A Fully Informative Phasor Measurement Unit for Distribution Networks With Harmonic Distortion

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ABSTRACT We introduce a fully informative distribution network phasor measurement unit (FI-DPMU), that is capable of performing a simultaneous estimation of phasor dynamics and harmonic components. This is in contrast with current state-of-the-art devices, that only provide information about the fundamental component of voltages/currents—by discriminating or filtering-out their harmonic content. The FI-DPMU hence represents a significant economical solution, since it bypasses the need to deploy power quality analyzers to retrieve full information about the network. To validate the accuracy of the FI-DPMU, we performed a hardware-in-the-loop implementation to emulate a distribution network that is subject to abrupt frequency variations and high harmonic distortion. The tests demonstrate that the FI-DPMU satisfies the standards of distribution network phasor measurement units (DPMUs), providing a real-time fast Fourier transform (FFT) as additional feature. Experimental results show a comparison between FI-DPMU measurement data with the information provided by a commercial DPMU.

INDEX TERMS Distribution network, harmonics estimation, phasor estimation, PMUs.

I. INTRODUCTION

Renewables are rapidly emerging as an economical option to provide clean, reliable and resilient local energy supply. However, to fully exploit the benefits of renewable resources, we require the capability to observe and control the grid at a much finer scale of resolution than ever before. Specifically, distribution networks must be completely transparent to the grid operator, to avoid destabilizing impacts from intermittent renewable resources, and emerging activities of new consumers/prosumers, e.g., electric vehicles and asynchronous generation. In this context, distribution network phasor measurement units (DPMUs) permit the development of high-precision and time-synchronized monitoring networks. This is a timely technology that completely aligns with the tenets of the current smart grid revolution [1], [2], [3], [4].

A DPMU estimates the magnitude and phase angle of voltages and currents with a high level of accuracy. Its time-synchronization is endowed by a GPS signal, and the monitored data are transferred via a diverse range of communication channels to a central server (see [5] for a general overview of DPMU technology). Moreover, this data-driven setting permits to implement further algorithms, e.g., DPMU applications in the distribution network, microgrids and load characterization [6], [7]. These techniques build and parameterize high-level models to understand how a particular load will respond under various options of load composition. For fault-detection, high-resolution and accurate DPMUs data substantially enhances the performance of these algorithms [8]. Another application is the estimation of the harmonic content of the network. The combination of DPMUs and other intelligent electronic devices allow mathematical quantification of the level of harmonic pollution in the whole network [9], [10]. In [11], the authors develop...
a network identification algorithm which use DPMU phase-angle and high-accuracy measurements that enable topology estimation. In network state estimation, the use of DPMU phasor values involves a linear optimization problem whose solution is obtained without need for iterative techniques, which considerably optimizes computation times [12]. The connection of a DPMU to the microgrid point of common coupling can also improve the resilience of the system since the data from the DPMU can also be used to detect situations in which it is convenient to initiate the intentional islanding process [13], [14]. Furthermore, in coordinated control of distributed generators (DG), DPMU measurement data allows to obtain a local foreknowledge of DG steady-state operating condition and, based on this information, we can develop measurement-based control [15]. A good example of a practical application of DPMUs can be found in the microgrid developed by the Illinois Institute of Technology (IIT) [16], [17], which has been equipped with 12 DPMUs to monitor and record real/reactive power generation, and to provide information to the microgrid controller. This breadth of applications and versatility have motivated a boom in the commercial development of DPMUs. Commercial devices satisfy the high standards of accurate phasor estimation and, provide new solutions for increasingly complex scenarios (see e.g. the survey of devices in [18]).

However, as in any new technology, the diffusion and start-up costs are additional challenges that prevent the fast adoption of DPMU devices as a standard asset in distribution networks. This economical dilemma is notorious when considering that phasor estimation itself does not solve every major challenge imposed by the ample presence of distributed generation and electric vehicles. This follows from the fact that DPMUs do not provide information about harmonic components [5], [19]. In other words, the information provided by commercial DPMUs is limited to the fundamental component of voltages and currents. In this paper, we focus on overcoming this issue by upgrading the capabilities of commercial DPMUs, without the need of additional hardware. This is a sincere attempt to endow DPMUs with a positive cost-benefit, which can facilitate their diffusion. In other words, DPMUs can potentially become a compelling technology once they are able to retrieve a full set of critical information, which can alleviate the most pressing issues in modern distribution networks.

