Synchronized measurements and power system dynamics: challenges and perspectives

Paolo Attilio Pegoraro

Associate Professor of Instrumentation & Measurement

University of Cagliari, Department of Electrical and Electronic Engineering, Italy.

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Outline

- Measurements in the presence of dynamic conditions
- Synchronized measurements: models and issues
- Tracking fast changes
- Future of synchronization
- Data quality, data analysis and latency monitoring
- Synchronized measurements for DC grids

Dynamic conditions

- The AC power systems should work in a **sinusoidal steady state** (at nominal frequency 50 Hz or 60 Hz).

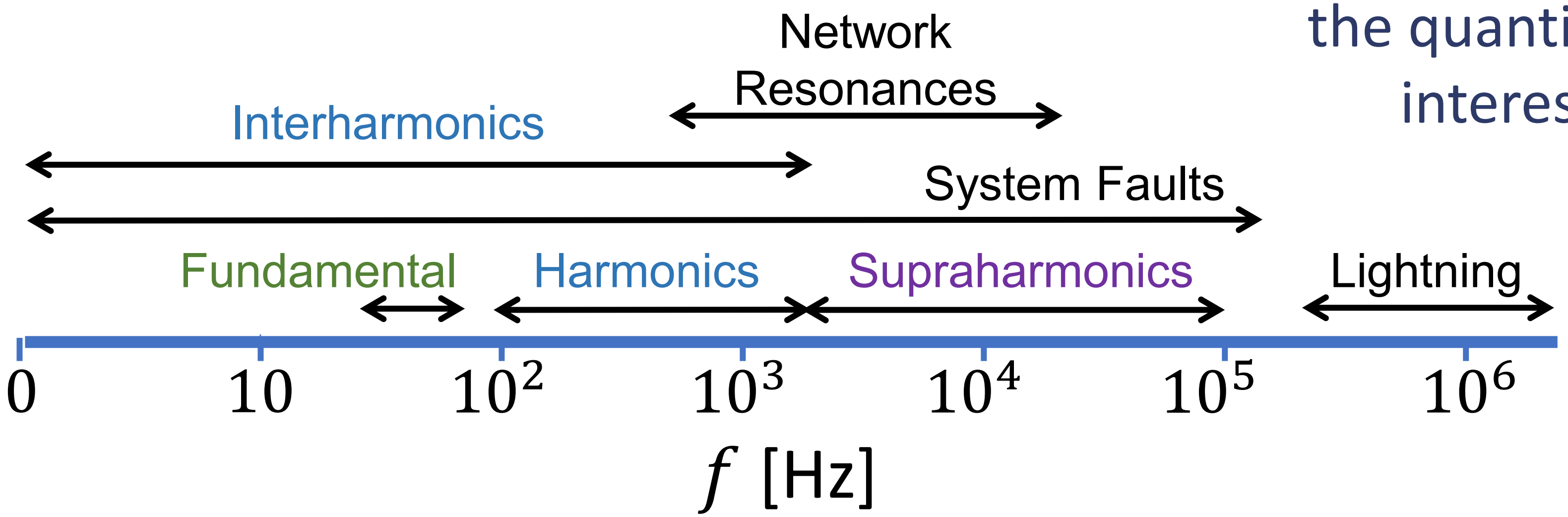
- The DC power systems are ideally represented by constant values.

- Voltage and current signals differ from these ideal conditions, in terms of **level variations**, **variable fundamental frequency** and **distorted waveforms**.

Different measurements for different monitoring applications:

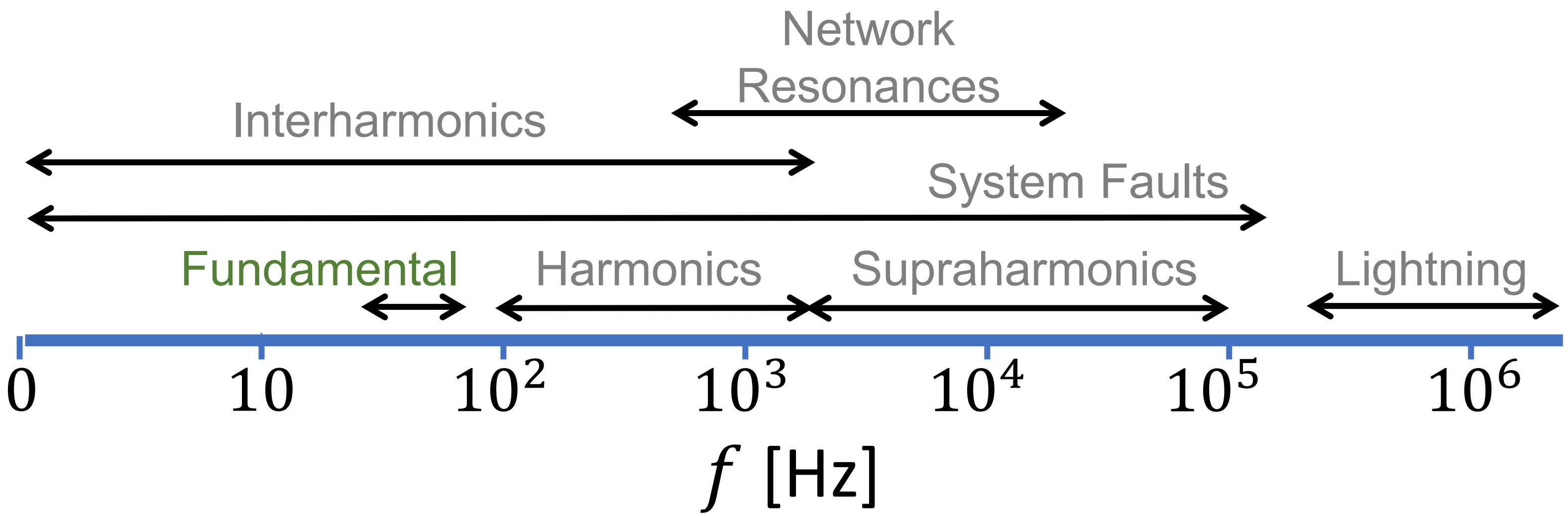
- Fundamental frequency synchrophasors
- Harmonics and interharmonics
- Supraharmonics
- Point-of-wave
- DC
- …

Dynamics and frequency range of interest depend on the quantity of interest



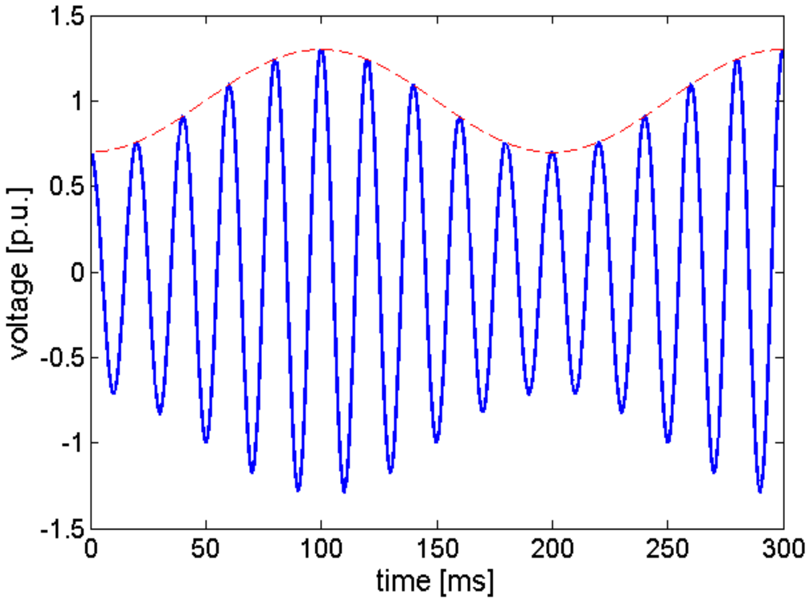
Different measurements for different monitoring applications:

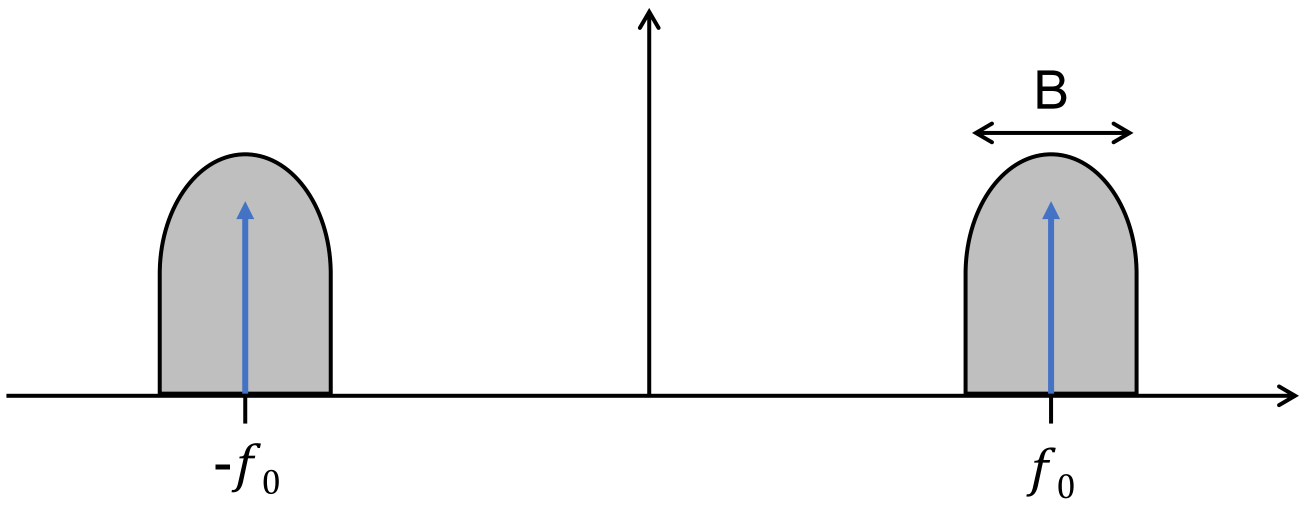
- Fundamental frequency phasors → Phasor Measurement Unit
- Harmonics and interharmonics
- Supraharmonics
- Point-of-wave
- …



Which is the measurand under dynamic conditions?

