Synchronized Sensing for Wide-Area Situational Awareness of Power Distribution Networks

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Outline

- Synchrophasor Networks and Phasor Measurement Units

- The Iterative-Interpolated Discrete Fourier Transform and its Application to Synchrophasor Estimation

- Advanced Calibrator for the Metrological Characterization of PMUs

- Time Dissemination Techniques for PMUs
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- Synchrophasor Networks and Phasor Measurement Units
- The Iterative-Interpolated Discrete Fourier Transform and its Application to Synchrophasor Estimation
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- Time Dissemination Techniques for PMUs
Situational Awareness in Power Grids via PMUs

Phasor Measurement Unit (PMU)

Phasor Data Concentrator (PDC)

Time Synchronization

Telecom Infrastructure
The Synchrophasor Model vs Power System Signals

Phasor → Nominal operating conditions signal model

\[ x(t) = A_0 \cdot \cos(2 \pi f_0 t + \varphi_0) = A_0 \cdot \cos \Phi_0 \quad \leftrightarrow \quad X = A_0 \cdot e^{i\Phi_0} \]
The Synchrophasor Model vs Power System Signals

Distorted operating conditions: static

\[ x(t) = A_0 \cdot \cos(2\pi f_0 t + \varphi_0) + v(t) + \eta(t) \]
The Synchrophasor Model vs Power System Signals

Distorted operating conditions: dynamic

\[ x(t) = A_0(t) \left( 1 + \varepsilon_{A_0}(t) \right) \cdot \cos \left( 2\pi f_0(t) t + \varphi_0 + \varepsilon_{\varphi_0}(t) \right) + \nu(t) + \eta(t) + \gamma(t) \]
The Synchrophasor Model vs Power System Signals

- Phasor

\[ x(t) = A_0 \cdot \cos(2 \pi f_0 t + \varphi_0) = A_0 \cdot \cos(\Phi_0) \leftrightarrow A_0 \cdot e^{j\Phi_0} \]

- Realistic non-stationary power system signal model

\[ x(t) = A_0(t) \left(1 + \varepsilon_{A_0}(t)\right) \cdot \cos(2\pi f_0(t) t + \varphi_0 + \varepsilon_{\varphi_0}(t)) + \eta(t) + \gamma(t) + \nu(t) \]


\[ x(t) = A_0(t) \cdot \cos(2 \pi f_0(t) t + \varphi_0) \leftrightarrow A_0(t) \cdot e^{j\Phi_0(t)} \]
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- The Iterative-Interpolated Discrete Fourier Transform and its Application to Synchrophasor Estimation
  

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Motivation

i-IpDFT for Synchrophasor Estimation

- Grids characterized by high shares of harmonic and interharmonic components

\[\begin{align*}
\text{P-class} & \quad \text{M-class} \\
\text{Protection} & \Rightarrow \text{Latency} & \Rightarrow \text{Accuracy}
\end{align*}\]

Single PMU satisfying both the P and M-class PMU requirements at the same time?

- Lower cost: the same PMU simultaneously supplies monitoring and protection functionalities
- Higher measurement reliability: protection and control applications are not degraded by disturbances (interharmonics)
DFT-based Synchrophasor Estimation Algorithms

- Input signal
- Sampling
- Windowing & time synch
- Synchrophasor Estimation
- Estimated Synchrophasor

Frequency $f_0$, Amplitude $A_0$, Phase $\varphi_0$
DFT-based Synchrophasor Estimation Algorithms

**Aliasing**

\[ F_s \gg f_{\text{max}} \]

\[ X_s(j \Omega) : (\Omega_s - \Omega_N) \rightarrow \Omega_s \rightarrow 2\Omega_s \]

**Incoherent Sampling** → **Spectral Leakage**

**Windowing**

**Incoherent Sampling** → **Spectral Sampling**

**Interpolation**

**Harmonic/Interharmonic Interference**

**Iterative IpDFT**

Time-invariant parameters

Short window length
The Interpolated DFT (IpDFT)