Certainly, it is unknown how proprietary software of commercial DPMUs process their measurement data. In particular, it remains undisclosed how do they deal with harmonic distortion, e.g., if they use a filtering stage to recover the fundamental component, as typically reported in the literature [20], [21]. In fact, to the best of the authors knowledge, there is no commercial device capable of simultaneously performing both tasks: phasor and harmonic estimation (see, e.g., the description of device capabilities in [18]). This fact suggests that commercial algorithms are focused on compensating harmonic distortion to guarantee accurate phasor estimation, while the estimation of the harmonic spectrum itself is not performed. For example, popular DPMU device manufacturers, propose the implementation of an additional parallel device, acting as a power quality analyzer (see e.g., [22]) to retrieve full information, i.e., phasor and harmonic estimation. Then the use of aggregators is suggested (e.g., [23]) to display data of phasor estimation and power quality to the operator. On the other hand, at the backstage of commercial developments, there are several remarkable approaches reported in the literature concerning phasor and harmonic estimation. For example, in [24], a phasor and harmonic estimator is presented using a Taylor-Fourier transform, alongside a theoretical example that permits to evaluate its performance. In [25], the authors propose a harmonic synchrophasor estimation with the purpose of compensating the frequency response function of the instrument transformer. Another relevant algorithm is presented in [20], where the issue of phasor and harmonic estimation is addressed using a Kalman filter bank according to every harmonic of interest. Summarizing, the general shortcomings found in the current literature are: (i) the use of purely theoretical algorithms that have not been tested on real-time devices, which undermines their commercial diffusion; (ii) the use of very particular harmonic signals for compensation purposes; and (iii) the use of legacy algorithms such as Kalman filters, where the assumption of a constant frequency must be kept to avoid the use of a Jacobian-based implementation, which yields only tangential approximations of the actual signal trajectories.

In contrast with the state-of-the-art in both, commercial devices and research literature, we propose a solution that retrieves both, phasor information of the fundamental component and the harmonic contents. We called this solution fully informative distribution network phasor measurement unit (FI-DPMU). We hence show that there is no need to increase the number of hardware devices to simultaneously perform phasor and harmonic estimation, which is detrimental for the underlying measurement and instrumentation costs. The FI-DPMU implies an upgrade of the DPMU algorithm, i.e., a software enhancement, to simultaneously operate as a power quality analyzer. This upgrade transforms the device into an economical solution for distribution networks with a high number of power converter interfaces and electronic loads, e.g., distributed renewable generation and electric vehicles. To show the advantages of the FI-DPMU, we use a hardware-in-the-loop implementation of a more realistic distribution network, using a dSPACE acquisition hardware. Then, we show that our estimated data satisfies the required standard for DPMUs, i.e., IEC/IEEE 60255-118-1 (see [1], [26]), even under abrupt frequency variations and considerable harmonic distortion. To illustrate the accuracy and high performance of the FI-DPMU, the measurement data is also compared with data provided by state-of-the-art commercial DPMUs. It is shown how the FI-DPMU provides full information by incorporating a real-time FFT, together with extremely accurate phasor estimations.
II. DISCRETE-TIME DESCRIPTION OF PHASOR DYNAMICS

The phasor estimation process consists in the identification of parameters $A$, $\omega$ and $\phi$ of the following sinusoidal signal:

$$v(t) = A \sin(\omega t + \phi).$$

(1)

The proposed approach must be able to perform the estimation of the actual parameters under the presence of abrupt or gradual changes around their nominal values. Hence, to distinguish between nominal values and actual parameters, we use $\bar{A}$, $\bar{\omega}$ and $\bar{\phi}$ to denote fixed nominal quantities, while $A$, $\omega$ and $\phi$ are the actual parameters that deviate from their nominal counterparts during the normal operation of the network. Notice that (1), considering a constant nominal frequency, represents a solution of a second-order differential equation of the form:

$$\frac{d^2}{dt^2} v(t) + \omega^2 v(t) = 0.$$

(2)