Amplitude, frequency and phase angle are not constant

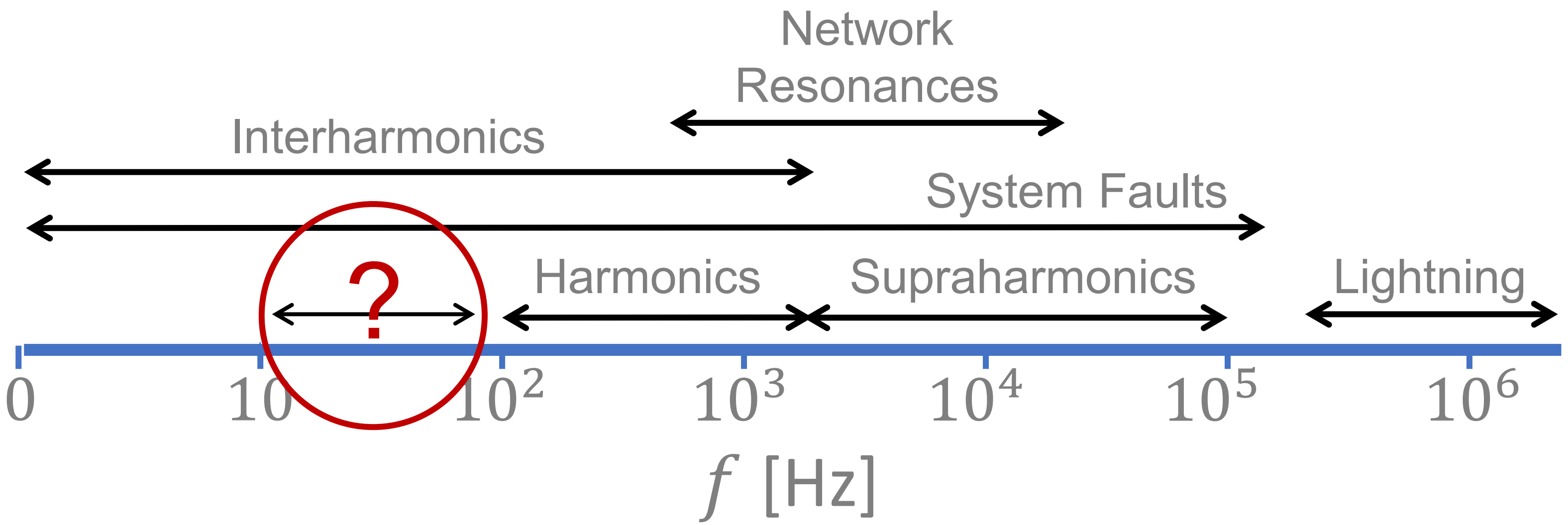




The signal of interest is a passband signal around the nominal frequency f_0

Measurements are time-tagged, so the behaviour can be followed

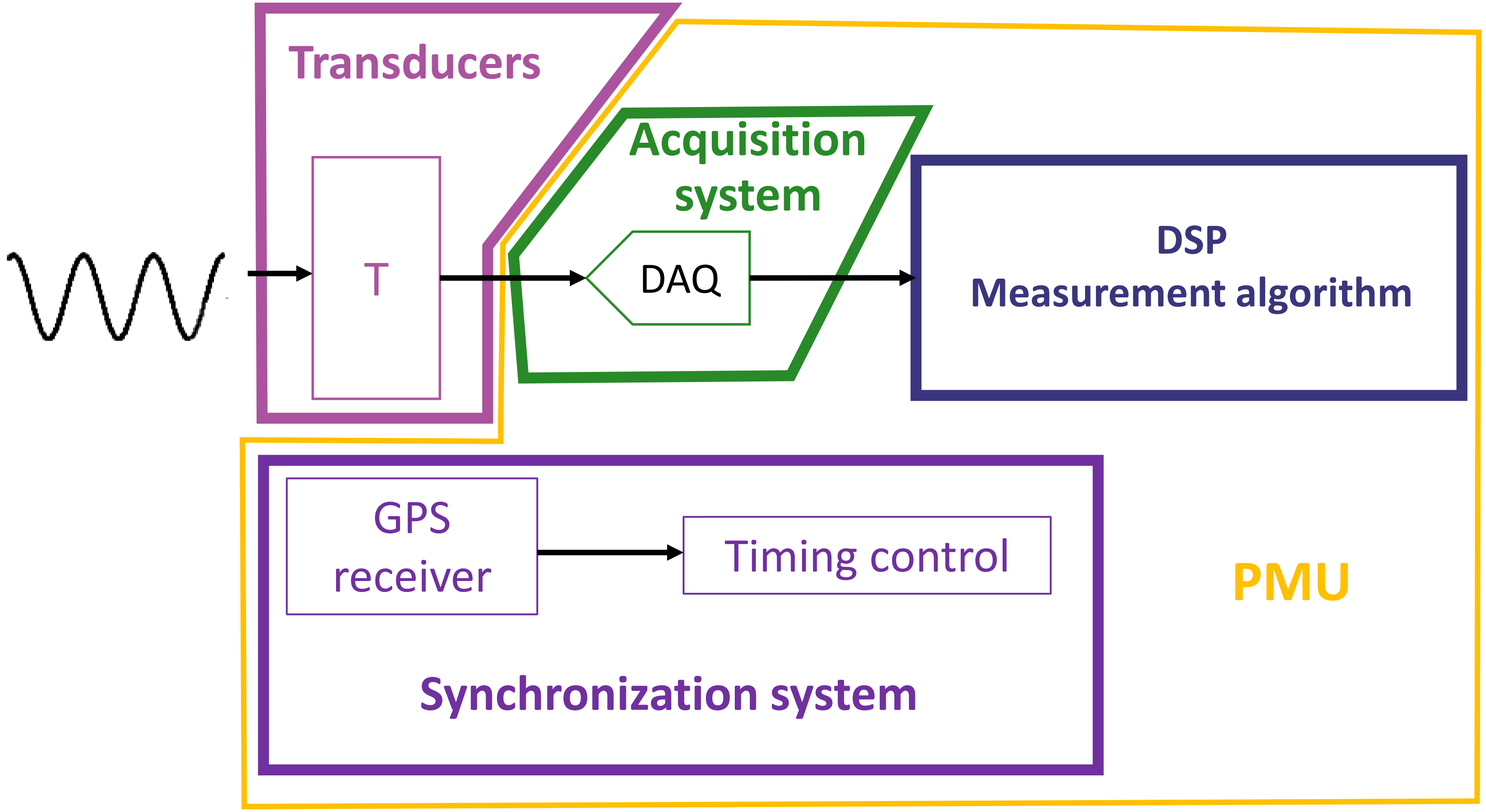
- The instrument must ***follow*** the signal of interest, "the measurand"
- The instrument must ***cancel*** the undesired components, i.e. "the disturbances"



Measurement chain

Every element of the chain is a source of uncertainty/error

The measurement method does not represent the overall measurement accuracy.



P. Castello, C. Muscas, P. A. Pegoraro, “Statistical Behavior of PMU Measurement Errors: An Experimental Characterization.” In press in IEEE Open Journal of Instrumentation and Measurement, 2022.
P. Castello, G. Gallus, C. Muscas, P. A. Pegoraro, D. Sitzia and S. Sulis, "A Statistical Investigation of PMU Errors in Current Measurements," 2023 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Kuala Lumpur, Malaysia, 2023, pp. 1-6, doi: 10.1109/I2MTC53148.2023.

PMU must comply with

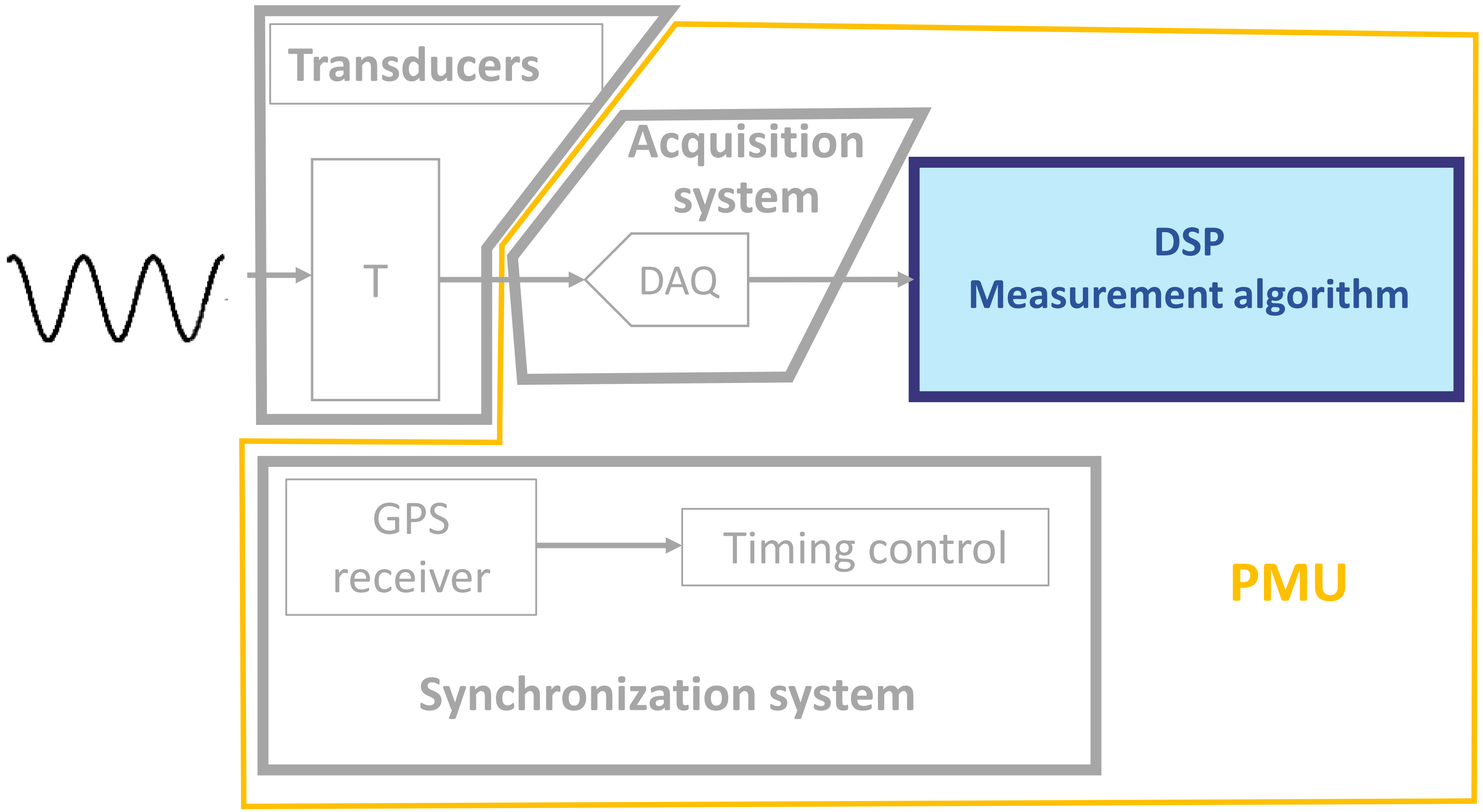
- IEC/IEEE 60255-118-1-2018 Measuring relays and protection equipment – Part 118-1: Synchrophasor for power systems – Measurements → for **metrological performance**

