Metrological Characterization of a Calibrator for Static and Dynamic Validation of Distribution Network PMUs

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Motivation of the Work

Active Distribution Networks (ADNs)

SOURCE: sine.ni.com

= Phasor Measurement Unit (PMU)

= Feeder Monitoring, Control Unit (PDC+RTSE+control+protection)
**Motivation of the Work**

*Measurement challenges in ADNs*

Compared to TNs, in ADNs waveform disturbances are more remarkable:

- **Harmonic distortion** beyond the IEEE Std. C37.118 specs.
  - Superposition of multiple harmonics (EN 50160).
  - Harmonics superposed to frequency fluctuations.
- **Higher measurement noise**, particularly in measured currents.
- R/X ratio close to 1, resulting in **limited phase difference**.
- **Reduced power flows**, limited to few MVA maximum.
- **Faster dynamics** w.r.t. renewables short-term volatility.

**Solution:** PMUs & Smart meters characterized by **enhanced accuracy** (*TVE ≤ 0.0x% in static*).
Motivation of the work

PMU accuracy requirements in ADNs

The “PMU calibrator” should provide a reference accuracy at least 10X better than PMUs under test.

Objective: to develop and characterize a validation system with $\text{TVE} \leq 0.00x\%$ in static.

- IEEE Std C37.118.1
  - $\text{TVE} \leq 1\%$

- PMUs in ADNs
  - $\text{TVE} \leq 0.0x\%$

- PMU calibrator
  - $\text{TVE} \leq 0.00x\%$
Presentation Outline

• Hardware Architecture

• Metrological Characterization
  – Reference value definition
  – Uncertainty contributions

• Phasor Analysis in Transient Events

• Conclusions
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Hardware Architecture

Chassis

NI PXI 1042Q

- Compatible with external time-base reference sources ➔ disciplined by GPS receiver and Rb atomic clock;
- Integrated synchronization schemes via dedicated channels ➔ perfectly synchronous generation/acquisition;
- Embedded μ-controller (RAM 2 GB) ➔ data processing and analysis
**Hardware Architecture**

**Time synchronization**

**NI PXI 6682**

- Disseminates the internal time-base within the other operational units;
- Rubidium atomic clock provides the 10 MHz and PPS (1 Hz) reference ➔ higher short-term stability;
- GPS receiver disciplines the atomic clock via PPS signal ➔ higher long-term stability
Hardware Architecture

Waveform generation

NI PXI 6289

- High-accuracy I/O data ➔ up to 100 kS/s (25 kS/s for 3 phase), at 16 bit;
- SNR = 93.5 dB, THD ≃ 10⁻⁵ %;
- Voltage range ±12 V ➔ compliant with MV/LV instrument transformer of IEC 61869;
Hardware Architecture

Phasor Data Concentrator (PDC)

- Aggregation of measurement data from PMUs \(ightarrow\) time-aligned based on timestamp;
- Single switch \(\rightarrow\) negligible latency introduced by network;

NI PXI

Optimized PDC
Hardware Architecture

Error assessment

- ADC waveform off-line processing ➔ reference values;
- Comparison with PMUs’ measures ➔ TVE, FE and RFE;
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**Metrological Characterization**

*Reference values estimation*

**Signal model:** generic time-variant noise-less power signal affected by disturbances:

\[
x(t) = A \left(1 + \varepsilon_A(t)\right) \cdot \cos \left(2\pi f t + \varphi_0 + \varepsilon_\varphi(t)\right) + \eta(t)
\]

- \(A, f, \varphi_0\): amplitude, frequency and initial phase of **fundamental component**
- \(\varepsilon_A, \varepsilon_\varphi\): **amplitude and phase fluctuations** (e.g. modulations)
- \(\eta\): **DC, harmonic and inter-harmonic components** and any transient condition affecting the spectrum other than fundamental component transient
Metrological Characterization

Reference values estimation

Working HP: $\varepsilon_A(t), \varepsilon_\varphi(t)$ and $\eta(t)$ are known a priori

