Std. C37.118 [8] and by their specific application to the case of distribution networks. Section III describes the structure of the proposed algorithm and its implementation into a RTU. Section IV presents the experimental characterization of the developed RTU and analyzes the influence of different quantities on its accuracy.

II. REQUIRED SYNCHROPHASORS ACCURACY FOR DISTRIBUTION NETWORKS APPLICATION

As known, the accuracy limits for the synchrophasor estimation defined by the IEEE Std. C37.118 [8] are associated to the value of the Total Vector Error (TVE) defined by the following relation:

$$TVE = \sqrt{\frac{\left(X_r(n) - X_r\right)^2 + \left(X_i(n) - X_i\right)^2}{X_r^2 + X_i^2}} \qquad (1)$$

where:

- X_r and X_i are the real and imaginary part of the theoretically true synchrophasor;
- $X_r(n)$ and $X_i(n)$ are the real and imaginary part of the estimated synchrophasor.

As the TVE defines the magnitude of the vector difference between the real and the estimated phasor, in per unit of the real phasor magnitude, its value is affected by both magnitude and phase errors [8]. Fig. 1 shows the separate influence of amplitude and phase errors on the TVE value.

Additionally, as synchrophasor estimation involves also the calculation of its frequency, a difference between the real and estimated frequencies produce a time varying TVE [9].

Fig. 1 shows that the 1% accuracy limit of the TVE specified in [8] corresponds to a 1 % error in the phasor magnitude estimation or to a 0.57 deg error in the phasor angle estimation.

It is worth noting that the TVE limit given by the IEEE Std. C37.118 are conceived for WAMS typically used in transmission networks. Therefore, the application of these limits to distribution networks, for the reasons earlier

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mentioned, need to be discussed. Indeed, with reference to typical distribution networks values of power flows (in the order of few MW or less) and feeder impedances (in the order of few hundreds mΩ/km) [10], one can generally expect phase differences between bus voltage synchrophasors not exceeding a few degrees. The synchrophasors-based state estimation in distribution networks requires, therefore, the development of specific RTUs characterized by lower TVE values than about 0.1 %, which corresponds to phase errors in the order of 10^{-2} deg (see Fig. 1).

Moreover the harmonic distortion of phase voltage waveforms is in general non negligible in distribution networks. In this respect, the algorithm for the synchrophasor estimation should implement the extraction of the fundamental frequency waveform avoiding any phase shift.

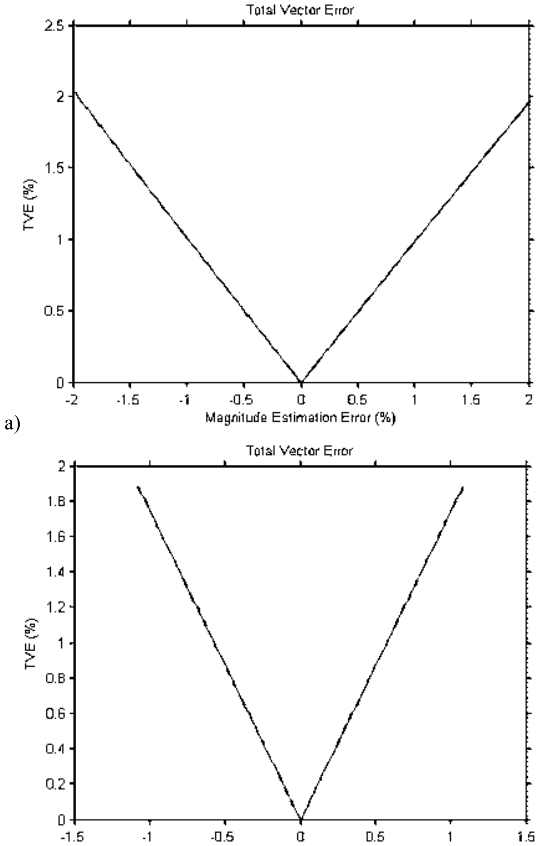

Fig. 1. Separate influence of amplitude (a) and phase (b) errors on the TVE. System frequency 60 Hz. Adapted from [8].

In order to clarify the influence of the synchrophasors error estimates (for both phasor RMS and phase), let us consider the simple case when the voltage synchrophasors are measured at two terminals of a line represented, in a first approximation, by its direct sequence longitudinal inductance (Fig. 2).