The IpDFT is a technique to extract the parameters $f_0$, $A_0$ and $\varphi_0$ of a sinusoidal waveform by interpolating the highest DFT bins of the signal spectrum. It mitigates the effects of incoherent sampling ($f_0/\Delta f \not\in \mathbb{N}$) by:

- Applying special windowing functions $\Rightarrow$ reduce spectral leakage
- Interpolating the highest DFT bins $\Rightarrow$ minimize spectral sampling

\[
\delta = a \cdot \varepsilon \frac{|X(k_m + \varepsilon)| - |X(k_m - \varepsilon)|}{|X(k_m - \varepsilon)| + 2|X(k_m)| + |X(k_m + \varepsilon)|}, \quad a = 1.5 \cos \theta, \quad a = 2 \text{ hann}
\]

- \(f_0 = (k_m + \delta)\Delta f\)
- \(\varphi_0 = \angle X(k_m) - \pi \delta\)
- \(A_{0C} = 4 \cdot |X(k_m)| \left| \frac{\delta^2 - 0.25}{\cos(\pi \delta)} \right|\)
- \(A_{0H} = |X(k_m)| \left| \frac{\pi \delta}{\sin(\pi \delta)} \right| |\delta^2 - 1|\)
### The Interpolated DFT (IpDFT)

<table>
<thead>
<tr>
<th>Assumptions behind the IpDFT</th>
<th>Possible solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>The input signal is characterized by time-invariant parameters</td>
<td>Window lengths containing few cycles of a signal at the rated power system frequency</td>
</tr>
<tr>
<td>The sampling rate is higher than the highest signal’s spectral component</td>
<td>Sampling rate $F_S$ in the order of tens of kHz</td>
</tr>
<tr>
<td>The DFT bins used to perform the interpolation are only generated by the positive image of the tone under analysis</td>
<td><strong>Enhanced IpDFT (e-IpDFT)</strong> ➔ Iterative compensation of the spectral interference produced by the main tone negative image</td>
</tr>
<tr>
<td></td>
<td><strong>Iterative IpDFT (i-IpDFT)</strong> ➔ Iterative compensation of the spectral interference produced by the nearby tones</td>
</tr>
</tbody>
</table>
The enhanced Interpolated-DFT (e-IpDFT)

\[ X_p(k) = P \]

\[ X(\hat{k}) \quad \text{IpDFT} \]

- Negative image estimation
- Negative image compensation
- Estimated Synchrophasor

Yes: Estimated Synchrophasor

No: Negative image estimation

\[ X_0^{-}(k) = A_0 e^{j\varphi_0} W(k - f_0/\Delta f) \]

\[ X_0^{+}(k) = X(k) - X_0^{-}(k) \]

\[ |X(k)| \]

\[ k \]

- DFT bins
- DTFT
- Fund pos im
- Fund neg im

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The iterative-IpDFT (i-IpDFT)

$X(k) \xrightarrow{\text{e-IpDFT}} q = Q, E_n > \lambda \xrightarrow{\text{yes}}$ Estimated Synchrophasor
$X_i(k) = X(k) - X_0(k)$

$X_0(k) = X(k) - X_i(k)$

Main tone estimation & compensation

Interharmonic tone estimation & compensation
## The iterative-IpDFT (i-IpDFT)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal system frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Window length</td>
<td>3-cycles (60 ms)</td>
</tr>
<tr>
<td>Window profile</td>
<td>Cosine &amp; Hanning</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>50 kHz</td>
</tr>
<tr>
<td>PMU reporting rate</td>
<td>50 fps</td>
</tr>
<tr>
<td># DFT bins</td>
<td>11 (cos) &amp; 8 (Hann)</td>
</tr>
<tr>
<td>IpDFT interpolation points</td>
<td>3-points</td>
</tr>
<tr>
<td># iterations (P)</td>
<td>2</td>
</tr>
<tr>
<td># iterations (Q)</td>
<td>16 (cos) &amp; 28 (Hann)</td>
</tr>
<tr>
<td>Noise</td>
<td>80 dB</td>
</tr>
</tbody>
</table>
Performance Assessment – 00BI