Reference values assessment via non-linear least-squares (NL-LSQ) fit [1]

$$\{\hat{A}, \hat{f}, \hat{\varphi}_0\} = \arg\min_{\mathcal{P}} \|x[n] - \hat{x}[n]\|_2$$

**Input:**
- $x(t) \rightarrow$ waveform model
- $x[n] \rightarrow$ acquired waveform
- $\mathcal{P}^* = \{A^*, f^*, \varphi_0^*\} \rightarrow$ initial guess (user-defined parameters)

**Output:**
- $\hat{\mathcal{P}} = \{\hat{A}, \hat{f}, \hat{\varphi}_0\} \rightarrow$ reference values
  - $\hat{s} = \hat{A} \cdot \exp(1j 2\pi \hat{f} nT_s + \hat{\varphi}_0) \rightarrow$ reference synchrophasor
  - $\hat{x}[n] = \hat{A} \cdot \cos(2\pi \hat{f} nT_s + \hat{\varphi}_0) \rightarrow$ recovered fundamental tone
Metrological Characterization

**NL-LSQ estimation accuracy**

We characterized the NL-LSQ accuracy in all the **IEEE Std C37.118.1 static tests**, by simulating 3-phase voltage signals, with the same sampling rate, SNR and THD. The test signals have a duration of 5 s.

NL-LSQ provides the reference synchrophasor related to *60-ms windows* with a *reporting rate of 50 fps*, in compliance with P-class PMUs but better performance can be achieved with higher sample number.
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Metrological Characterization

Uncertainty sources

We evaluate the uncertainty contributions produced by the different blocks of the PMU calibrator, i.e. we perform a thorough characterization of NI PXI 6682 and 6289 boards.

We compare the PMU calibrator estimates with the measurement provided by high-accuracy instrumentation:

- **Amplitude**: HP3458A digital voltmeter (DVM) with a resolution of 1 μV;
- **Frequency**: SR620 universal time counter (DFM) with a resolution 10 nHz.
- **Initial Phase**: we consider a 5s waveform processed with IpDFT [2] with a resolution of 10 nrad.

NB: hardware instrumentation guarantees optimal performance only in the absence of time variations / interference ➔ error characterization performed only in steady-state conditions.
We identify three main error sources:

- **DAC & ADC accuracy** affects magnitude, frequency and phase uncertainty;
- **Time-base stability** affects frequency and phase uncertainty;
- **Synchronization** affects phase uncertainty.

For each source, we consider waveform in steady-state conditions of 5s duration (corresponding to 248 estimates at 50 fps), and characterize the deviation between estimated and measured values in terms of:

1) **mean value**, $\mu$ that is fixed can be **compensated**;
2) **standard deviation**, $\sigma$ that is random represents the **actual uncertainty**.

By assuming a **Gaussian error distribution**, in each test we evaluate the **worst-case uncertainty** as **$3\sigma$ range**.
Metrological Characterization

Synchrophasor magnitude uncertainty

In terms of magnitude uncertainty (MU), we compare the NL-LSQ estimates with DVM measurements (res. $\pm 1 \, \mu V$). The instrument is triggered by the same clock of DAC / ADC $\Rightarrow$ guaranteed synchronization.

As function of signal frequency, we determine a worst-case uncertainty $MU < 12 \, \mu V \ (1 \, \text{ppm} @ \text{full input range})$
In terms of phase uncertainty (PU), we should consider the contribution due to both frequency and initial phase. To this end, we compare the NL-LSQ estimates with DFM and IpDFT measurements.

The instrument is triggered by the same clock of DAC / ADC \( \rightarrow \) guaranteed synchronization.

As function of signal frequency, we determine a worst-case uncertainty \( PU < 0.8 \mu\text{rad} \).
**Metrological Characterization**

*Time reference stability*

**Time reference error (TE)**: deviation between PPS of PMU calibrator (PXI-PPS) and UTC-CH (UTC-CH) in METAS. Over two days, standard deviation $\sigma < 11.5$ ns, that corresponds to a phase uncertainty of 4 $\mu$rad at 50 Hz.