Several tests under different conditions

- IEEE C37.118.2-2024 IEEE Standard for Synchrophasor Data Transfer for Power Systems → for **data transmission**

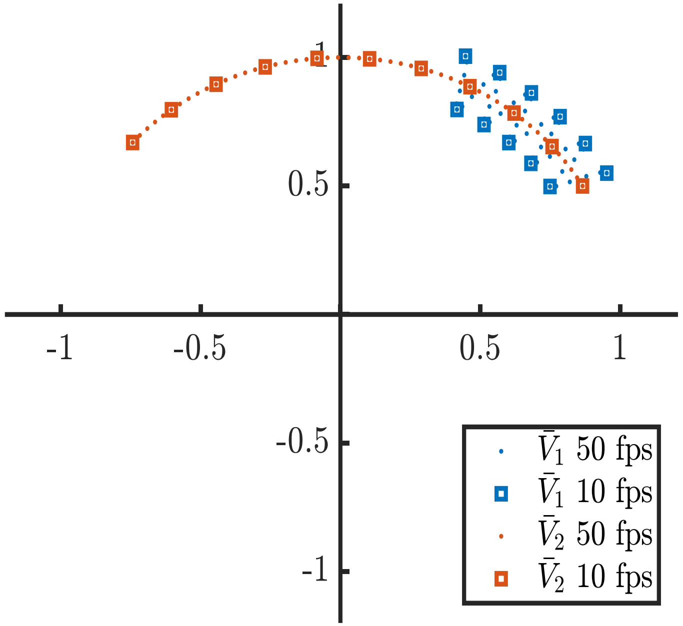
Transmission protocol

The measurement method plays a critical role under dynamic conditions



To track fast changes PMUs should have:

- High reporting rate
- High accuracy
- Low response time



To help control actions, PMUs should also have:

- Low latency

To be “reliable”, PMUs should also have:

- Stable metrological behaviour
- No “bad data”

PMU standard provides **dynamic** test conditions:

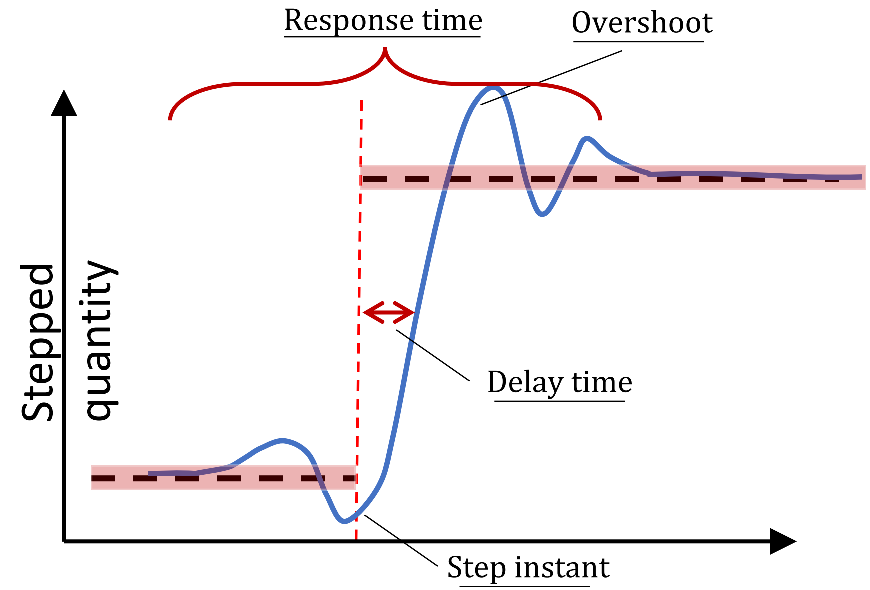
- Amplitude modulated signals
- Phase (i.e. frequency) modulated signals

Limits in terms of:

- Total Vector Error (TVE)
- Frequency Error (FE)
- ROCOF Error (RFE)

PMU standard provides **step** test conditions:

- Amplitude step test
- Phase step test



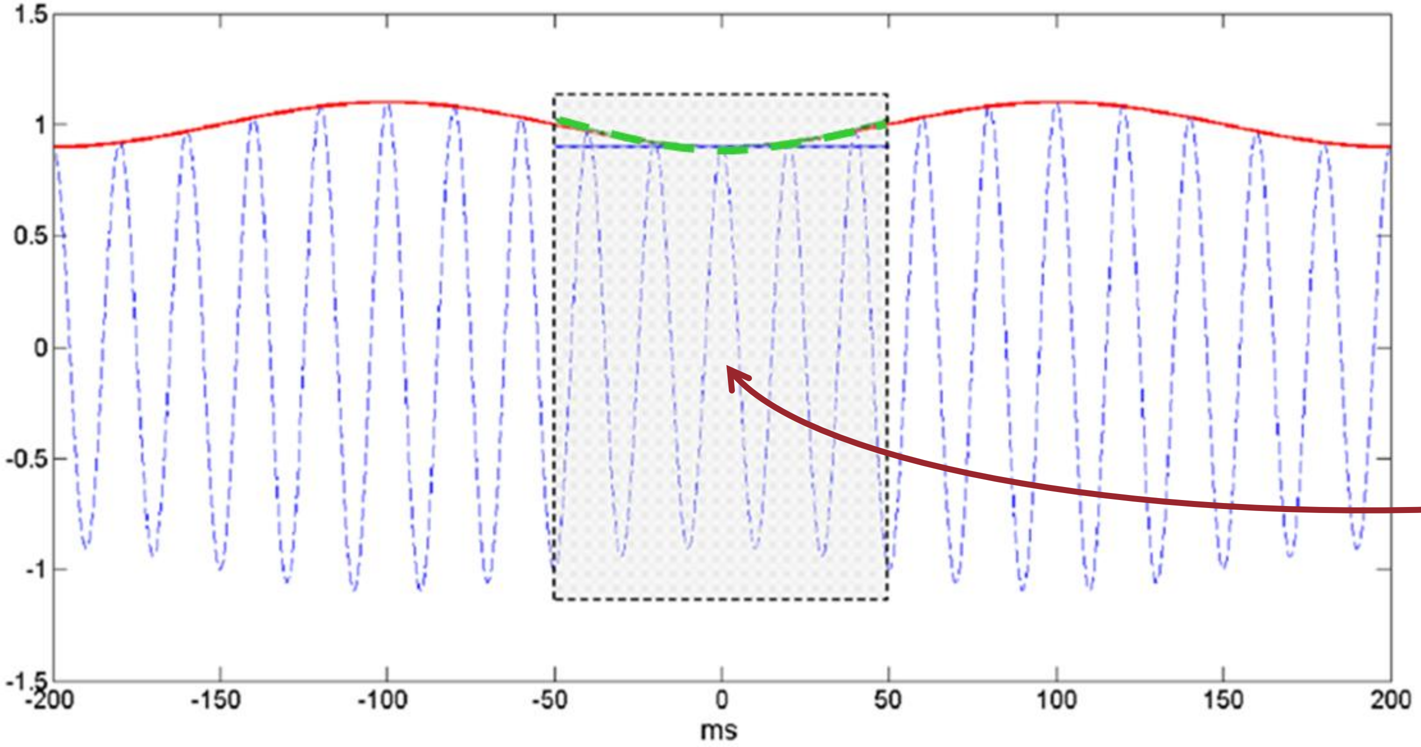
Limits in terms of:

- Response time
- Delay time
- Over/Undershoot

To improve accuracy:

- Improve the signal model using an intrinsically dynamic model
- Reject disturbances like harmonics, noise, etc.

Taylor-Fourier Multifrequency Model (TFM)



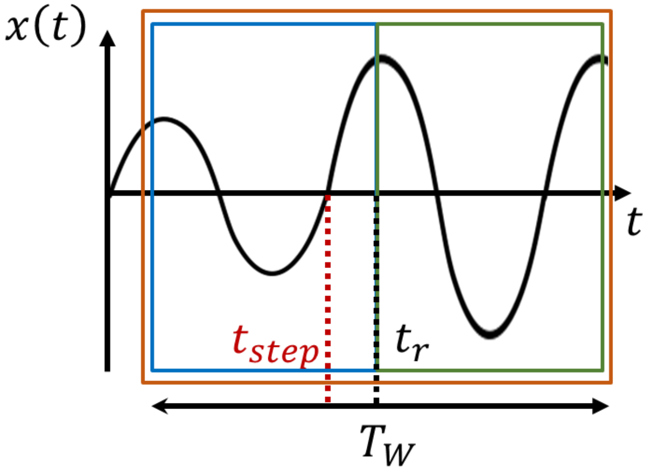
phasor described through a polynomial expansion around the measurement instant (timestamp)

Tracking fast changes

To improve response time, we need to reduce the effect of abrupt changes:

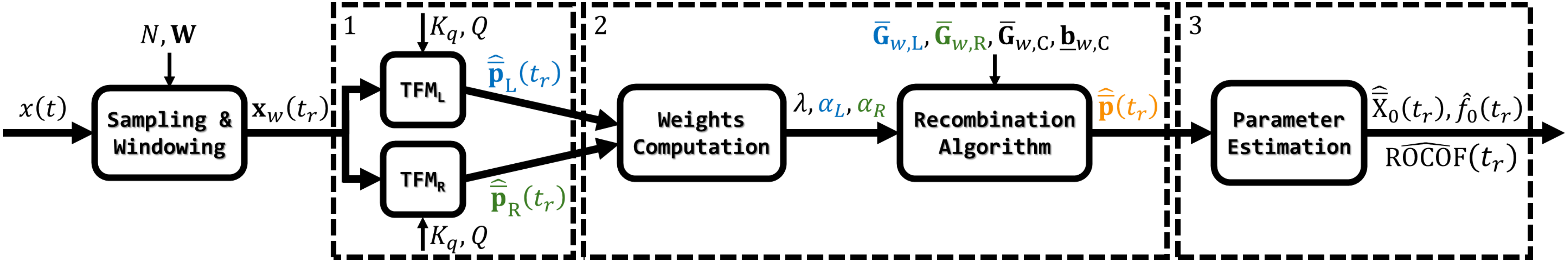
Model split into **left and right side** (with respect to the measurement instant t_r):

- Discontinuity detected in one of the two portions
  → Model matching on the other portion to minimize estimation errors, overshoots and oscillatory trends
- Fast transients not detected
  → The TFM model covers the full window, which guarantees the best rejection of quasi-stationary disturbances



Amplitude step detected in **left sub-window**

Model defined mainly in the **right sub-window**



- Collect samples around measurement instant
- Compute left and right estimates
- Computes the weights to recombine the estimates
- Estimate phasor, frequency and ROCOF

Automatic model definition: valid for both steady-state and dynamic conditions

G. Frigo, G. Gallus, P. A. Pegoraro and S. Toscani, "Combining Steady-State Accuracy and Responsiveness of PMU Estimates: An Approach Based on Left and Right Taylor–Fourier Expansions," in IEEE Transactions on Instrumentation and Measurement, vol. 73, pp. 1-13, 2024, Art no. 9002713, doi: 10.1109/TIM.2024.3384553.