Max Errors:

TVE
\[ M = 1.3\% \]
\[ \cos = 0.02\% \]
\[ \text{hann} = 0.08\% \]

FE
\[ M = 10 \text{ mHz} \]
\[ \cos = 1.1 \text{ mHz} \]
\[ \text{hann} = 4.1 \text{ mHz} \]

RFE
\[ \cos = 0.1 \text{ Hz/s} \]
\[ \text{hann} = 0.4 \text{ Hz/s} \]
### Embedded Hardware Implementation

**National Instruments compactRIO 9039:**
- Xilinx Kintex-7 325T FPGA
- 6 channels (3V, 3I)

**FPGA Allocation:** 54%

**Latency [ms]:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>1 ch</th>
<th>6 ch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q = 0</td>
<td>0.34</td>
<td>2.04</td>
</tr>
<tr>
<td>Q = 28</td>
<td>1.20</td>
<td>7.20</td>
</tr>
</tbody>
</table>

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**Diagram:**
- Network adapter
  - C37.118 data frames
- Real-time processor
  - Clock drift compensation
  - ROCOF Phase
    - $f_0, A_0, \phi_0$
- FPGA
  - Clock drift measurement
  - DFT
    - $X(k)$
  - Synchrophasor Estimation
    - $x(n)$
  - subPPS
- Input channels – ADC converters
  - NI 9225
  - NI 9227
- Time-synchronization source
  - UTC-time
  - PPS
  - GPS
  - WR
Conclusion

i-IpDFT for Synchrophasor Estimation

- We discussed the limits of IpDFT when estimating parameters of a signal corrupted by interharmonic
- We formulated a technique resilient against spectral leakage generated by any interfering tone
- We conducted a sensitivity analysis to tune the algorithm parameters
- IpDFT-based SE algorithm for P and M-class compliant PMUs
- First IpDFT-based synchrophasor estimation technique resilient to OOBI
- During OOBI test the maximum TVE is 0.08% (being 1.3% the maximum allowed limit) and the maximum FE is 4 mHz (being 10 mHz the maximum allowed limit)
- We implemented the i-IpDFT into an embedded device
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Motivation

Advanced Calibrator for the Metrological Characterization of PMUs

IEEE Std. C37.118
TVE ≤ 1 %

State-of-the-art PMUs
TVE ≤ 0.0x %

PMU calibrator
TVE ≤ 0.00x %
The proposed PMU calibrator

1. GPS receiver
2. Clock
3. NI PXI 1042Q
4. DACs
5. ADCs
6. PDC
7. Waveform analysis
8. Error assessment
9. PMU errors
10. User param
11. AMPL
12. Switch
13. PMU1
14. PMU2
15. PMU_N
16. N PMUs under test

Flow:
- i. GPS receiver
- ii. Clock
- iii. NI PXI 1042Q
- iv. DACs
- v. ADCs
- vi. PDC
- vii. Waveform analysis
- viii. Error assessment
- ix. PMU errors
- x. AMPL
- xi. Switch
- xii. PMU1
- xiii. PMU2
- xiv. PMU_N
- xv. N PMUs under test

Date: 21/10/2019
Location: IEEE SmartGridComm, Beijing, China
Reference values estimation

Signal model ➔ Generic time-variant noise-less power signal affected by disturbances:

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

Working HP ➔ \( \varepsilon_A(t), \varepsilon_\varphi(t) \) and \( \eta(t) \) known a priori

Reference values ➔ estimation via non-linear least-squares (NL-LSQ) fit:

\[ \{ \hat{A}, \hat{f}, \hat{\varphi}_0 \} = \text{argmin}_\mathcal{P} \| x[n] - \hat{x}[n] \|_2 \]

\[ \mathcal{P}^* = \{ A^*, f^*, \varphi_0^* \} \]

\[ \hat{x}[n] = \hat{A} \cdot \cos \left( 2\pi \hat{f} nT_s + \hat{\varphi}_0 \right) \]
Metrological Characterization