In METAS, we also compare the phase noise obtained in 3 different setups:

- PXI only;
- PXI + GPS receiver;
- PXI + GPS receiver + atomic clock \(\Rightarrow\) enhanced short-term variability
Metrological Characterization

Internal synchronization uncertainty

Synchronization error (SE): initial phase displacement due to imprecise synchronization between DAC and ADC.

Three-steps procedure accounts for the initial phase contribution that can vary from experiment to another.

On varying signal frequency within [10, 1000] Hz, we obtain a worst case uncertainty $SE < 4.85 \ \mu\text{rad}$
Based on MU, PU, SE and TE, we characterize the equivalent TVE provided by the PMU calibrator within the entire test set of IEEE Std C37.118.1.

<table>
<thead>
<tr>
<th>Test</th>
<th>TVE [%]</th>
<th>FE [Hz]</th>
<th>RFE [Hz/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal</td>
<td>$2.03 \cdot 10^{-4}$</td>
<td>$2.29 \cdot 10^{-6}$</td>
<td>$2.29 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>signal frequency</td>
<td>$3.56 \cdot 10^{-4}$</td>
<td>$4.31 \cdot 10^{-6}$</td>
<td>$4.31 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>harmonic dist.</td>
<td>$1.74 \cdot 10^{-4}$</td>
<td>$4.19 \cdot 10^{-6}$</td>
<td>$4.19 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>out-of-band dist.</td>
<td>$4.02 \cdot 10^{-4}$</td>
<td>$1.50 \cdot 10^{-6}$</td>
<td>$1.50 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>meas. bandwidth</td>
<td>$3.57 \cdot 10^{-2}$</td>
<td>$1.34 \cdot 10^{-3}$</td>
<td>$1.34 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>ampl. modulation</td>
<td>$2.53 \cdot 10^{-5}$</td>
<td>$6.40 \cdot 10^{-5}$</td>
<td>$6.40 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>phase modulation</td>
<td>$2.52 \cdot 10^{-2}$</td>
<td>$1.34 \cdot 10^{-3}$</td>
<td>$1.34 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>frequency ramp</td>
<td>$9.17 \cdot 10^{-3}$</td>
<td>$4.86 \cdot 10^{-5}$</td>
<td>$4.86 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>step change</td>
<td>$4.24 \cdot 10^{-4}$</td>
<td>$7.19 \cdot 10^{-6}$</td>
<td>$7.19 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>
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Phasor Analysis in Transient Events

**Step test implementation**

\[ x(t) = A \left( 1 + A_T \cdot \frac{1}{1 + e^{-k(t-T)}} \right) \cdot \cos(2\pi f t + \phi_0) \]

\( k \): determines the bandwidth of the transient event

**IEEE Std. synchrophasor representation**: signal DFT consists of one / few narrow-band components, but during step:

- incomplete representation of entire signal information content
- PMU accuracy evaluation based on TVE might lose significance

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**Amplitude Envelope**

<table>
<thead>
<tr>
<th>magnitude [a.u.]</th>
<th>k=5</th>
<th>k=50</th>
<th>k=500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Signal DFT in \( T_T \)**

- STEP
- NOM

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Metrological Characterization of a PMU Calibrator for ADNs
Phasor Analysis in Transient Events

RMSE-based performance evaluation

We compare the performance of three estimation algorithms, as function of increasing transient bandwidth $k$:

- **NL-LSQ** (non-linear fit, known signal model) [1];
- **CS-TFM** (dynamic signal model) [3];
- **IpDFT** (static signal model) [2].

First, we consider the canonical TVE performance evaluation:

- **NL-LSQ**: almost independent from $k$;
- **CS-TFM**: degradation, but within 1% limit;
- **IpDFT**: error diverges as $k$ increases.
Phasor Analysis in Transient Events

*RMSE-based performance evaluation*

We compare the performance of three estimation algorithms, as function of increasing transient bandwidth $k$:

- **NL-LSQ** (non-linear fit, known signal model) [1];
- **CS-TFM** (dynamic signal model) [3];
- **IpDFT** (static signal model) [2].