Let us assume that the RMS and phase errors of both $\overline{E}_1, \overline{E}_2$ phasor measurements are ΔE and $\Delta\theta$ and let us also define the phase angle difference between phasors $\overline{E}_1, \overline{E}_2$ as δ so that the error of this last quantity associated to the phasors angle error is $\Delta\delta = 2\cdot\Delta\theta$.

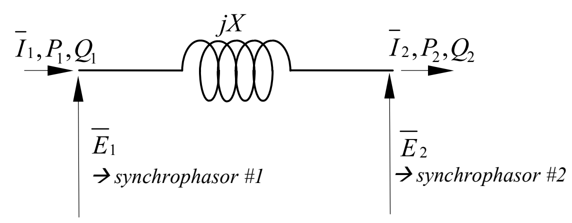

Fig. 2. Simple case of voltage synchrophasor measurements at the beginning and at the end of a line represented by its direct-sequence longitudinal inductance.

By referring to $\overline{E}_1^*, \overline{E}_2^*$ as the true phasors values and to $P_{1,2}$* and $Q_{1,2}$* as the true power fluxes at the beginning and at the end of the line, it is possible to express the link between the phasor measurement errors and the power flows errors as follows[1]:

$$\begin{aligned}
\Delta P\big|_{\Delta E} &= 3\frac{\left(E_1^* + \Delta E\right)\left(E_2^* + \Delta E\right)}{X}\sin\delta^* - 3\frac{E_1^* E_2^*}{X}\sin\delta^* \\
\Delta P\big|_{\Delta\delta} &= 3\frac{E_1^* E_2^*}{X}\sin\left(\delta^* + \Delta\delta\right) - 3\frac{E_1^* E_2^*}{X}\sin\delta^* \\
\Delta Q_2\big|_{\Delta E} &= 3\frac{\left(E_2^* + \Delta E\right)}{X}\left[\left(E_1^* + \Delta E\right)\cos\delta^* - \left(E_2^* + \Delta E\right)\right] - 3\frac{E_2^*}{X}\left[E_1^*\cos\left(\delta^*\right) - E_2^*\right] \\
\Delta Q_2\big|_{\Delta\delta} &= 3\frac{E_2^*}{X}\left[E_1^*\cos\left(\delta^* + \Delta\delta\right) - E_2^*\right] - 3\frac{E_2^*}{X}\left[E_1^*\cos(\delta) - E_2^*\right]
\end{aligned} \tag{2}$$

By writing the above power flow errors as a function of relative quantities (Δp, Δq and Δe) with respect to the true power flows $P^* = 3\frac{E_1^* E_2^*}{X}\sin\delta^*, Q^* = 3\frac{E_2^*}{X}\left[E_1^*\cos\left(\delta^*\right) - E_2^*\right]$, the following expression are obtained:

$$\begin{aligned}
\Delta p\big|_{\Delta E} &= \frac{\Delta P\big|_{\Delta E}}{P^*} = 2\Delta e \\
\Delta p\big|_{\Delta\delta} &= \frac{\Delta P\big|_{\Delta\delta}}{P^*} = \frac{\Delta\delta}{\delta} = \frac{2\Delta\theta}{\delta} \\
\Delta q_2\big|_{\Delta E} &= \frac{\Delta Q_2\big|_{\Delta E}}{Q^*} = 2\Delta e \\
\Delta q_2\big|_{\Delta\delta} &= \frac{\Delta Q_2\big|_{\Delta\delta}}{Q^*} = \frac{\Delta\delta}{\delta} = \frac{2\Delta\theta}{\delta}
\end{aligned} \tag{3}$$

Fig. 3 shows the dependency between the relative power flow errors (Δp and Δq) as a function of the phasor RMS and phase errors. As expected, a linear dependence between the power flows and phasor RMS errors is obtained. Concerning the dependence between the power flows and phase errors, for fixed values of this last quantity, a hyperbolic dependence as a function of the phasors angle difference δ is obtained. For the case of transmission networks, typical values of δ can be in the range of few or tens of degree and, therefore, phase errors in the order of 0.1 can provide satisfactorily results. For the case of distribution network, usually characterized by power flows in the order of few MVA (or less) and direct-sequence feeder impedances in of few hundreds of mΩ/km, typical values of δ can be in the range of few degree or less. Therefore, the influence on power flows estimates of phase uncertainty is larger than the influence of the phasor amplitude

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[1] In order to simplify the equation notation, the reactive power flow makes reference to the Q_2 value only of Fig. 2.

uncertainty.