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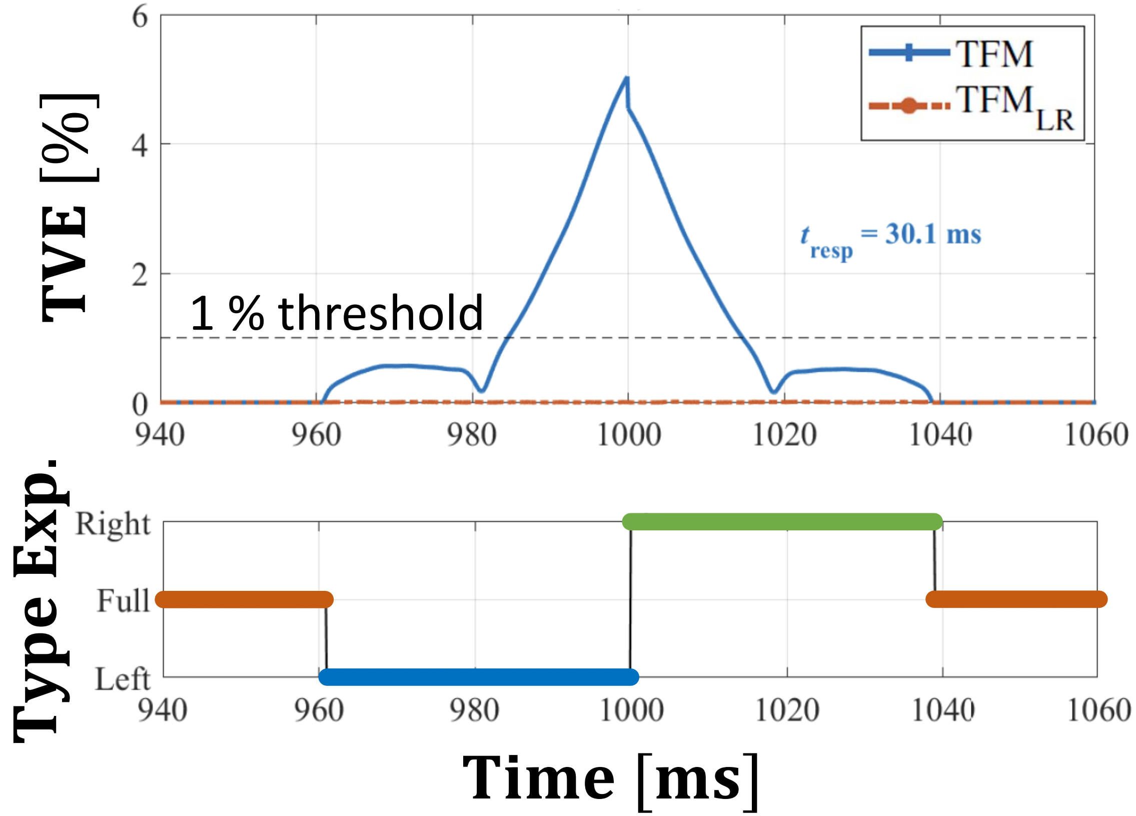
P-class PMU

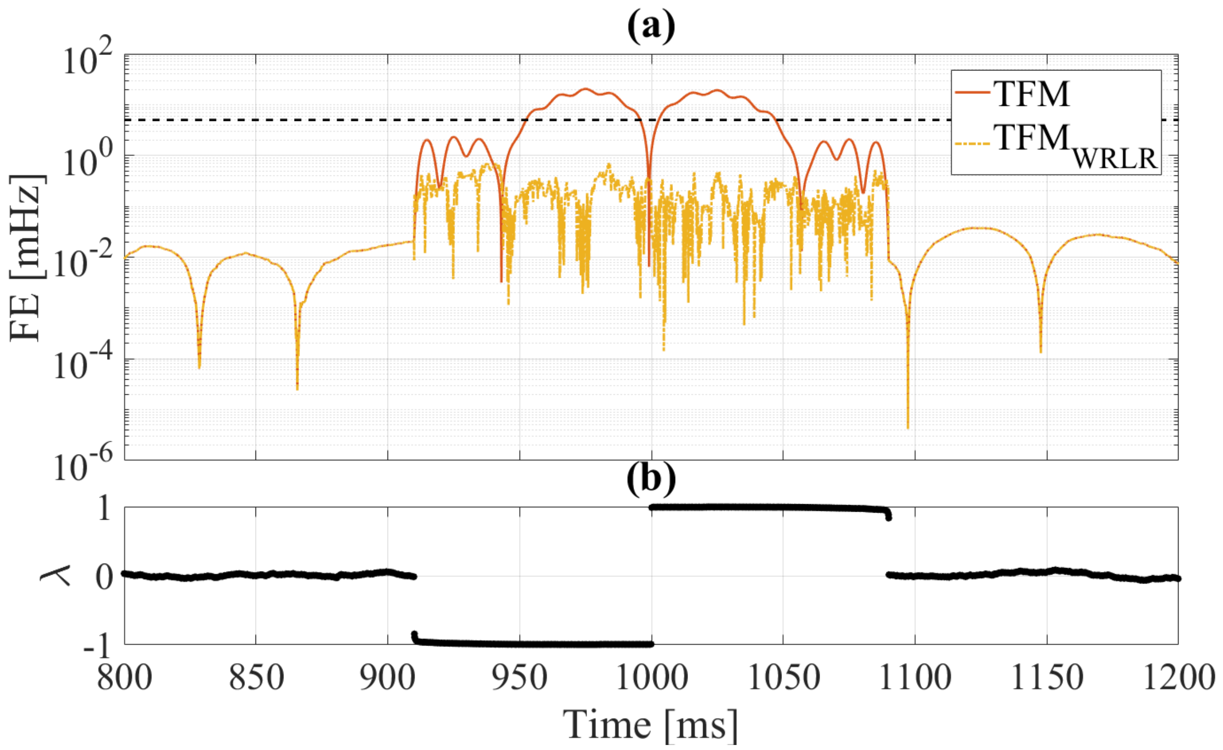
Amplitude step test with SNR = 80 dB



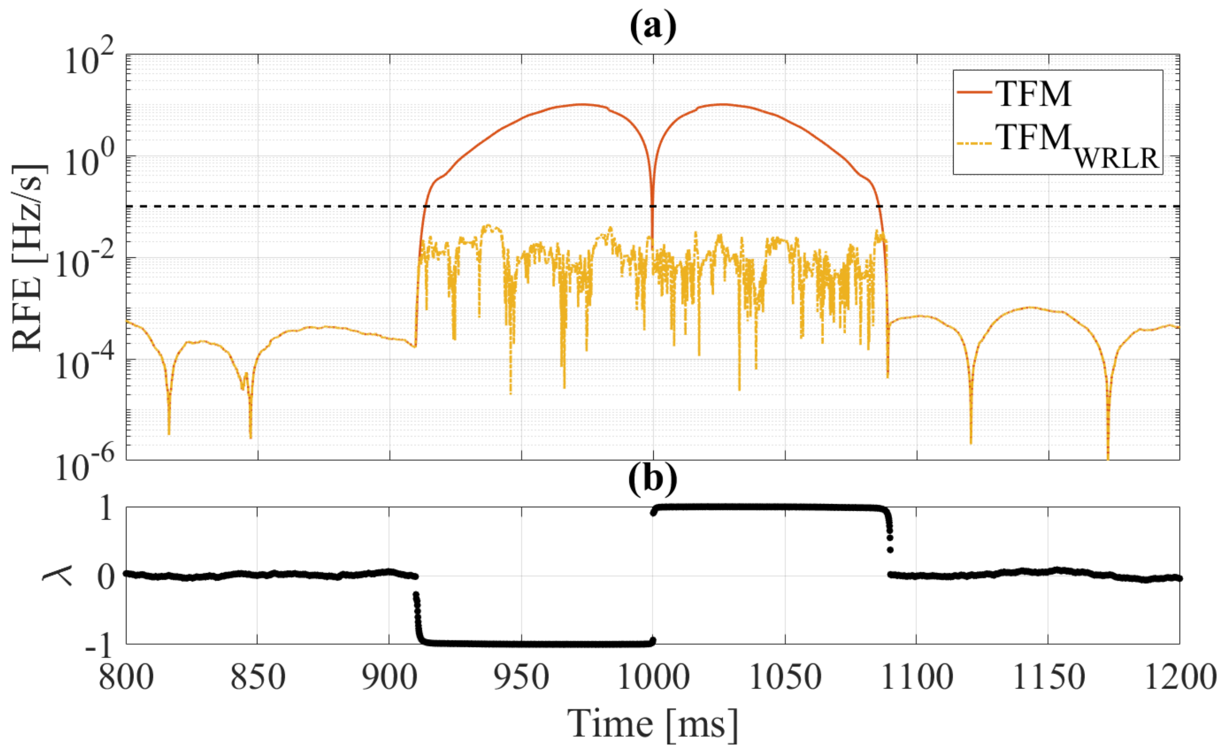
M-class PMU

Algorithm	RR [fps]	TVE response time [ms]	
		Amplitude step	Phase step
IEEE 60255-118-1:2018 M	60	-	66.0
IREQ FIR-M Non-Causal	60	30.6	37.5
M-MW-FIR	50	61.6	76.9
PMU Algorithm P+M	50	18.0	22.0
i-IpDFT P+M	50	28.0	32.0
HT-IpDFT P+M	50	22.9	26.4
FiIpDFT P+M	50	28.1	34.1
eIpD2FT M	50	14.0	24.0
Space Vector M	50	37.5	42.5
Conventional TFM M	50	42.5	50.1
Proposed TFM_{WRLR} M	**50**	**0**	**0**

Frequency measurement



ROCOF measurement



Much lower errors, effect of the transient almost negligible

No "invalid" data

Synchronize instrumentation via:

- Global Navigation Satellite Systems (GNSS) like GPS:
  - An antenna for each instrument
  - Need of line of sight to the sky

