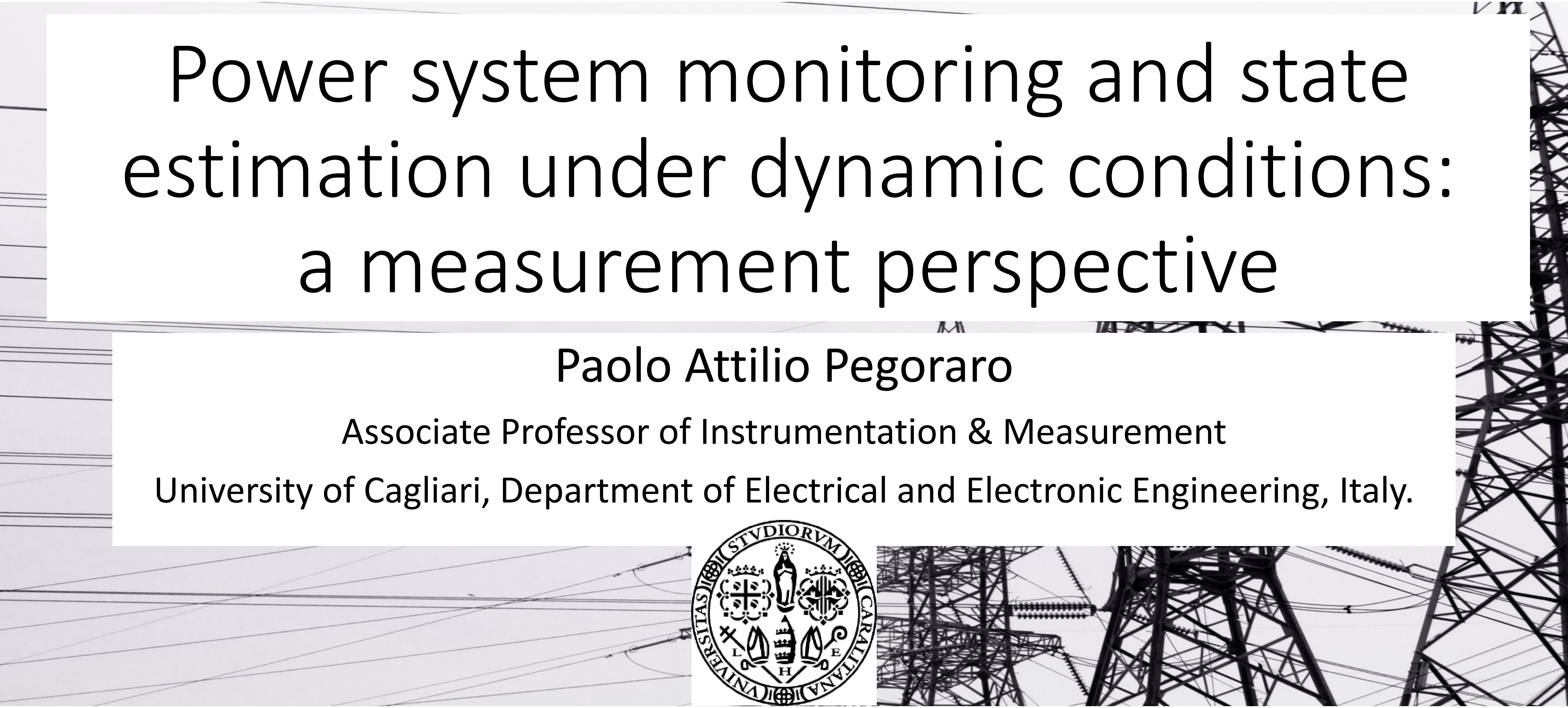
6 DynPOWER 2022

Typhoon HIL

Zürcher Hochschule
für Angewandte Wissenschaften
zh
aw
School of
Engineering
IEFE Institut für Energiesysteme
und Fluid-Engineering



Power system monitoring and state estimation under dynamic conditions: a measurement perspective

Paolo Attilio Pegoraro

Associate Professor of Instrumentation & Measurement

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

Outline

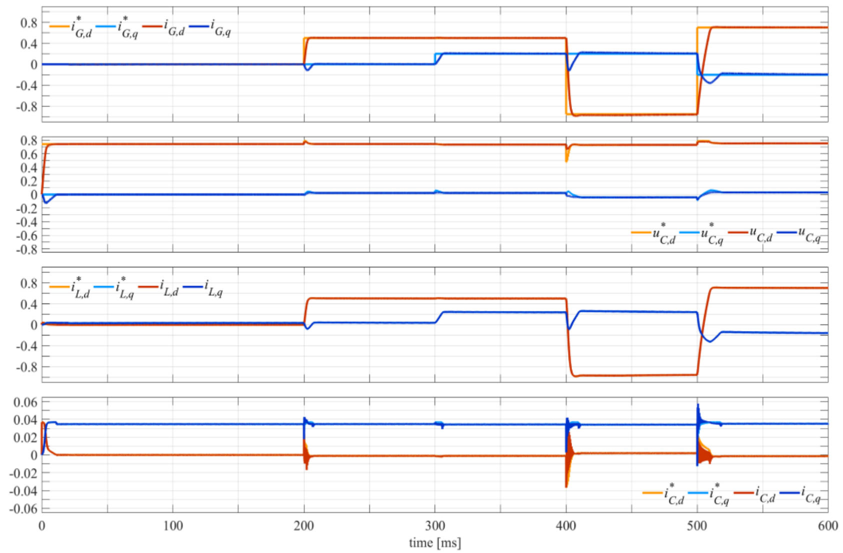
- Measurements in the presence of dynamic conditions
- The measurement process
- Synchronized measurements: models and issues
- Tracking signal evolutions
- State estimation in dynamic conditions