As a consequence, we have characterized the RTU in terms of both TVE (as required by the IEEE Std. C37.118) and phasor amplitude/phase uncertainties which appear more appropriate for distribution networks applications.

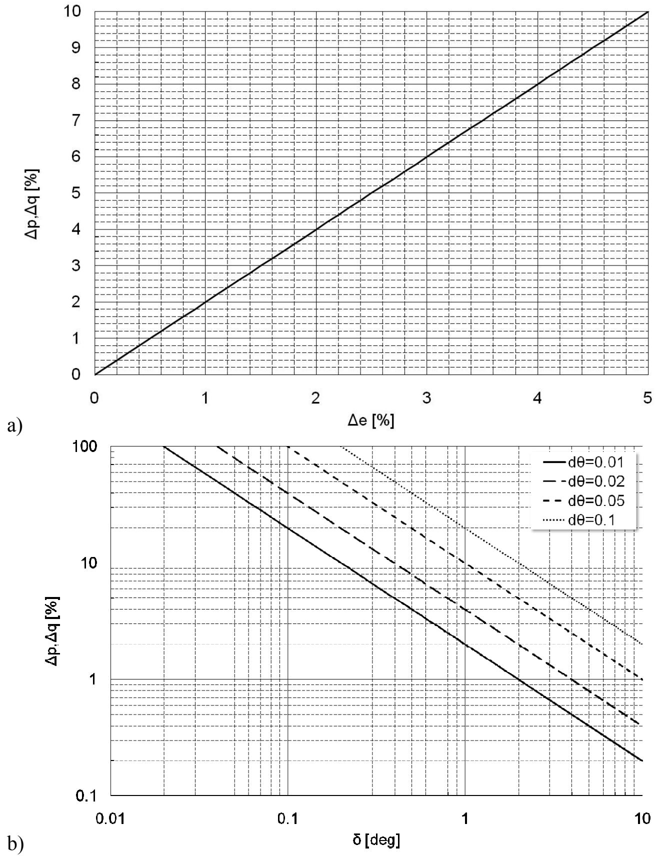


Fig. 3. Dependence of relative power flow errors (Δp and Δq defined by (3)) as a function of the phasor RMS and phase errors.

III. STRUCTURE OF THE PROPOSED ALGORITHM AND ITS IMPLEMENTATION

This section illustrates the proposed algorithm together with its implementation into a specific hardware.

As the accuracy targets discussed in the previous section are obtained by integrating the algorithm into a specific hardware, a brief illustration of it is here provided. The proposed algorithm has been implemented into a real-time microcontroller (National Instruments Compact Rio) equipped with a FPGA (Field Programmable Gate Array) bus. The microcontroller is characterized by a 400 MHz real-time processor with 2 GB nonvolatile storage, 128 MB DRAM memory linked with a with a 3 Mgate FPGA working at 40 MHz. The sampling of the voltage waveforms is realized by means of three parallel 16-bits digitizers that synchronously operate at the FPGA level together with the availability of the UTC-GPS time frame provided by an IRIG-B GPS unit characterized by a time uncertainty of 100 ns.

The proposed algorithm is characterized by the following main steps:

1. sampling of the three phase voltages in correspondence of the UTC-GPS synchronization signal (1 or 10 PPS);
2. extraction of the fundamental frequency (f_n) tone (i.e. a sinusoidal signal characterized by a single frequency) within a specific frequency window (e.g. $f_n \pm 0.01$ Hz);
3. estimation of the synchrophasor amplitude, phase and frequency.

A description of each step of the algorithm is following reported.