The roots of the frequency domain representation of this equation, after application of the Laplace transform ($\mathcal{L}$), are located on the imaginary-axis, i.e., $s = \pm j\bar{\omega}$, which corresponds to an oscillatory dynamics at frequency $\bar{\omega}$. If (2) is expressed in its state-space form (first-order terms), then $y$ can be equivalently generated by

$$\frac{d}{dt} \begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix} = \begin{bmatrix} 0 & \bar{\omega} \\ -\bar{\omega} & 0 \end{bmatrix} \begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix}; \quad v(t) = [1 \ 0] \begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix},$$

(3)

whose time-domain solution can be obtained as

$$v(t) = [1 \ 0] \mathcal{L}^{-1} \begin{bmatrix} 1 & 0 \\ 0 & -\bar{\omega} \end{bmatrix} \begin{bmatrix} x_\alpha(0) \\ x_\beta(0) \end{bmatrix}. $$

(4)

Note that, for convenience, we selected the state-space basis $[x_\alpha, x_\beta]^T$ that accounts for the fixed reference frame coordinates, i.e., the $\alpha\beta$-coordinates (see [27]), encompassing the fundamental component $v = v_\alpha$ and its $(90^\circ$-shifted) square-phase companion $v_\beta$.

To be in agreement with the standard IEC/IEEE 60255-118-1, which defines the DPMUs operation (see [1], [26]), this paper focuses on modeling discrete-time quantities. For this, we first obtain the following time-domain solution of (3) for some arbitrary initial conditions $[x_\alpha(0), x_\beta(0)]^T$:

$$\begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix} = \begin{bmatrix} \cos(\bar{\omega}t) & -\sin(\bar{\omega}t) \\ \sin(\bar{\omega}t) & \cos(\bar{\omega}t) \end{bmatrix} \begin{bmatrix} x_\alpha(0) \\ x_\beta(0) \end{bmatrix}. $$

(5)

This equation can be evaluated at any time instant $t_k \in \mathbb{R}$ ($k = 1, 2, 3, \ldots$) according to

$$\begin{bmatrix} x_\alpha(t_{k+1}) \\ x_\beta(t_{k+1}) \end{bmatrix} = \begin{bmatrix} \cos(\bar{\omega}T_s) - \sin(\bar{\omega}T_s) \\ \sin(\bar{\omega}T_s) \cos(\bar{\omega}T_s) \end{bmatrix} \begin{bmatrix} x_\alpha(t_k) \\ x_\beta(t_k) \end{bmatrix},$$

(6)

where $T_s \in \mathbb{R}_+$ is the sample time and $t_{k+1} = t_k + T_s$. Expression (5) can be rewritten using the shift-operator $\sigma$ as follows:

$$\begin{bmatrix} x_\alpha \sigma \\ x_\beta \sigma \end{bmatrix} = \begin{bmatrix} \cos(\bar{\omega}T_s) & -\sin(\bar{\omega}T_s) \\ \sin(\bar{\omega}T_s) \cos(\bar{\omega}T_s) \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix},$$

(7)

where operator $\sigma$ acts on a discrete-time (sampled) variable $v(t_k)$ as $\sigma v(t_k) = v(t_k + T_s)$. Notice that (6) is a discrete-time system valid for any arbitrary initial condition. The phasor vector $[x_\alpha, x_\beta]^T$ can be expressed in polar form using the following transformation from $\alpha\beta$- to $dq$-coordinates (see [28]), also called discrete-time inverse Park transformation:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos(\bar{\omega}T_s) - \sin(\bar{\omega}T_s) \\ \sin(\bar{\omega}T_s) \cos(\bar{\omega}T_s) \end{bmatrix}^{-1} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix}. $$

(9)

III. ADAPTIVE PHASOR AND HARMONIC ESTIMATION

In the following sections, we propose, based on this model, a phasor estimation scheme with adaptive capabilities to deal with signals subject to parameter variations.