Then, we consider the **RMSE discrepancy** between acquired and recovered fundamental time-domain trend:

$$\text{RMSE} = \sqrt{\frac{\sum_n (\hat{x}[n] - x[n])^2}{N_m}}$$

- **NL-LSQ**: performance almost **constant** over time;
- **CS-TFM, IpDFT**: both error **diverge**, in the presence of step.
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Conclusions

- We have derived the **accuracy requirements** needed by **PMUs operating in ADNs** and discussed the inadequacy of the IEEE Std. C37.118.1, and particularly its 1% TVE limit.

- We have **developed and characterized a highly accurate calibration system** for PMUs in ADNs, that is able to reproduce all the test conditions defined by the IEEE Std. C37.118.1.

- The developed PMU calibrator is characterized by a **TVE \( \approx 0.00x \% \) in static conditions** and **TVE \( \approx 0.0x \% \) in dynamic conditions**.

- We have discussed the validity and **appropriateness of TVE as function of the observed signal bandwidth**, and proposed an **alternative performance index** based on the **RMSE** between acquired and recovered fundamental trend **in the time-domain**.
References


Thank You!

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Motivation of the Work

Two-port equivalent line model

**Working HP:** A PMU used to monitor an ADN must be capable of correctly measuring the amplitude and phase angle differences at the extremities of a transmission line for both voltage and current phasors.

![Two-port equivalent model diagram]

Mathematically, this can be represented as:

\[
\begin{bmatrix} V_b \\ I_b \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_e \\ I_e \end{bmatrix}
\]
Motivation of the Work

Accuracy requirements derivation

1. Definition of scenarios:
   - The nominal voltage of the line $4.16 \leq V_n \leq 36$ [kV]
   - The line type (cable/overhead), and relevant parameters $r, c, l, g$
   - The line length $100 \leq \lambda \leq 5000$ [m]
   - The line load at the end of the line $(S_e, \cos \varphi_e)$ or, equivalently, $(P_e, Q_e)$

2. Computation of the voltage and current phasors at the end of the line:
   
   $V_e = \frac{V_n + j0}{\sqrt{3}}$, $I_e = \left(\frac{P_e + jQ_e}{V_e}\right)^*$

3. Computation of the voltage and current phasors at the beginning of the line:
   
   $\begin{bmatrix} V_b \\ I_b \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_e \\ I_e \end{bmatrix}$

4. Computation of the following differences and equivalent TVE:
   
   $\begin{align*}
   \epsilon_{V,m} &= |V_b| - |V_e| \\
   \epsilon_{V,p} &= \angle V_b - \angle V_e \\
   TVE_V &= \frac{|V_b - V_e|}{V_e}
   \end{align*} \quad \begin{align*}
   \epsilon_{I,m} &= |I_b| - |I_e| \\
   \epsilon_{I,p} &= \angle I_b - \angle I_e \\
   TVE_I &= \frac{|I_b - I_e|}{I_e}
   \end{align*}$
Motivation of the Work

Simulation Results ➔ Equivalent Voltage TVE

\[ V_n = 4.16 \, kV \]

\[ V_n = 20 \, kV \]

- The equivalent voltage TVE is influenced by both line length and line load and becomes smaller as the line gets shorter and/or the power flow smaller.
- Particularly with higher nominal voltages, the related PMU requirements become quite challenging.

Line length [m]

Line load [kVA]
Metrological Characterization

**NL-LSQ numerical stability**

\[
\{\hat{A}, \hat{f}, \hat{\phi}_0\} = \arg\min_{\mathbf{p}} \|x[n] - \hat{x}[n]\|_2
\]

The considered optimization problem is **strictly non-convex**, and thus **numerically ill-conditioned**.

The convergence to optimal solution depends on the **initial guess** \( \mathcal{P}^* = \{A^*, f^*, \phi^*_0\} \).