Step1: in order to save computational resources, the start of the phase voltages sampling is triggered by the occurrence of the GPS-PPS (pulse per second). In this way the sampling process performed by the microcontroller is operated only once per PPS and the definition of the number of PPS directly results into the definition of the number of synchrophasor estimates per second. Considering that the acquisition of the GPS-PPS signal is performed at the FPGA level, the operating frequency of the FPGA (henceforth called f_{FPGA}) directly results into a delay time of the phase voltages sampling that is one of the component of the phase error $\Delta\theta$. Typical values of f_{FPGA} are in the range of 40 – 160 kHz (160 kHz represents the upper limit for the adopted hardware). After GPS-PPS trigger, all the phase voltages are synchronously sampled in a time window of 80 ms at a frequency that, due to hardware constraints, has been settled equal to $f_{\mathrm{FPGA}}/2$ (see Fig. 4).

Fig. 5 shows the structure of the implemented algorithm: i) simultaneous sampling of the phase voltages performed at the FPGA level, ii) each group of samples, namely the three phase voltages and the GPS-UTC PPS signal, is inserted into a DMA-FIFO memory, iii) the real time microcontroller accesses to the DMA-FIFO at each PPS to extract the corresponding number of samples and perform, within the critical time loop, the steps 2 and 3 of the algorithm.

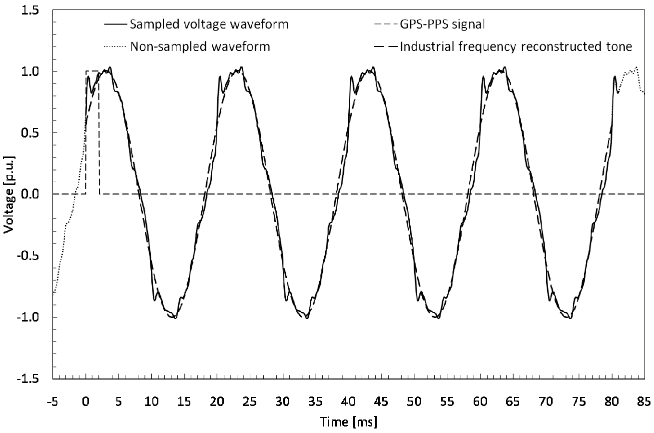


Fig. 4. Sampled voltage waveform triggered by the GPS-PPS and industrial frequency tone extraction/reconstruction.

Step 2. For each critical time loop (that correspond to a frequency equal to the number of PPS), the fundamental frequency tone is extracted from the sampled voltage waveforms (see Fig. 4). Such an extraction is realized through:

i) the application of a Fast Fourier Transform (FFT) algorithm to the sampled waveforms over the sampling time window;

ii) the identification of the fundamental frequency tone within a frequency window of $f_n \pm 0.01$ Hz;

iii) the reconstruction of the voltage waveform containing the identified fundamental frequency tone only.

Considering that tone extraction and its reconstruction are obtained within the time loop of the real time microcontroller, the obtained single tone voltage waveform is not affected by phase shifts, due to the use of filters. Additionally, as the sampling frequencies are in the order of 40 – 80 kHz ($f_{\text{FPGA}}/2$), it is possible to avoid the presence of anti-aliasing filters in view of the fact that the harmonic distortion in distribution network does not reach such high frequency values.

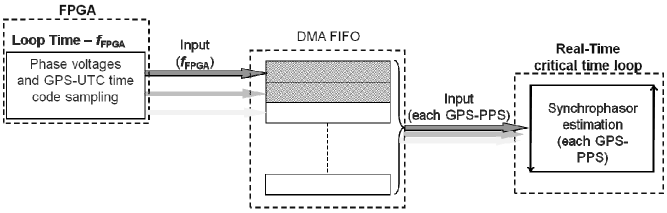


Fig. 5. Structure of the synchronous sampling of voltages and GPS-UTC time signals implemented into the RTU real time microcontroller.

Step 3. By referring to the fundamental frequency tone provided by step 2, the algorithm estimates its frequency, amplitude and phase. As illustrated in Fig. 6, phase value θ is estimated as a function of the time interval between the UTC-GPS PPS wavefront, that correspond to the first sample of the voltage waveforms, and the voltage waveform zero crossing, The zero crossing time is estimated by a linear interpolation between the two consecutive samples before and after the waveform sign change of the reconstructed industrial frequency tone.