A. ADAPTIVE ESTIMATION OF $\alpha\beta$ COMPONENTS AND FREQUENCY

Based on model (9), the following estimator is proposed, which involves an additional correction component and an integral-like equation to ensure angular frequency estimation:

$$\begin{bmatrix} x_\alpha \hat{\sigma} \\ x_\beta \hat{\sigma} \end{bmatrix} = \begin{bmatrix} \cos(\hat{\omega}T_s) & -\sin(\hat{\omega}T_s) \\ \sin(\hat{\omega}T_s) \cos(\hat{\omega}T_s) \end{bmatrix} \begin{bmatrix} x_\alpha \hat{\sigma} \\ x_\beta \hat{\sigma} \end{bmatrix} - \frac{\varepsilon}{T_s} (\hat{x}_\alpha - x_\alpha),$$

(10)

where $\hat{x}_\alpha$, $\hat{x}_\beta$ and $\hat{\omega}$ are the estimated variables; and $\gamma$ and $\varepsilon$ are tunable adaptation gains. Notice that the feedback

1From this point on, we deal only with discrete-time quantities, consequently there is no risk of ambiguity by relaxing the notation.
term only involves $x_\alpha$ since this is the only output available (i.e., $v = x_\alpha$).

We now transform from $a\beta$- to $dq$-coordinates to construct the phasor dynamics using the Park inverse transformation:

$$
\begin{bmatrix}
\hat{x}_d \\
\hat{x}_q
\end{bmatrix} =
\begin{bmatrix}
\cos(\omega t) & -\sin(\omega t) \\
\sin(\omega t) & \cos(\omega t)
\end{bmatrix}^{-1}
\begin{bmatrix}
\hat{x}_a \\
\hat{x}_\beta
\end{bmatrix}.
$$

(11)

The shift operator $\sigma$ is applied to both sides of (11) to obtain the dynamic model of the estimated variables in $dq$-coordinates, i.e.,

$$
\sigma \begin{bmatrix}
\hat{x}_d \\
\hat{x}_q
\end{bmatrix} =
\begin{bmatrix}
\cos(\omega t) & -\sin(\omega t) \\
\sin(\omega t) & \cos(\omega t)
\end{bmatrix}^{-1}
\sigma \begin{bmatrix}
\hat{x}_a \\
\hat{x}_\beta
\end{bmatrix}.
$$

(12)

Notice that $\hat{x}_d$ and $\hat{x}_q$ vary for $\omega \neq \bar{\omega}$ since the system and the transformation do not rotate at the same speed.

**Remark 1:** We follow a similar analysis to the one proposed in [28] to ensure that the estimates $[\hat{x}_a, \hat{x}_\beta, \bar{\omega}]^T$ asymptotically converge towards their corresponding references $[x_a, x_\beta, \omega]^T$. As a result, the following sufficient conditions are obtained: $0 < \varepsilon < 4 \frac{\gamma T_s}{\bar{\sigma}^2} < \gamma < \frac{\varepsilon}{T_s\bar{\sigma}^2}$, where $x_d$ is $v(0)$ in (1).

The estimate of the fundamental component phasor, in its polar form (according to (8)), is given by

$$
\hat{Y} := \hat{A} \angle \hat{\phi};
$$

(13)

with $\hat{A} = \sqrt{\hat{x}_d^2 + \hat{x}_s^2}$ and $\hat{\phi} = \arctan(\hat{x}_q/\hat{x}_d)$.

The following section presents a method for simultaneous estimation of harmonics in the reference signal, which represents an extension of the above adaptive phasor estimator.