Uncertainty Sources

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

True value ➔ High-accuracy instrumentation (steady-state only)

- Amplitude ➔ HP3458A digital voltmeter (DVM) - resolution $1 \mu V$
- Frequency ➔ SR620 universal time counter (DFM) - resolution $10 \text{nHz}$
- Initial Phase ➔ 5s waveform processed with IpDFT - resolution of $10 \text{nrad}$

- Deviation between reference (NL-LSQ estimates) and true (instrument measures) values:
  - mean value $\mu$ ➔ fixed ➔ can be compensated
  - standard deviation $\sigma$ ➔ random ➔ represents the actual uncertainty (HP: Gaussian)
- Test waveforms: 5 s, NL-LSQ observation interval 60 ms, reporting rate 50 fps
Metrological Characterization

Synchrophasor Magnitude Uncertainty (MU)

- NL-LSQ estimates vs DVM measurements (res. ±1 μV)
- DVM and DAC / ADC triggered by the same clock ➔ guaranteed synchronization
- Signal frequency [45, 55 Hz] ➔ Worst-case MU < 12 μV (1 ppm @ full input range)
Metrological Characterization

Synchrophasor Phase Uncertainty (PU)

- NL-LSQ estimates vs:
  - DFM measurements (res. $\pm 10$ nHz): contribution to PU due to frequency
  - IpDFT estimates (res. $\pm 10$ nrad): contribution to PU due to initial phase
- DFM and DAC / ADC triggered by the same clock $\Rightarrow$ guaranteed synchronization
- Signal frequency [45, 55 Hz] $\Rightarrow$ Worst-case PU < 0.8 $\mu$rad
Metrological Characterization

Time Reference Uncertainty (TU) (Stability)

- PPS of PMU calibrator (PXI-PPS) vs UTC-CH (UTC-CH) @ METAS
- Over two days
- Worst-case $\text{TU} \sigma < 11.5 \text{ ns} \Rightarrow \text{PU} < 4 \mu\text{rad} @ 50 \text{ Hz}$
# Metrological Characterization

## IEEE Std C37.118

- Based on MU, PU, SU, TU ➔ equivalent TVE
- True Value: Steady state single-tone ➔ High-accuracy instruments
- Dynamic Tests ➔ User Parameters

## Test Results

<table>
<thead>
<tr>
<th>Test</th>
<th>TVE [%]</th>
<th>FE [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>2.03·10^{-4}</td>
<td>2.29·10^{-6}</td>
</tr>
<tr>
<td>Signal Amplitude</td>
<td>1.84·10^{-3}</td>
<td>2.02·10^{-5}</td>
</tr>
<tr>
<td>Signal Frequency</td>
<td>3.56·10^{-4}</td>
<td>4.31·10^{-6}</td>
</tr>
<tr>
<td>Harmonic Distortion</td>
<td>1.74·10^{-4}</td>
<td>4.19·10^{-6}</td>
</tr>
<tr>
<td>OOBI</td>
<td>4.02·10^{-4}</td>
<td>1.50·10^{-6}</td>
</tr>
<tr>
<td>Amplitude Modulation</td>
<td>2.53·10^{-5}</td>
<td>6.40·10^{-2}</td>
</tr>
<tr>
<td>Phase Modulation</td>
<td>2.52·10^{-2}</td>
<td>1.34·10^{-3}</td>
</tr>
<tr>
<td>Frequency Ramp</td>
<td>9.17·10^{-2}</td>
<td>4.86·10^{-3}</td>
</tr>
<tr>
<td>Step</td>
<td>4.24·10^{-4}</td>
<td>7.19·10^{-6}</td>
</tr>
</tbody>
</table>
Conclusion

Advanced Calibrator for the Metrological Characterization of PMUs

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

- We described the hardware and the software of the proposed PMU calibrator.