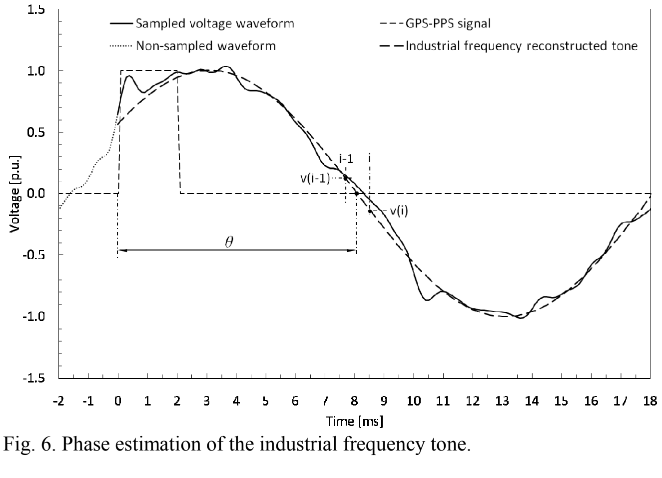


Fig. 6. Phase estimation of the industrial frequency tone.

The above-described three steps of the algorithm are executed within the deterministic time window between two subsequent PPS (typically 1 or 0.1 s) by the real-time microcontroller.

IV. RTU EXPERIMENTAL CHARACTERIZATION

In what follows the assessment of the developed RTU uncertainties in terms of TVE, phasor RMS and angle is presented. We shall make reference to the ideal case of single-tone signals and, then, the more general case of distorted signals.

The RTU characterization has been performed by generating a reference signal by means of an Agilent 33250A function generator running at 1 MSa/s. The sync-signal of the function generator has been aligned with the GPS-PPS signal provided by a Meinberg GPS 169 PCI card with an overall uncertainty of 100 ns that corresponds, at 50 Hz, to an absolute phase uncertainty of 0.0018 deg. By means of such a synchronization, component X_r of (1) correspond to the RMS value of the reference signal and component X_i is equal to zero.

A. *Industrial frequency single-tone signal*

This section illustrates the RTU characterization for the case of a single-tone signal at the industrial frequency of 50 Hz. The RMS value of the reference signal has been measured by means of an Agilent 34401A digital multimiter suitably synchronized with the GPS-PPS signal provided by a Meinberg GPS 169 PCI card. The characterization makes reference to 1000 subsequent synchrophasors estimates.

Fig. 7 shows the cumulative probability distributions for different f_{FPGA} frequencies of TVE, RMS and phase errors of the synchrophasor estimated by the developed RTU.

In view of what above described, the value of the f_{FPGA} has a direct influence on the phase estimate and, therefore, on the TVE and, as expected, not on the RMS. Therefore, the best performances of the RTU are obtained in correspondence of the highest f_{FPGA} value (160 kHz) for which, by means of the probability density distribution reported in Fig. 8, the following uncertainties that corresponds to the 90% occurrence values are obtained: TVE=0.092%, $\Delta RMS=\pm0.015$ %, $\Delta\theta=\pm0.042$ deg.

By making reference to these obtained characteristics and what illustrated by Fig. 3, the consequent uncertainties in the power flows estimates obtained with developed RTU are, as expected, due to the phase uncertainty only. In particular, for phasors angle differences δ above 1 deg, Δp and Δq are below 5 % (see Fig. 3).

B. *Distorted signals*

This section illustrates the RTU characterization for the case of a distorted signal. The spectrum components of such a distorted signal, shown in Fig. 9, have been selected as equal to the limit values provided by the standard EN 50160 [11].

For this case the RMS value of the industrial frequency tone of the reference signal has been estimated through the spectrum analysis of the reference signal sampled at 100 kHz by means of a NI-9215 16 bit card also synchronized with the GPS-PPS signal provided by the Meinberg GPS 169 PCI card. The characterization makes reference to 1000 subsequent synchrophasors estimates.

Fig. 10 shows the cumulative probability distributions for different f_{FPGA} frequencies of TVE and phase errors of the synchrophasor estimated by the developed RTU (the distribution of RMS has not been reported as it corresponds to the one of Fig. 7b).