**B. HARMONIC ESTIMATION**

One of the main benefits of the present approach is its modularity, which allows its extension towards the estimation of harmonic components. For this, consider that the measured signal $y$ is distorted and has a Fourier series representation comprising a fundamental component plus higher-order odd harmonics (typically present in a distribution network), i.e.,

$$
v = x_\alpha + x_{\alpha,3} + x_{\alpha,5} + \cdots.
$$

Odd harmonics

Notice that this description naturally involves the extension of the estimator state-space, which incorporates now the components $\text{col}(x_{\alpha,n}, x_{\beta,n})$ ($n \in \{3, 5, 7, \ldots\}$) corresponding to the state variables of every harmonic of interest. Therefore, in the presence of harmonics, the adaptive phasor estimation consists in reformulating (10) as follows:

$$
\begin{bmatrix}
\hat{x}_a \\
\hat{x}_\beta
\end{bmatrix} =
\begin{bmatrix}
\cos(\omega_t T_s) & -\sin(\omega_t T_s) \\
\sin(\omega_t T_s) & \cos(\omega_t T_s)
\end{bmatrix} \begin{bmatrix}
\hat{x}_a \\
\hat{x}_\beta
\end{bmatrix} - \left[\begin{array}{c}
\varepsilon T_s (\hat{y} - \hat{y}) \\
0
\end{array}\right],
$$

$$
\begin{array}{c}
\sigma \hat{\omega} = \hat{\omega} + \gamma T_s \hat{x}_\beta (\hat{y} - \hat{y}), \\
\hat{\gamma} = \hat{x}_a + \hat{x}_{a,3} + \hat{x}_{a,5} + \cdots;
\end{array}
$$

(14)

where the estimation of the $n$-th harmonic component of interest ($n \in \{3, 5, 7, \ldots\}$) is performed according to

$$
\sigma \begin{bmatrix}
\hat{x}_{a,n} \\
\hat{x}_{\beta,n}
\end{bmatrix} =
\begin{bmatrix}
\cos(n\bar{\omega} T_s) & -\sin(n\bar{\omega} T_s) \\
\sin(n\bar{\omega} T_s) & \cos(n\bar{\omega} T_s)
\end{bmatrix} \begin{bmatrix}
\hat{x}_{a,n} \\
\hat{x}_{\beta,n}
\end{bmatrix} - \left[\begin{array}{c}
\varepsilon T_s (\hat{y} - \hat{y}) \\
0
\end{array}\right],
$$

(15)

where $\gamma$, $\varepsilon$ and $\varepsilon_n$ ($n \in \{3, 5, 7, \ldots\}$) are tunable adaptation gains.

The proposed harmonic estimation extension has two benefits. First, it deals with the harmonic distortion that typically undermines an accurate fundamental component phasor estimation. Hence, it is no longer necessary to implement low-pass filters nor lead compensators to clean-up the signal, as the fundamental component phasor is estimated by the algorithm without error nor delay. Second, a power quality analyzer functionality is implemented, that simultaneously determines the parameters of the fundamental component (phasor estimation) and the harmonic components (FFT analysis).

The capabilities of the proposed FI-DPMU and its implementation is illustrated in Fig. 1a, which is compared against a typical state-of-the-art commercial set-up shown in Fig. 1b.

**Remark 2:** **Parameter tuning:** The following explicit conditions to tune the estimator parameters ($a\beta$ components and fundamental frequency) have been obtained following the procedure described in [28]:

$$
\varepsilon < 4\bar{\sigma};
$$

$$
0.83 \left(\frac{\sigma}{\lambda_d}\right)^2 \leq \gamma \leq 4.88 \left(\frac{\sigma}{\lambda_d}\right)^2;
$$

where $\omega_{BW}$ is the desired bandwidth of the closed loop system. In addition, the gain $\varepsilon_n$ for the $n$-th harmonic component ($n \in \{3, 5, 7, \ldots\}$) must satisfy
\[ \varepsilon_t = \frac{\Delta v}{v_{\text{nom}}}; \]  where \( \tau_{s,n} \) is the desired settling time. These conditions guarantee precise and fast convergence of the estimates towards their corresponding references.