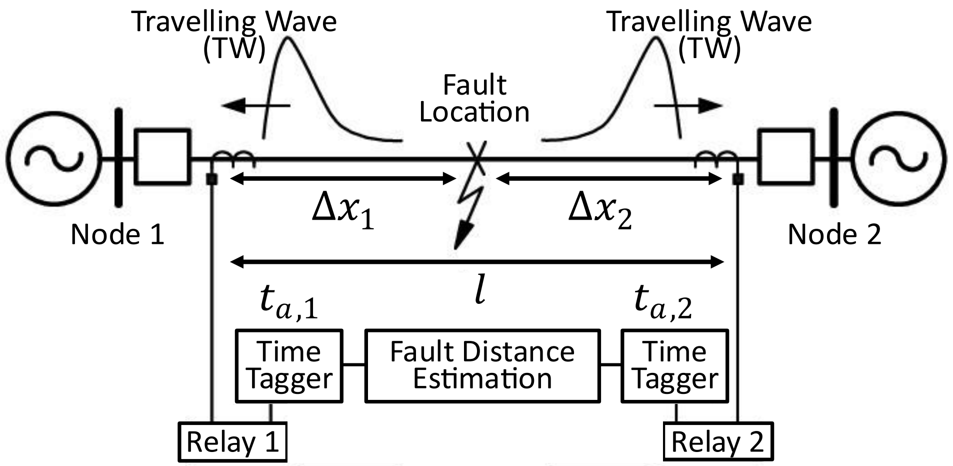
- Packet-switched based protocols:
  - Precision Time Protocol (PTP): Power Profile or Utility Profile
  - **White Rabbit (WR)? Is it feasible? Is it useful?**

Note: Italian Quantum Backbone (IQB) can carry WR

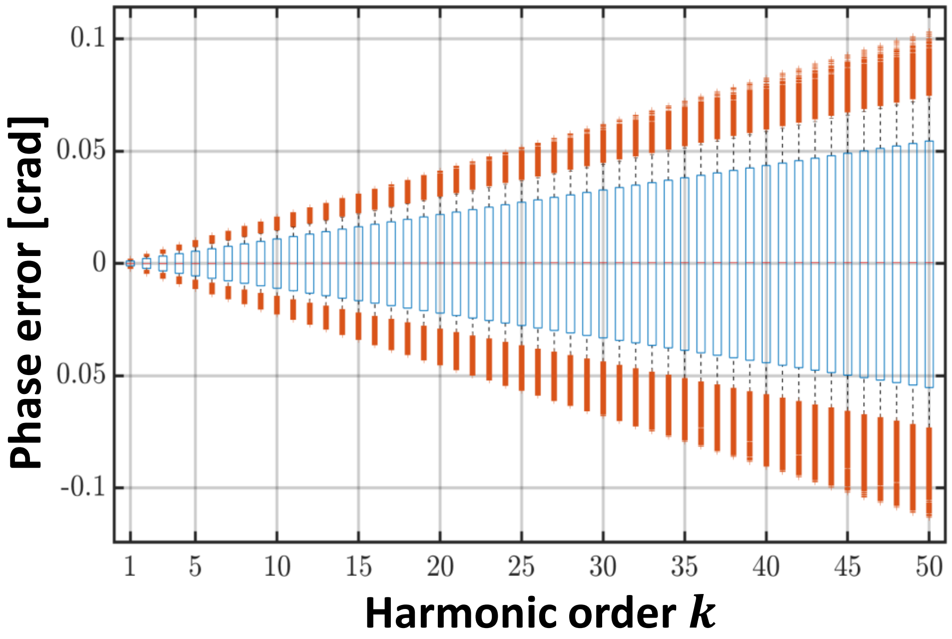
https://www.inrim.it/it/ricerca/infrastrutture/italian-quantum-backbone

Preliminary studies on practical application of **WR** to power systems:

- PMU synchronization
- Harmonic PMU synchronization
- SAMU synchronization
- Travelling wave fault location application



Boxplot of the phase error for WR Module case



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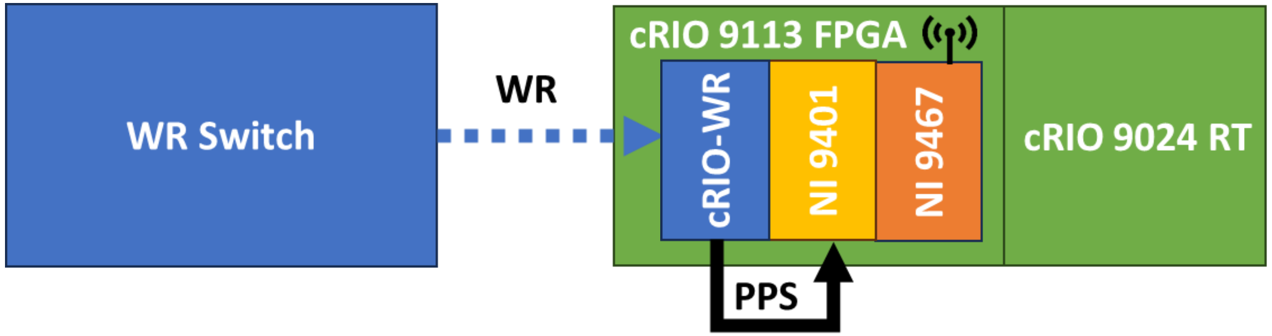

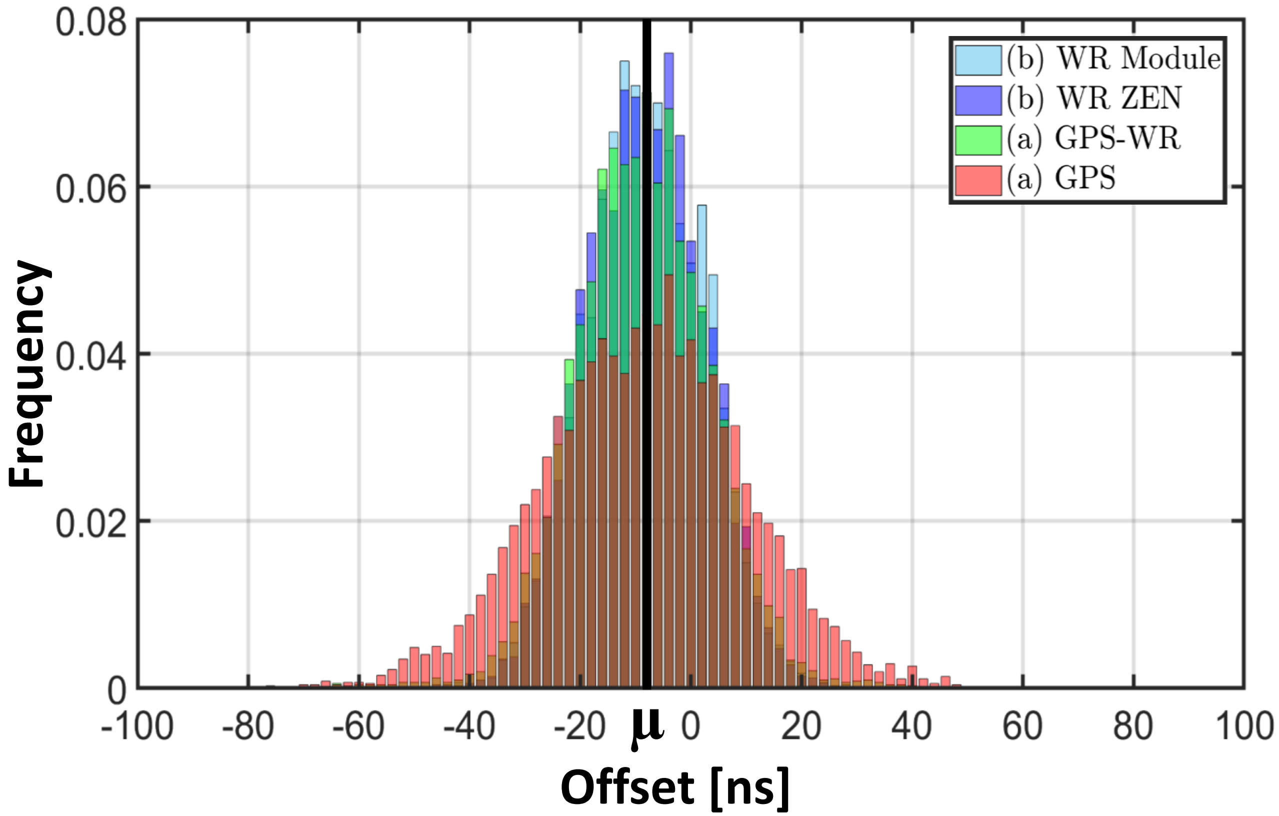

G. Frigo, P. Castello, G. Gallus, P. A. Pegoraro and S. Toscani, "Internal Time Reference Enhancement via White Rabbit Synchronization: A Power System Measurement Perspective," 2024 International Conference on Smart Grid Synchronized Measurements and Analytics (SGSMA), Washington, DC, USA, 2024, doi: 10.1109/SGSMA58694.2024.

Data quality requires:

- Methods to tell anomalies in measurement data from real events and grid phenomena
- Methods to tell local from global events from synchronized data
- Methods applicable to different types of data:
  - PMU data
  - Synchronized waveform data (Sampled Values, SVs)

Fast, scalable and modular methods can be implemented in:

- Merging Units
- IEDs
- …

European Project GridData (24DIT05) “Metrology for reliable power grid data analytics”

- Aim: Develop a metrological framework to test and validate grid data analysis methods
- This involves:
  - **Quantification of data quality** of measurement data
  - Generation of simulated data to complement measurement data
  - Extensive testing of algorithms incl. AI/ML-based methods
- Targeted grid phenomena:

  Frequency deviations – Sub-synchronous oscillations –

  Power quality disturbances – Grid asset faults – Congestion forecasting

- Data analysis must be fast and with few parameters to tune
- Both algorithmic, statistical, and machine learning methods need to be explored