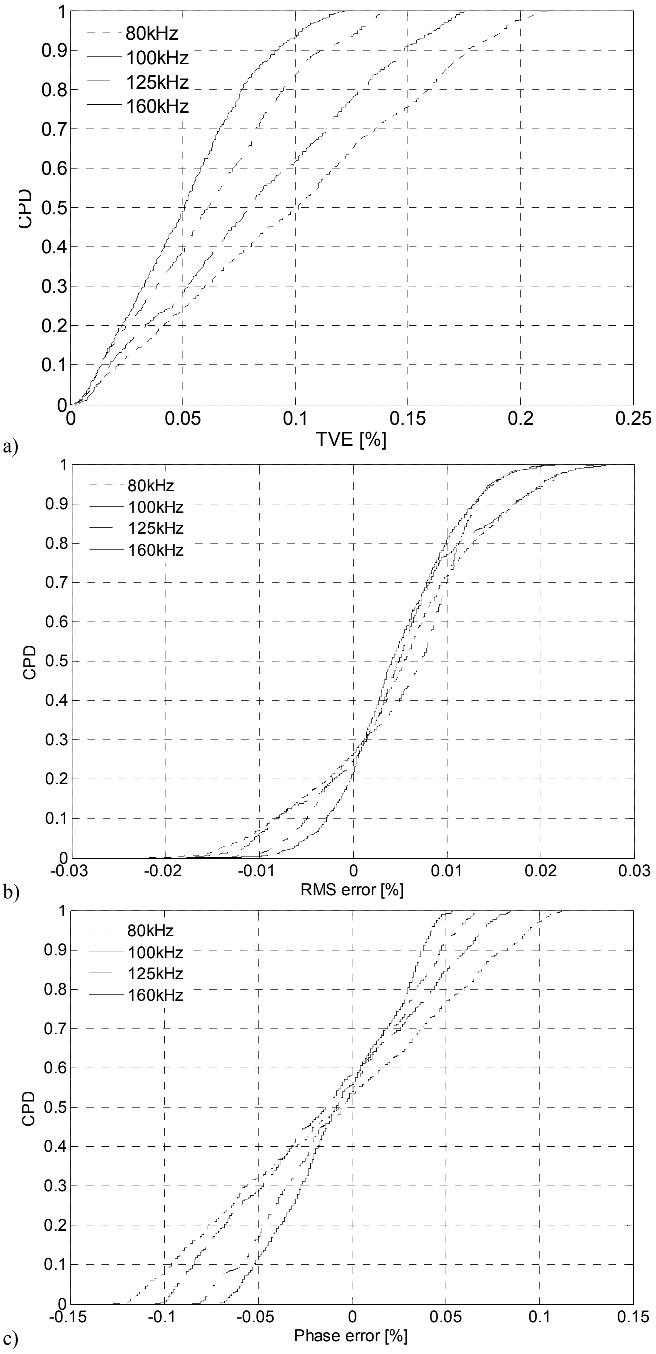


Fig. 7. Cumulative probability distribution functions (CPD) for different f_{FPGA} frequencies of TVE, RMS and phase errors of the synchrophasor estimated by the developed RTU for the case of a single-tone signal: a) TVE; b) RMS error, c) phase error.