**IV. EXPERIMENTAL VALIDATION**

The proposed FI-DPMU was experimentally validated using hardware-in-loop. The implementation was performed in a digital board based on a DSPACE DS1007 programmed with Simulink. The tests include the estimation of magnitude, phase, frequency and harmonic distortion. In every test, the response of the FI-DPMU is compared to the limits imposed by the standard described in [26], using the figures of merit: total vector error (TVE), frequency error (FE) and rate of change of frequency error (RFE). The results are compared against actual measurements using commercial DPMUs developed by Powerside [18]. Furthermore, to corroborate the performance of the algorithm in a practical application, a case study of a microgrid is implemented as well.

**A. PHASOR DYNAMICS AND HARMONIC ESTIMATION**

This first set of tests focuses on the adaptive phasor estimator, where a voltage network signal \( v(t) \) is emulated in Simulink, and serves as the input to the FI-DPMU algorithm. Unless otherwise indicated, the parameters used for this first set of tests are: \( \gamma = 6, \varepsilon_1 = 480, \varepsilon_3 = \varepsilon_5 = \varepsilon_7 = 100 \), with a sampling frequency of \( f_s = 10 \) kHz \( (T_s = 0.1 \) ms).

1) TEST 1. PURE SINUSOIDAL \( v(t) \)

The reference signal \( v(t) \) includes only a fundamental component of 110 V of amplitude, with fundamental frequency \( \bar{f} = 60 \) Hz \( (\bar{\omega} = 2\pi \bar{f} \) rad/s). The dynamical response of the phasor algorithm is shown in Fig. 2. Notice that the \( \alpha \) component of the algorithm rapidly converges to \( v(t) \). Fig. 3 shows, magnitude and phase estimation, which coincide with the parameters of the reference signal \( (V = 110/\phi^\circ \text{ V}) \). Fig. 4 shows the evolution of the indicators TVE, FE and RFE, which achieve 0.01%, 0 Hz and 0.01 Hz/s, respectively, in the steady-state. These results satisfy by far the aforementioned standard, where the steady-state limits for the TVE, FE and RFE indicators are fixed to 1%, 0.005 Hz and 0.4 Hz/s, respectively.

2) TEST 2. \( v(t) \) WITH ODD HARMONICS DISTORTION

The IEEE 519 Std. [29] indicates that, if the signal is not measured at the PCC, then the harmonic distortion can be greater than 5%. To study this situation, in this test, the reference signal \( v(t) \) has been distorted with harmonics 3, 5, 7; whose amplitudes are fixed to 20%, 16% and 12% of the fundamental, respectively. These harmonics suddenly enabled at time 0.1 s to exhibit the transient. Fig. 5 shows the time response of the FI-DPMU. Note that, despite the harmonic distortion appearing in \( v(t) \), the \( \alpha \beta \) signals from the estimator achieve, after few cycles, an almost sinusoidal waveform. That is, the FI-DPMU estimates the parameters of the fundamental component while alleviating the effect of harmonic distortion. Moreover, as above mentioned, the algorithm is able to simultaneously work as a power quality analyzer providing an estimate of the harmonics magnitude as shown in Fig. 6.

3) TEST 3. \( v(t) \) WITH MAGNITUDE CHANGE AND PHASE JUMPS

Fig. 7 shows the estimates responses in \( \alpha \beta \) coordinates under simultaneous abrupt changes on magnitude and phase on \( v(t) \). For this, the magnitude is abruptly changed from
110 V to 99 V, i.e., a reduction of 90% of its magnitude, while the phase jumps from 0° to 10°. Then, after about 4 cycles, \( v(t) \) is returned to its original amplitude and phase. Fig. 8 shows the corresponding estimated phasor quantities. Fig. 9 shows the evolution of the indicators TVE, FE, and RFE derived from this test. The standard in [26] limits the indicators, in steady-state, to 1% TVE, 0.005 Hz FE, and 0.4 Hz/s RFE, while the response times are limited to \( 2f \), \( 4.5f \) and \( 6f \) for TVE, FE and RFE, where \( f \) is the fundamental frequency of the system. Notice that, after the abrupt changes, errors appear that are captured by those indicators; however, they rapidly vanish satisfying the standard specified in steady-state terms.