Example:
Matrix Profile (time series analysis) for PMU and SV data

- Immediate interpretation
- Very simple to use
- Many routines available

Example: MP for PDC enhancement

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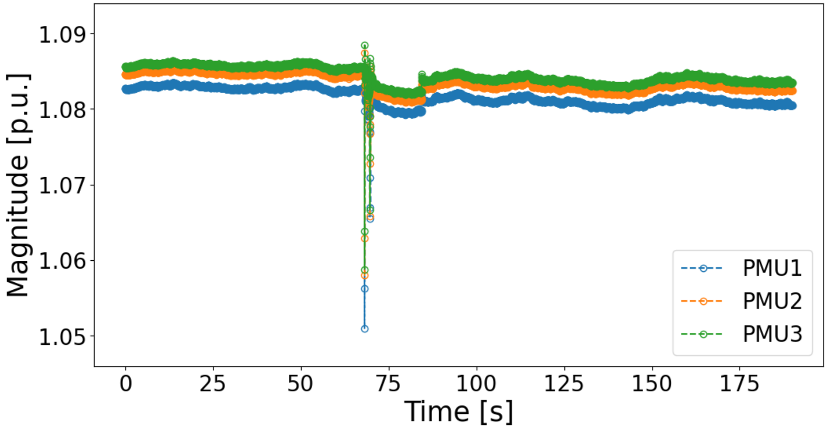
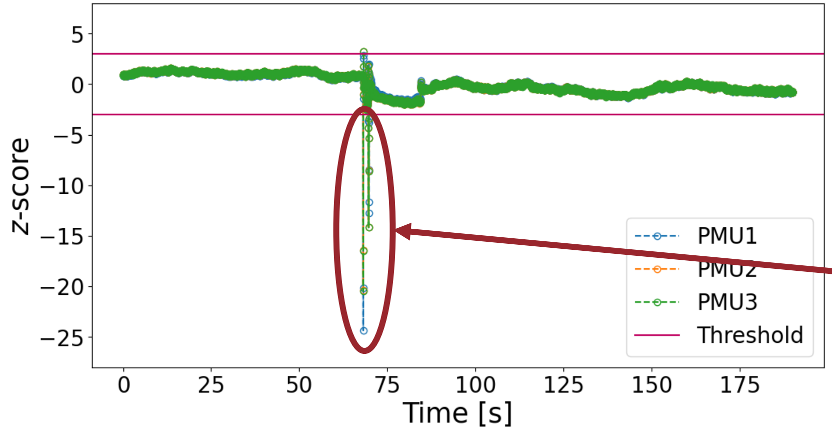
Analysis of PMU magnitude measurements

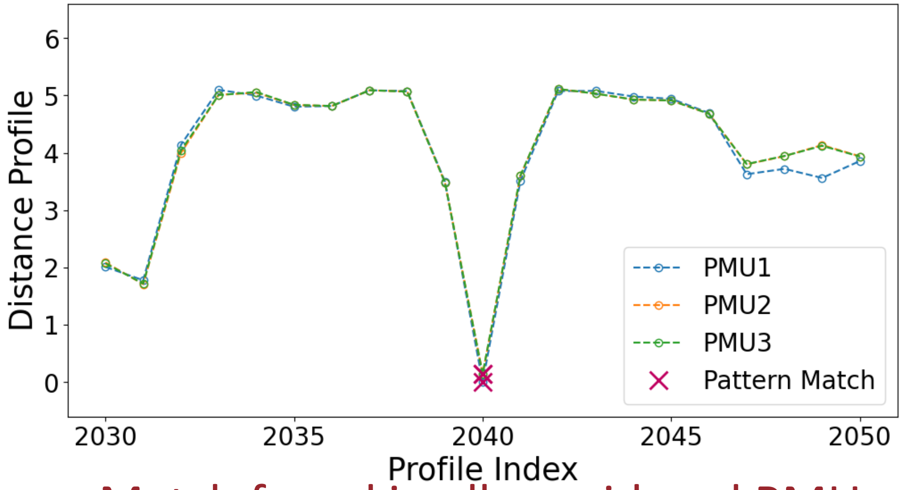




MP score computation

- All three PMUs exceed threshold
- Presence of a disturbance

Reference pattern extraction

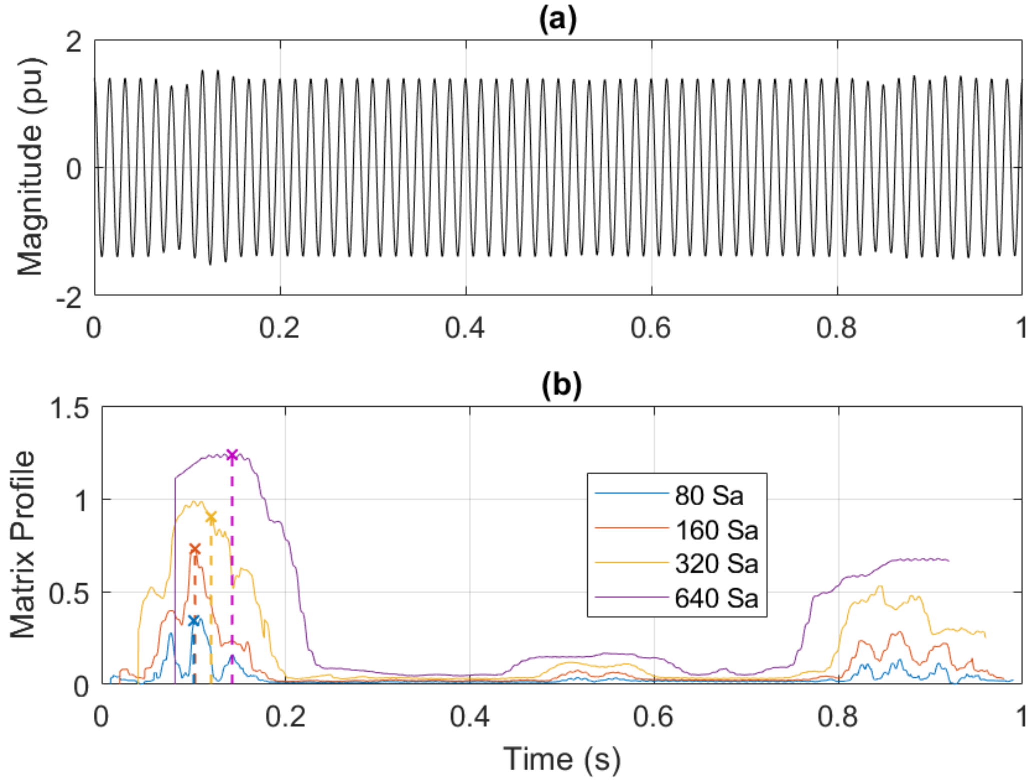


Match found in all considered PMUs → Event classified as **global**

P. Castello, D. Sitzia, S. Sulis and G. Frigo, "Utilizing Matrix Profile for Enhanced Detection of Events in Sampled Values," 2024 IEEE 14th International Workshop on Applied Measurements for Power Systems (AMPS), Caserta, Italy, 2024, doi: 10.1109/AMPS62611.2024.10706669.

Example: MP for SV analysis

- Waveforms can also be analyzed to find relevant events
- Merging Unit can become decentralized screening elements
- A single parameter need to be optimized (sequence length)