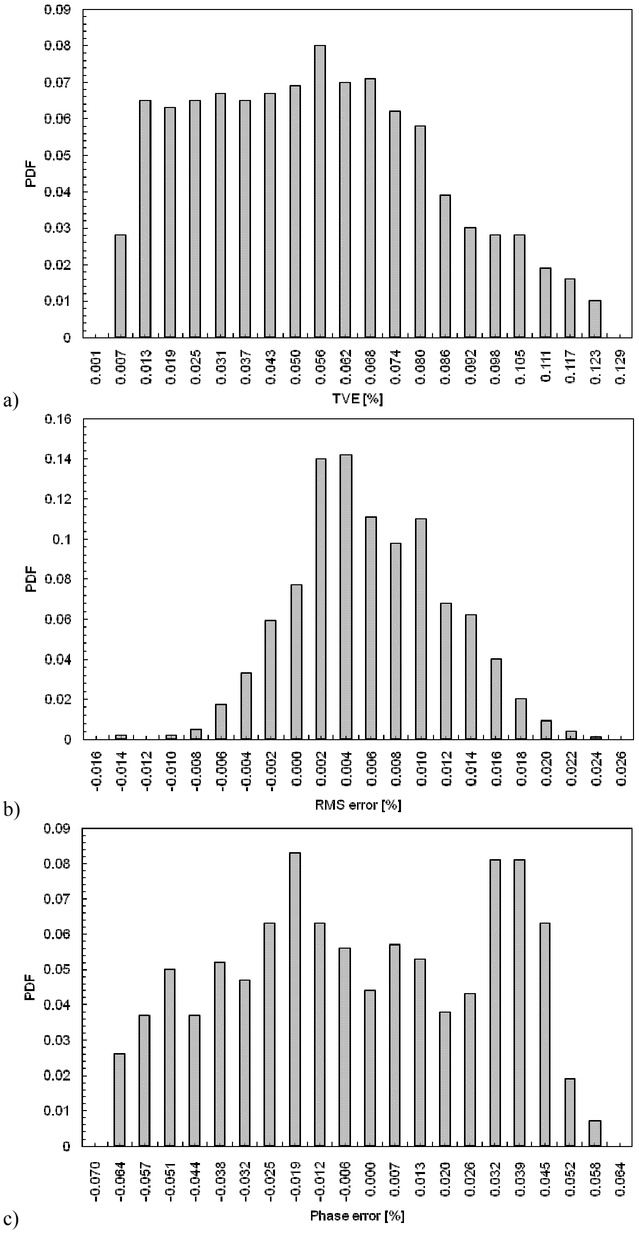


Fig. 8. Probability density functions (PDF) of TVE, RMS and phase errors of the synchrophasor estimated by the developed RTU for the case of a single-tone signal and f_{FPGA}=160 kHz: a) TVE; b) RMS error, c) phase error.

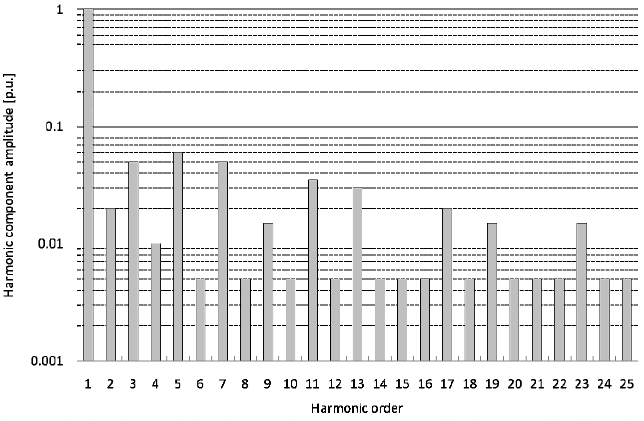
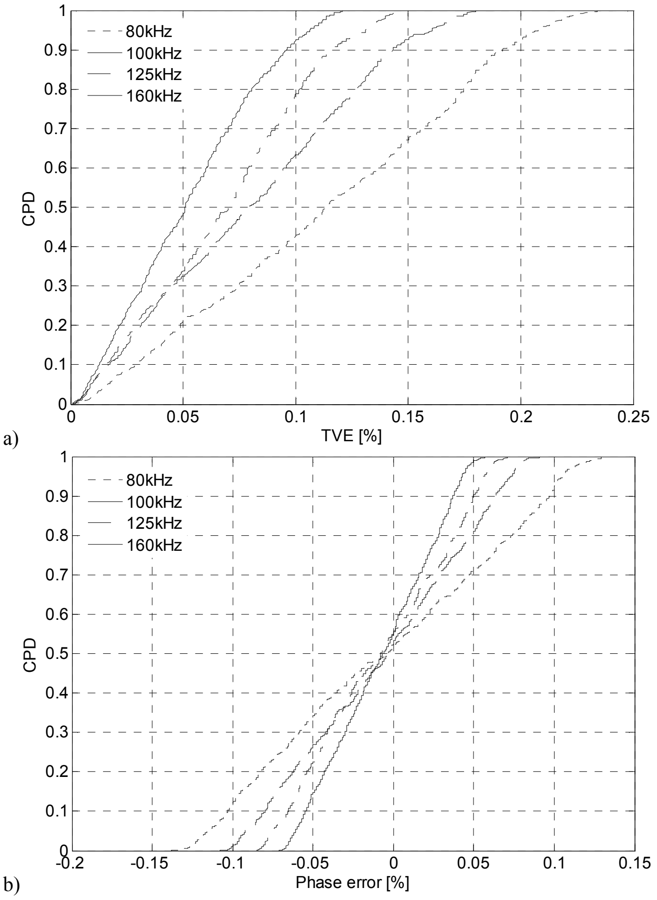


Fig. 9. Limit values of the harmonic component amplitudes provided by the EN 50160 [11] expressed in p.u. of the fundamental frequency tone amplitude.