4) TEST 4. \( v(t) \) WITH A GRADUAL FREQUENCY VARIATION

Fig. 10 shows the response of the frequency estimate under a gradual variation of the frequency (red) \( f \) following a linear rate of change \( \pm 1 \text{ Hz/s} \) from 58 Hz to 62 Hz and vice versa. Fig. 11 shows the transient response of the phasor estimate (magnitude and phase). Note that the frequency variation produces such a particular phase behavior (phase restricted to}

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**FIGURE 14.** Information delivered by the FI-DPMU.

A. **PHASOR AND HARMONIC ESTIMATION IN A NETWORK**

This set of tests was prepared to further evaluate the performance of the simultaneous phasor and harmonic estimation capability of the proposed FI-DPMU in a network application. For this, we consider to use the FI-DPMU as a monitoring device in the single-phase microgrid shown in Fig. 13, where the measuring points are indicated by J₁, J₆ and J₇. This microgrid is emulated using the dSPACE digital board and Simulink. The resistances, inductances and capacitances per unit length of the distribution line are given by $R = 0.2 \, \Omega/km$, $L = 0.004 \, H/km$ and $C = 5.7 \, mF/km$. The fundamental frequency is 60 Hz and the internal impedance of the external network and DGs are $0.5 + j0.43 \, \Omega$ and $1 + j0.86 \, \Omega$, respectively. Loads 1 to 3 are all $100 + j0.01 \, \Omega$, while load 4 is $200 + j0.01 \, \Omega$. Additionally, we compare the estimations coming from the FI-DPMU with the measurement of in-situ commercial DPMUs.

**5) TEST 5. MICROGRID APPLICATION: PHASOR AND HARMONIC ESTIMATION IN STEADY-STATE**

The network frequency is equal to $f = 60$ Hz, the voltage amplitude of the sources is 110 V. Furthermore, the DG1 associated to J₁ and DG2 associated to J₇, have been perturbed with the 3rd, 5th and 7th harmonics, whose amplitudes, as percentage (%) of the fundamental voltage, are set to $0^\circ$ and $360^\circ$). Fig. 12 shows that, after this tests, the indicators TVE, FE and RFE reach peaks of 0.01%, 0.008 Hz and 0.38 Hz/s, respectively, that fully satisfy the limits imposed by the standard given by 1% of TVE, 0.01 Hz of FE, and 0.4 Hz/s of RFE.
20%, 16% and 12%, respectively. Fig. 14 shows the information provided by the FI-DPMU from the measurement point. Fig. 14a shows the phasor estimate of the measuring point J1. Fig. 14b shows the levels of the estimated harmonics at point J7. A similar full information can be retrieved for the measurement points J1 and J7 out of the FI-DPMUs deployed in those points. Figs. 15 and 16 show the responses of the estimated phasors for voltages and currents using the FI-DPMU, and compare them against the responses obtained with commercial DPMUs. Please notice that the commercial DPMU only reports steady-state values, and the FI-DPMU exhibits the whole dynamical response. In Table 1, the comparison results are shown (commercial DPMU, FI-DPMU); obtaining the magnitude, phase for each measurement point and the TVE (described in standard IEC/IEEE 60255-118-1 [26]) taking the response of the commercial DPMU as the actual phasor. The addition of harmonics does not affect the phasor estimation response of the FI-DPMU. We emphasize that even though both, the commercial DPMU and the FI-DPMU, are able to accurately estimate phasors, only the FI-DPMU is able to additionally provide harmonic estimation.