- The developed PMU calibrator is characterized by a $\text{TVE} \approx 0.00x\ %$ in static conditions and $\text{TVE} \approx 0.0x\ %$ in dynamic conditions.
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- Time Dissemination Techniques for PMUs

**Motivation**

Time Dissemination Techniques for PMUs

<table>
<thead>
<tr>
<th>IEEE Std. C37.118</th>
<th>Common practice</th>
<th>State-of-the-art PMUs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE Std. C37.118</td>
<td>Common practice</td>
</tr>
<tr>
<td>Accurate: 1 µs</td>
<td>GPS ±100 ns uncertainty</td>
<td>Phase uncertainty</td>
</tr>
<tr>
<td>Reliable: 24/7</td>
<td>31 µrad @ 50 Hz</td>
<td>5 µrad</td>
</tr>
<tr>
<td>Available: urban area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secure: timing attacks</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Transmission grids ➔ TVE 1% ➔ 1 µs [IEEE Std]

Distribution grids ➔ TVE 0.01% ➔ 10 ns [NASPI]
Time Dissemination Techniques for PMUs

Satellite-based
Network-based

Synchrophasor phase error source:
\[ \Delta \varphi = 2\pi f \Delta t + \varepsilon_{alg} + \varepsilon_{acq} \]
## Time Dissemination Techniques for PMUs

<table>
<thead>
<tr>
<th>Satellite-based</th>
<th>Network-based</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Position System (GPS)</strong></td>
<td><strong>Precision Time Protocol (PTP)</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>100 ns</th>
<th>1 µs</th>
<th>1 ns</th>
</tr>
</thead>
</table>

### Features
- Low installation cost
- Widely used
- Standard profile for power systems
- Reliability
- Determinism

### Limitations
- Accessibility
- Security
- Accuracy
- Non-determinism
- Fiber physical layer
The White Rabbit Protocol

- Ultra-precise timing for CERN’s accelerators

- Based on:
  - PTPv2 [IEEE 1588]
  - Ethernet [IEEE 802.3]
  - Synchronous Ethernet [SyncE]
  - Precise phase measurement

- Deployable on already existing fiber-based networks
The Developed PMU – Hardware Platform

National Instruments compactRIO

FPGA level:
- Time synchronization
- Signal acquisition
- Synchrophasor estimation

- Same hardware platform
- Same synchrophasor estimation
- Only difference is the time sync

- i-IpDFT: \( T = 60 \text{ ms}, \quad Fr = 50 \text{ fps}, \quad Fs = 50 \text{ kHz} \) \( \Rightarrow \) phase error \( \epsilon_{alg} < 5 \mu \text{rad} \)
The Measurement Setup

- **PMU calibrator**
  - Meinberg GPS169PCI
  - Clock 10 MHz
  - PXI 6682 PMU Calib
  - OMICRON CMS356

- **GPS**
  - Meinberg GPS180PEX
  - NI 9467 GPS PMU

- **PTP**
  - Tektron NTS100
  - PTP PMU

- **WR**
  - Meinberg GPS180PEX
  - WR Switch
  - WR cRIO WR PMU

- Synchronous signals:
  - PPS
  - 10 MHz
  - 10 V
  - 300 V

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Performance Assessment – Phase Error

- Worst-case scenario: 24 h – single-tone voltage 50 Hz, 300 V, 0 rad

Cumulative distribution function

- GPS
- PTP
- WR

Allan deviation

- GPS
- PTP
- WR

Standard deviation

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>18.1 µrad</th>
<th>PTP</th>
<th>25.9 µrad</th>
<th>WR</th>
<th>8.1 µrad</th>
</tr>
</thead>
</table>

CDF [%] (Cumulative distribution function)

σ(τ) [rad] (Allan deviation)
Conclusion

Time Dissemination Techniques for PMUs

- We discussed the uncertainty contribution of the time dissemination technology on the synchrophasor estimation for PMU applications.

- We carried out a performance comparison using:
  - Same hardware platform (NI-cRIO)
  - Same synchrophasor estimator (i-IdPFT)
  - Different time synchronization sources: GPS, PTP and WR

- The WR-PMU is capable of minimizing the time dissemination uncertainty contribution and thus optimizing the performance of the synchrophasor estimation algorithm.

- The WR-PMU produces a phase error always lower than 8 μs.
References


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