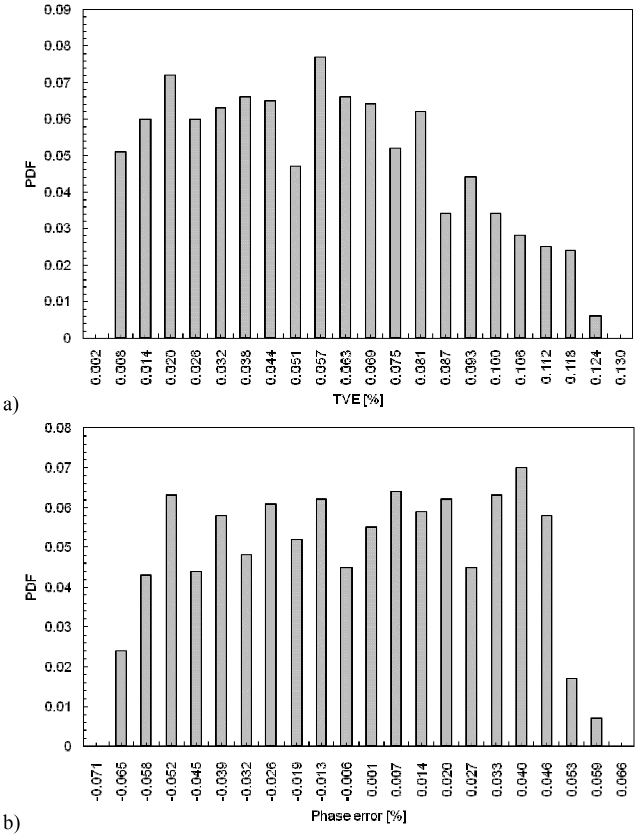


a) b)

Fig. 10. Cumulative probability distributions for different f_{FPGA} frequencies of TVE, RMS and phase errors of the synchrophasor estimated by the developed RTU for the case of a distorted signal characterized by the harmonic spectrum shown in Fig. 9: a) TVE; b) phase error.

By comparing the results of Fig. 7 with those of Fig. 10, it can be seen that the characteristics of the developed RTU in terms of TVE and phase uncertainties are basically independent from the distortion level of the considered signal. Such a characteristic is of particular importance for the synchrophasor applicability in power distribution networks as these systems, compared to transmission networks, are characterized by higher values of voltage harmonic distortion.

Also for this case, the best performances of the RTU are obtained in correspondence of the highest f_{FPGA} value (160 kHz) for which, by means of the probability density distribution reported in Fig. 11, the following uncertainties that corresponds to the 90% occurrence values are obtained: TVE=0.09%, $\Delta\theta$=±0.047 deg.



a) b)

Fig. 11. Probability density distributions of TVE, RMS and phase errors of the synchrophasor estimated by the developed RTU for the case of a distorted signal characterized by the harmonic spectrum shown in Fig. 9 and f_{FPGA}=160 kHz: a) TVE; b) phase error.

V. CONCLUSIONS

The paper has presented a synchrophasor estimation algorithm and its implementation into a real-time microcontroller. Compared to transmission networks applications, the peculiar characteristics of distribution feeders require major improvements of synchrophasors estimation accuracy that result into: i) low values of the TVE, RMS and, above all, phase uncertainties, ii) independence against harmonic distortion. The paper has illustrated the structure of the proposed algorithm, of its hardware implementation and the experimental characterization of the developed RTU with special attention to the above mentioned points.

The main conclusions are: i) the characteristics of the developed RTU in terms of TVE, RMS and phase uncertainties are basically independent from the distortion level of the considered signal and ii) the obtained uncertainty levels are compatible with the requirements of power distribution networks applications of synchrophasors, which support the adequacy of such a monitoring technique for active distribution networks.

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