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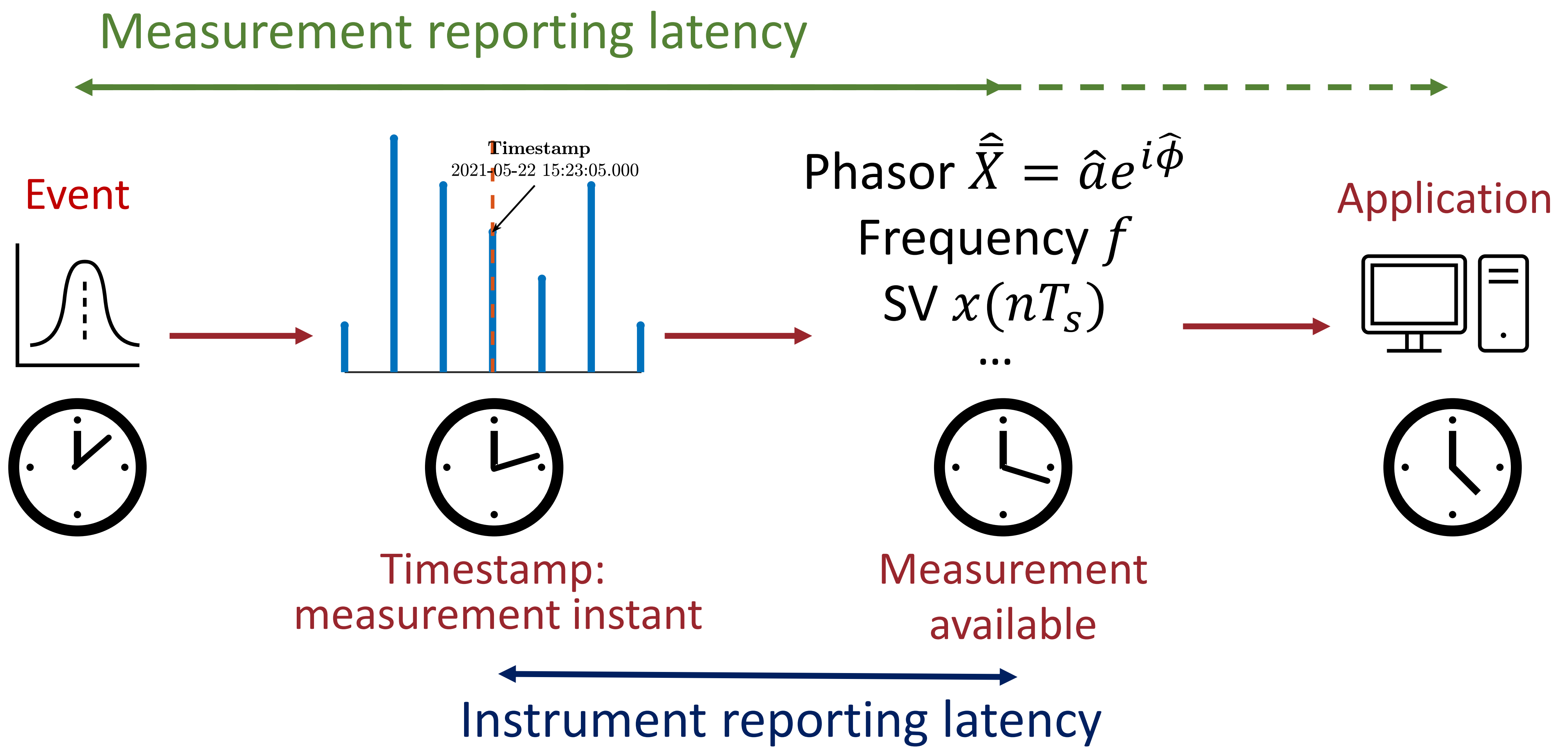
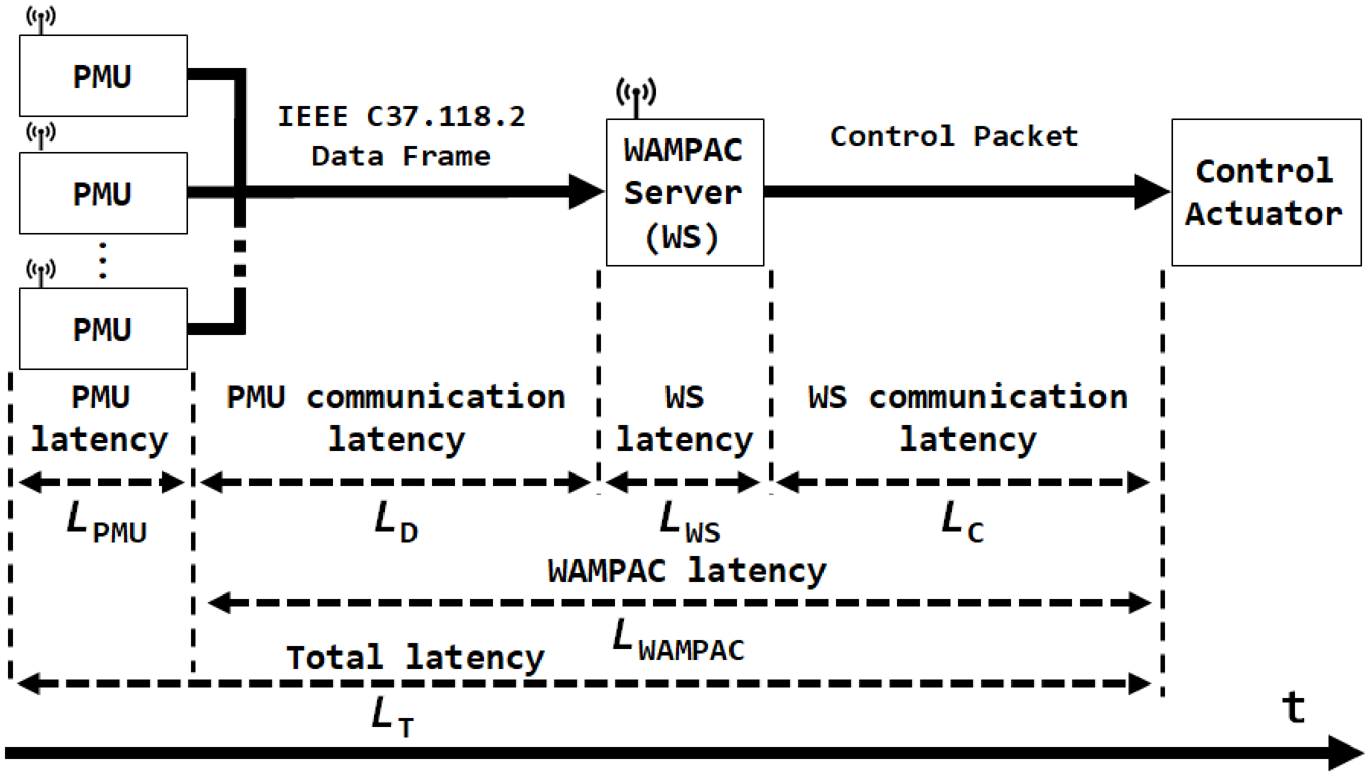
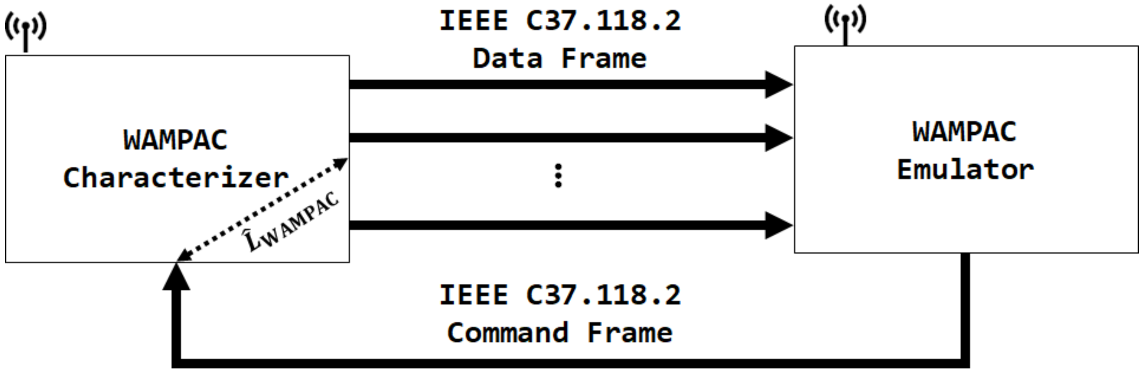
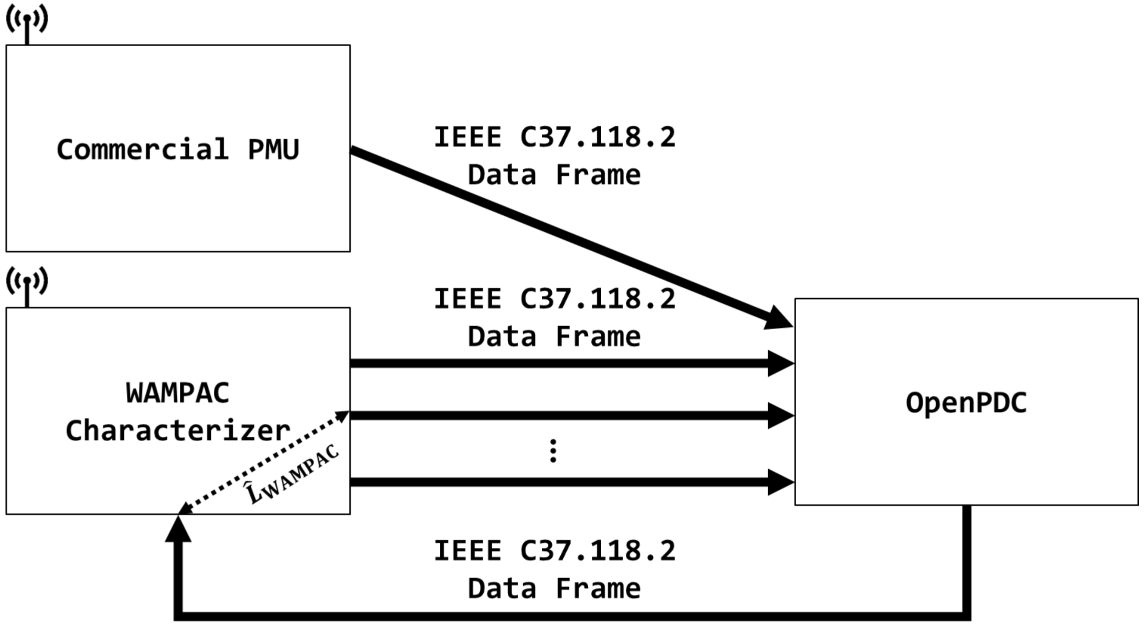


Measurement reporting latency
Event
Timestamp
2021-05-22 15:23:05.000
Phasor $\hat{\bar{X}} = \hat{a}e^{i\hat{\phi}}$
Frequency f
SV $x(nT_s)$
...
Application
Timestamp:
measurement instant
Measurement
available
Instrument reporting latency

- Instrument latency is characterized in the laboratory and depends on reporting rate, processing time, transmission time, …
- The **measurement reporting latency** is the key parameter of interest for **control applications**
- An **instrument** or a **framework** is needed to assess the overall latency in realistic conditions and in a real **WAMS** or **WAMPAC** system.







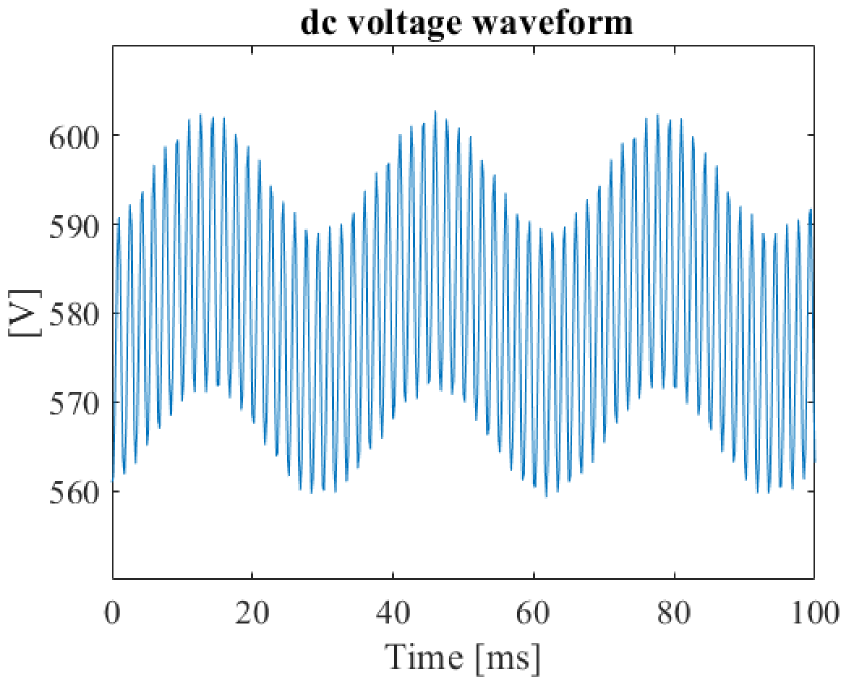
Design and test of a Characterizer for WAMPAC latency

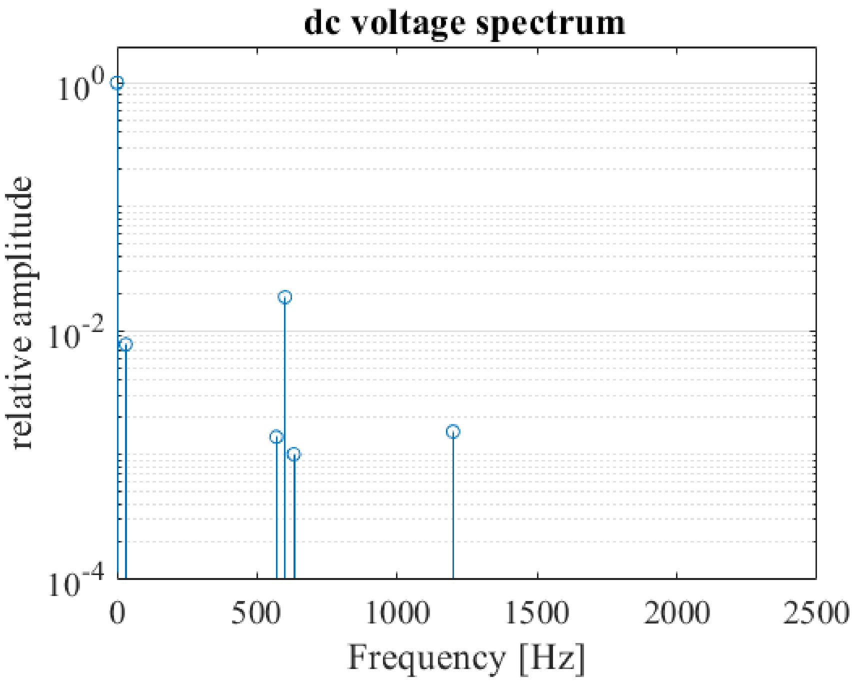
Real field testing through the Characterizer of an OpenPDC-based WAMPAC

P. Castello, G. Gallus, C. Muscas, P. A. Pegoraro, D. Sitzia, L. Campisano, G. M. Giannuzzi, C. Maiolini, P. Pau, "Latency Characterization of a Wide Area Monitoring Protection and Control Application in the Italian Transmission System," 2022 IEEE 12th International Workshop on Applied Measurements for Power Systems (AMPS), Cagliari, Italy, 2022, doi: 10.1109/AMPS55790.2022.9978892.