Given the true values \( \mathcal{P} = \{1, 50, \pi\} \), the confidence interval that guarantees **convergence to optimal solution** \( \mathcal{P}^{\text{min}} \)

\[
A^* = 0.9 \div 1.1 \\
f^* = 48 \div 52 \\
\phi^*_0 = (\pi \div 3\pi)/2
\]

\[
A = 1 \\
f = 50 \\
\phi_0 = \pi
\]
Metrological Characterization

Internal synchronization uncertainty

Synchronization error (SE): initial phase displacement due to imprecise synchronization between DAC and ADC

1) ADC+DAC initial phase: typical calibration procedure, signal generated and simultaneously acquired, then processed with IpDFT [2] \( \phi_{0}^{DAC+ADC} \)
Metrological Characterization

Internal synchronization uncertainty

Synchronization error (SE): initial phase displacement due to imprecise synchronization between DAC and ADC

1) ADC+DAC initial phase: typical calibration procedure, signal generated and simultaneously acquired, then processed with IpDFT [2] \( \phi_{0}^{DAC+ADC} \)

2) ADC initial phase: subPPS signal derived from internal clock, synchronously acquired by ADC and processed with IpDFT [1] \( \phi_{0}^{ADC} \)
Metrological Characterization

**Internal synchronization uncertainty**

Synchronization error (SE): initial phase displacement due to imprecise synchronization between DAC and ADC

1) ADC+DAC initial phase: typical calibration procedure, signal generated and simultaneously acquired, and processed with IpDFT [2] \( \phi_{DAC+ADC} \)

2) ADC initial phase: subPPS signal derived from internal clock, synchronously acquired by ADC and processed with IpDFT [2] \( \phi_{ADC} \)

3) “Only DAC” initial phase: subtraction of 1) – 2) \( \phi_{DAC+ADC} - \phi_{ADC} = \phi_{DAC} \)
Metrological Characterization

**Phase definition in transient**

Actual metering devices sense steps (particularly phase/frequency) not only as a succession of two different steady-state conditions, but as large frequency (and thus ROCOF) variations

⇒ problems for frequency-based applications (e.g. load shedding)

Possible solutions:
1) Enlarging the window length ⇒ worse response time;

2) More complex signal models to account for time-varying trend ⇒ increased complexity

- Static signal model (Fourier series analysis)

\[ x(t) = A(t) \cdot \cos(2\pi ft + \phi_0) = A(t) \cdot \cos(\theta(t)) \]

- Taylor-Fourier signal model (Frigo et al.)

\[ x(t) = \Re \left\{ \sum_k \frac{t^k}{k!} \left[ \frac{p^k}{\sqrt{2}} e^{1j2\pi ft} + \frac{(p^k)^*}{\sqrt{2}} e^{-1j2\pi ft} \right] \right\} \]

- Underlying freq. signal model (Kirkham et al.)

\[ x(t) = A(t) \cdot \cos(\theta(t) + \psi(t)) \]
Given a general sinusoidal signal and the corresponding synchrophasor representation

\[ x(t) = A(t) \cdot \cos(2\pi f(t) t + \phi_0(t)) = A(t) \cdot \cos(\psi(t)) \quad \text{and} \quad X(t) = A(t) \cdot e^{1j\psi(t)} \]

and the estimated quantities \( \hat{A}, \hat{f}, \hat{\phi}_0 \), we can retrieve the time-domain and synchrophasor representations:

\[ \hat{x}(t) = \hat{A}(t) \cdot \cos \left( 2\pi \hat{f}(t) t + \hat{\phi}_0(t) \right) \quad \hat{X}(t) = \hat{A}(t) \cdot e^{1j\hat{\psi}(t)} \]

Performance indices to assess the estimation accuracy:

1) TVE (IEEE Std) relies on synchrophasor model

2) RMSE (Frigo et al.) relies on time-domain

\[ RMSE = \sqrt{\frac{\sum_n (\hat{x}[n] - x[n])^2}{N_m}} \]

3) GoF (Kirkham et al.) accounts also for model d.o.f.

\[ GoF = 20 \log \frac{A}{\sqrt{\frac{1}{N-m} \sum_n (x[n] - \hat{x}[n])^2}} \]