6) TEST 6. MICROGRID APPLICATION: PHASOR ESTIMATION UNDER FREQUENCY VARIATIONS AND HARMONIC DISTORTION

In this test, the DG2 frequency varies linearly from 58 Hz to 62 Hz at the rate of ±1 Hz/s, as described in the standard IEC/IEEE 60255-118-1 [26]. Moreover, as in the previous tests, the DG1 and DG2 have been perturbed with the

| Branch | Voltage DPMU [V] | Voltage FI-DPMU [V] | TVE [%] | Current DPMU [A] | Current FI-DPMU [A] | TVE [%] |
|--------|-----------------|---------------------|--------|-----------------|---------------------|--------|
| J1     | 109.82±0.000°   | 109.73±0.018°       | 0.09   | 0.786±2.95°     | 0.790±2.89°        | 0.04   |
| J6     | 109.34±359.54°  | 109.24±359.50°      | 0.15   | 1.09±359.55°    | 1.09±359.47°       | 0.2    |
| J7     | 109.96±0.053°   | 110.00±0.000°       | 0.02   | 0.745±359.65°   | 0.742±359.89°      | 0.5    |

**FIGURE 17.** Comparison between the frequency estimation of (red) the FI-DPMU, and (blue) the commercial DPMU, at the measurement points J1, J6 and J7.

**FIGURE 18.** Estimated voltage phasors of (red) FI-DPMU, and (blue) commercial DPMU under a linear frequency variation in DG2, at the measurement points J1, J6 and J7. (a) Voltage phasors at J1 measurement point. (b) Voltage phasors at J6 measurement point. (c) Voltage phasors at J7 measurement point.
The measurement points $J_1$, $J_6$, and $J_7$, respectively, where it can be observed the effect that the frequency variation in $DG_2$ has on the frequency of the other points ($J_1$, $J_6$). Notice that, despite of such a disturbance, both algorithms are able to accurately estimate the frequency. Fig. 18 and Fig. 19 show, a comparison of the voltage and current phasors at each measurement point between the commercial device and the FI-DPMU. The accuracy of the estimation is corroborated by the computation of the TVE in Fig. 20.

V. CONCLUSION

We presented a fully-informative DPMU (FI-DPMU) for the simultaneous estimation of phasor dynamics and harmonic contents. The proposed FI-DPMU exhibits all-in-one capabilities with respect to the current state-of-the-art and commercial devices. The FI-DPMU was tested using a hardware-in-the-loop implementation showing its adaptive capabilities to abrupt parametric changes on the network signal parameters. The state estimation was compared with measurements provided by commercial DPMUs. The results corroborated the high accuracy of the estimation, which was measured according to the IEC/IEEE 60255-118-1 standard. Computations were reduced to basic arithmetic operations, which can be easily implemented using low-cost microcontrollers, e.g., the C2000 family [30]. In terms of practical implementations, the aforementioned technical characteristics of the FI-DPMU result in a low-cost device that facilitates the diffusion of DPMU technology and its rapid deployment over modern distribution network. In terms of applications, the proposed FI-DPMU provides data to alleviate not only current state-of-the-art and legacy problems in distribution network such as state estimation, fault detection, phase identification, data-driven modeling, etc.; but also enables emerging applications that up to now could be performed using a single device such as e.g., harmonic responsibility sharing assessment (see e.g. [31], [32], and [33]). In the latter case, FI-DPMUs are capable to simultaneously retrieve information of the power injection contribution by distributed generation in terms of phasor dynamics, and information about the contribution of each source to the harmonic distortion within the network. This emerging capability fosters also the propagation of asynchronous renewable generation by endowing the operator with the capability to fully assess the impact of distributed resources in real-time.

Finally, we conclude that, since the core algorithm that permits simultaneous phasor and harmonic estimation is based on the solution of standard discrete-time equations, it is a straightforward matter to include yet more equations to the algorithm. This was illustrated when adding the harmonic estimation capability, which can arbitrarily accommodate any number of harmonics of interest. Hence, such algorithmic flexibility can accommodate further discrete-time algorithms within the device and then provide important local information, e.g., island detection. Beside, it is worth noticing that one of the most compelling features of DPMUs is their capability to act in a synchronized coordinated way, since there is an additional value of retrieving information in a collective way, by mapping a relevant part of the network or even the whole distribution circuit. Consequently, although...
the core algorithm is very well capable of hosting further algorithms, it remains to the operator to determine if the algorithms should be implemented in an all-in-one device (i.e., simultaneous phasor and harmonic estimation plus a further algorithm with an additional application) or if they wish to retrieve information from different DPMUs, and then run a different application algorithm at the level of a control room.

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