P. Castello, G. Gallus, P. A. Pegoraro, S. Sulis, "Measurement Platform for Latency Characterization of Wide Area Monitoring, Protection and Control Systems," in IEEE Transactions on Instrumentation and Measurement, vol. 73, pp. 1-12, 2024, Art no. 5500812, doi: 10.1109/TIM.2023.3334360.

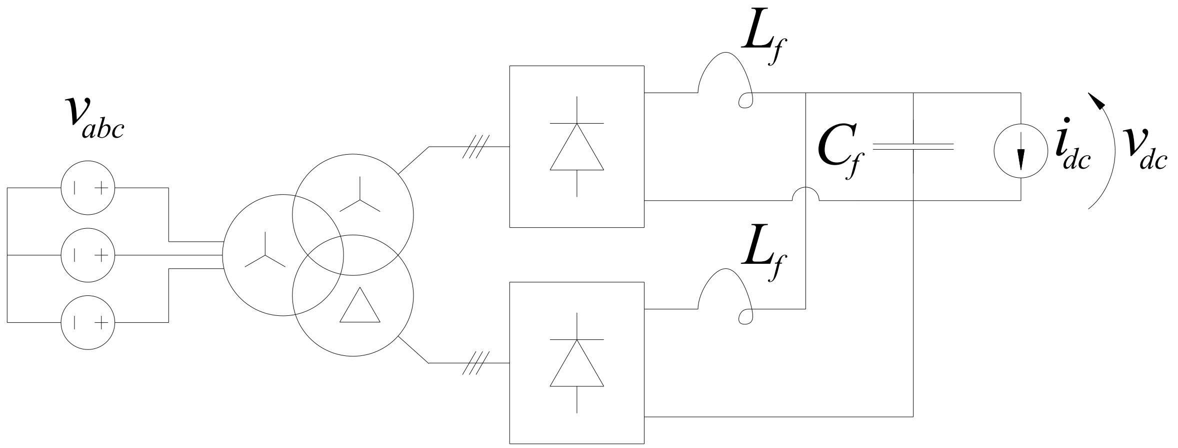
- Are synchronized measurement useful in DC systems?
- Are they feasible?
- What can they reveal?



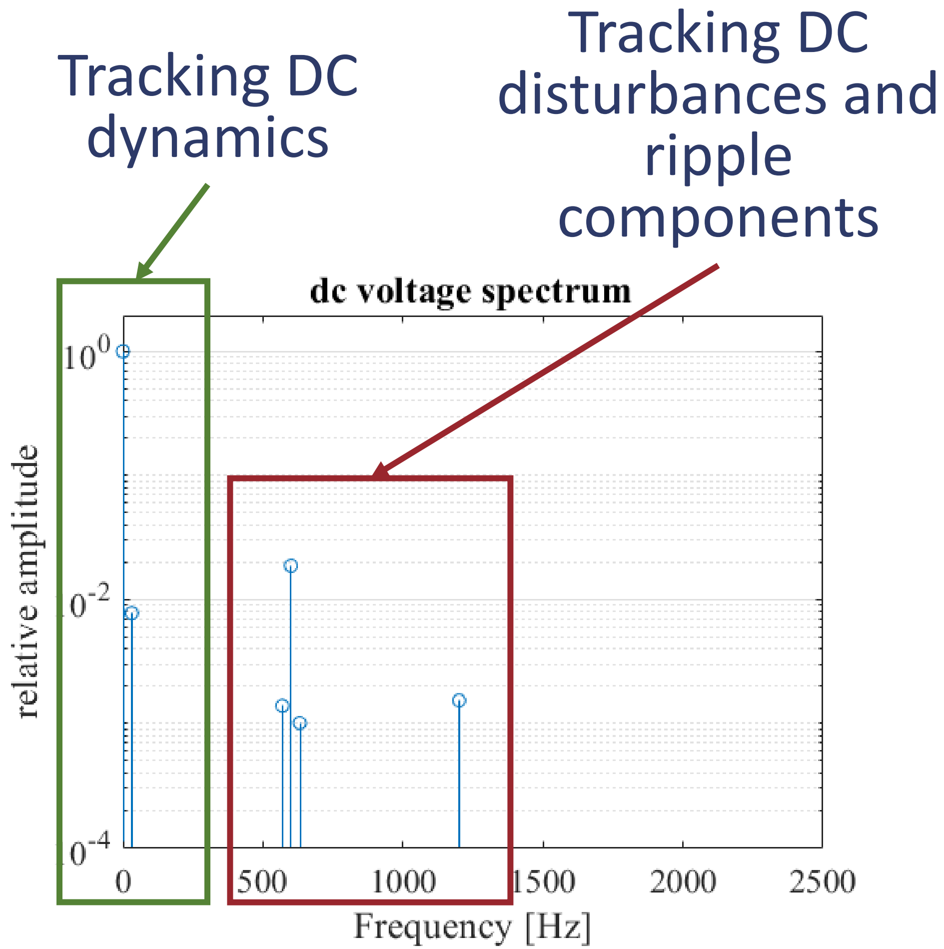


A new **synchronized** instrument to:

- Follow DC evolution
- Identify ripple components and track them



Example: rectifier like in tramway supply



M. Zanoni, R. Chiumeo, L. Tenti, C. Laurano, S. Toscani and P. A. Pegoraro, "Synchronized Measurements for Monitoring Power Quality in DC Systems: A Proposal," 2023 IEEE 13th International Workshop on Applied Measurements for Power Systems (AMPS), Bern, Switzerland, 2023, doi: 10.1109/AMPS59207.2023.10297218.

R. Chiumeo et al., "Taylor–Fourier Multifrequency Approach to Power Quality Monitoring in DC Grids," in IEEE Transactions on Instrumentation and Measurement, vol. 74, pp. 1-13, 2025, Art no. 9004713, doi: 10.1109/TIM.2025.3568087.

Synchronized measurements for DC grids

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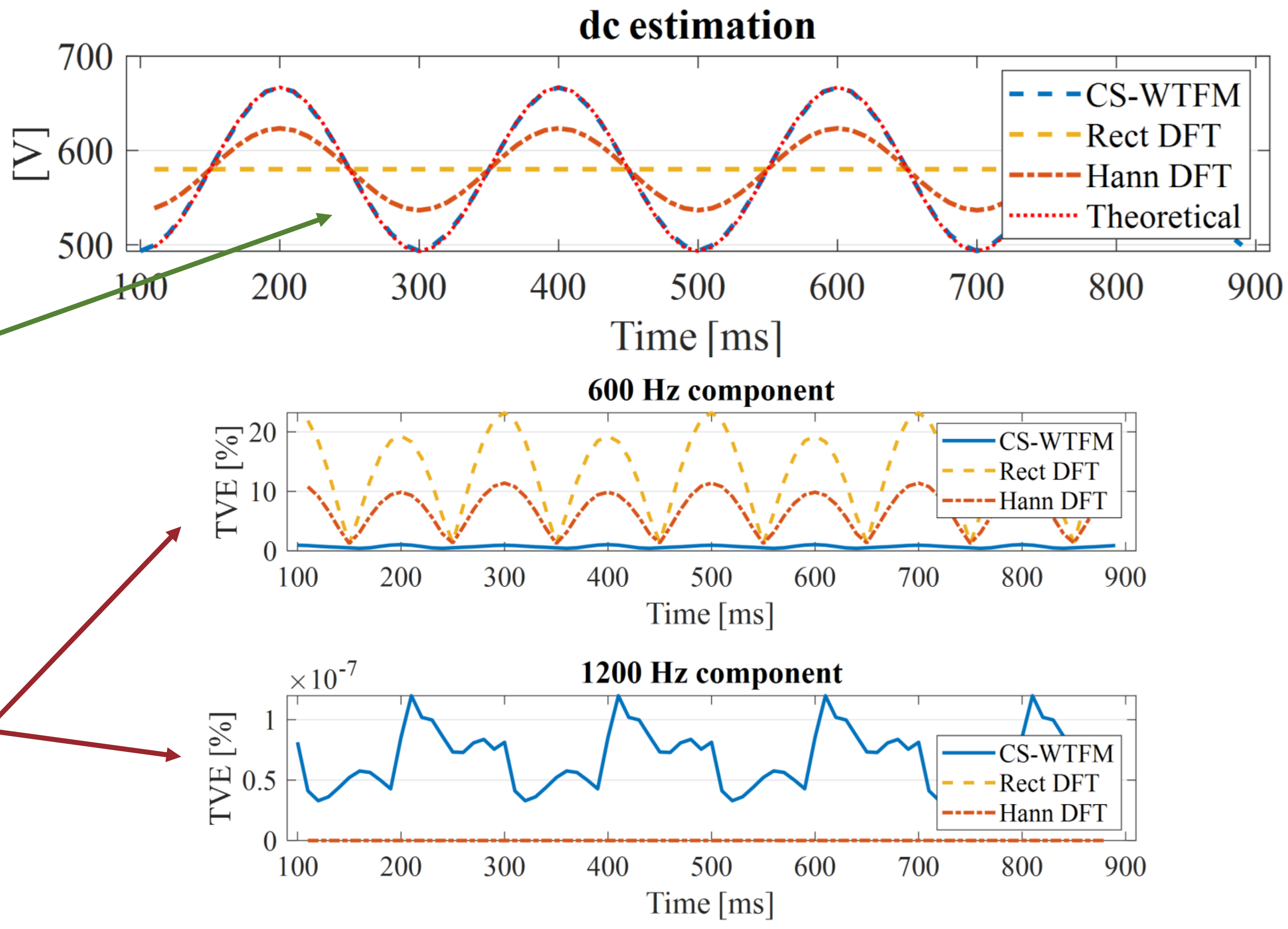
- High reporting rate
- Possibility to coordinate multipoint measurements

Tracking DC dynamics

Tracking even small alternate components with high accuracy



- Dynamic conditions require new measurements and ask for accuracy, synchronization, tracking etc.
- There is fervent activity on **new monitoring techniques** and strategies
- New algorithms are needed to deal with **fast and abrupt dynamics**
- **New synchronization** methods can unlock new applications
- Data analysis is mandatory to isolate **anomalies** and **find events**
- Applications (WAMPAC) require to monitor **latency**
- **DC grids** are a new field for **synchronized** measurements

Thank you for your attention!

for any additional question or further discussion,

please contact me at:

paolo.pegoraro@unica.it