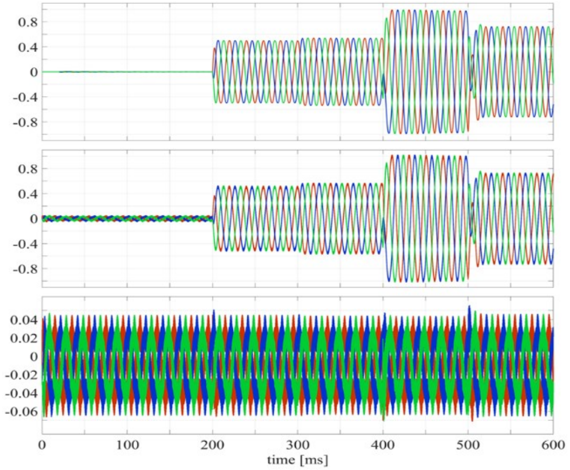
Dynamic conditions

- 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**.

Dynamic signals

- In the presence of renewable generation and intermittent loads, the signals become highly varying.
- In the presence of power converters and electronic loads the AC network signals can be highly non-sinusoidal.
- Thus, AC system usually operates in a **narrow band** around the nominal frequency.
- Transitions and evolutions occur in the DC links





Monitoring applications and requirements

Monitoring for **real-time** or **off-line applications**: billing, interarea oscillations detection, congestion/contingency management, stability verification, line parameter evaluation, fault detection, Power Quality monitoring, state estimation, post-mortem analysis,...

Requirements (application dependent) in terms of:

- **Accuracy** – instrument and conditions
- **Synchronization** – e.g. 100 ns → 10 ms → 1 s → no synch
- **Latency**, **bandwidth** – measurement and communication system
- **Computation** – e.g. centralized/decentralized system

“Local” and “global” monitoring

Depending on the application there are two types of measurements in power systems:

- **Local:** a single instrument or a single measurement point is involved. Measurements are focused on **accuracy** and **speed**.
- **Global:** measurements are needed across different subsystems and/or locations. Measurement methods and architectures are focused also on **coordination** (synchronization, bandwidth, algorithms, etc.)

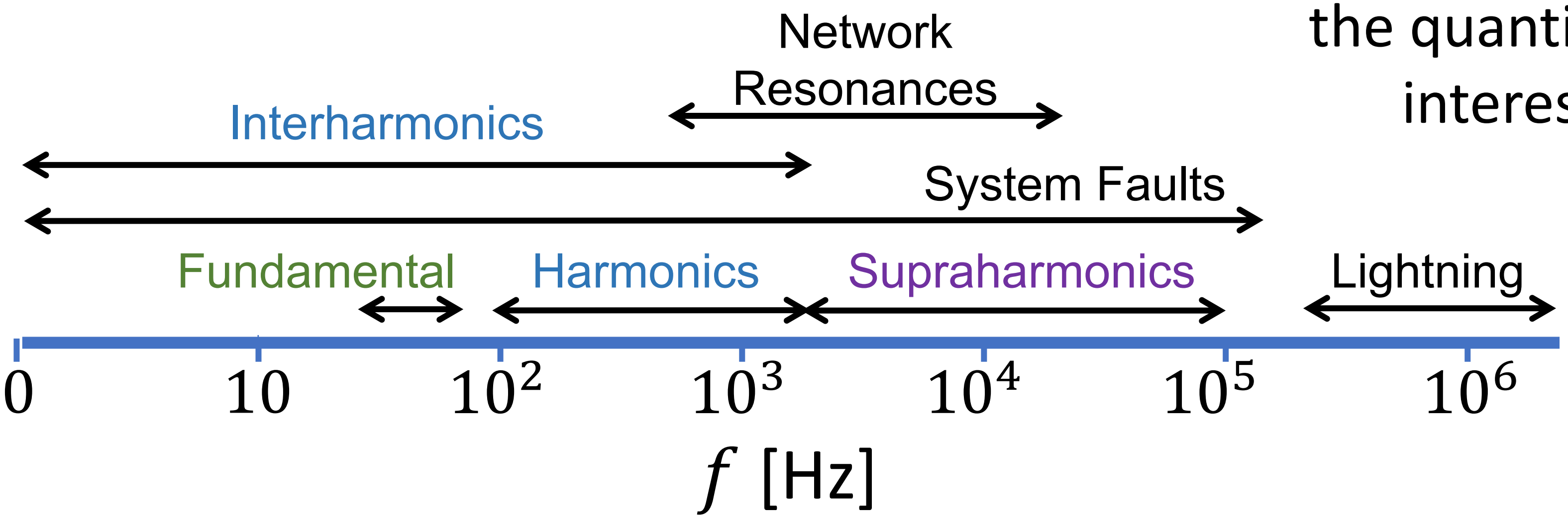
Measured quantities (AC systems)

Paolo Attilio Pegoraro

Different measurements for different monitoring applications:

- Fundamental frequency phasors
- Harmonics and interharmonics
- Supraharmonics
- Point-of-wave
- …

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

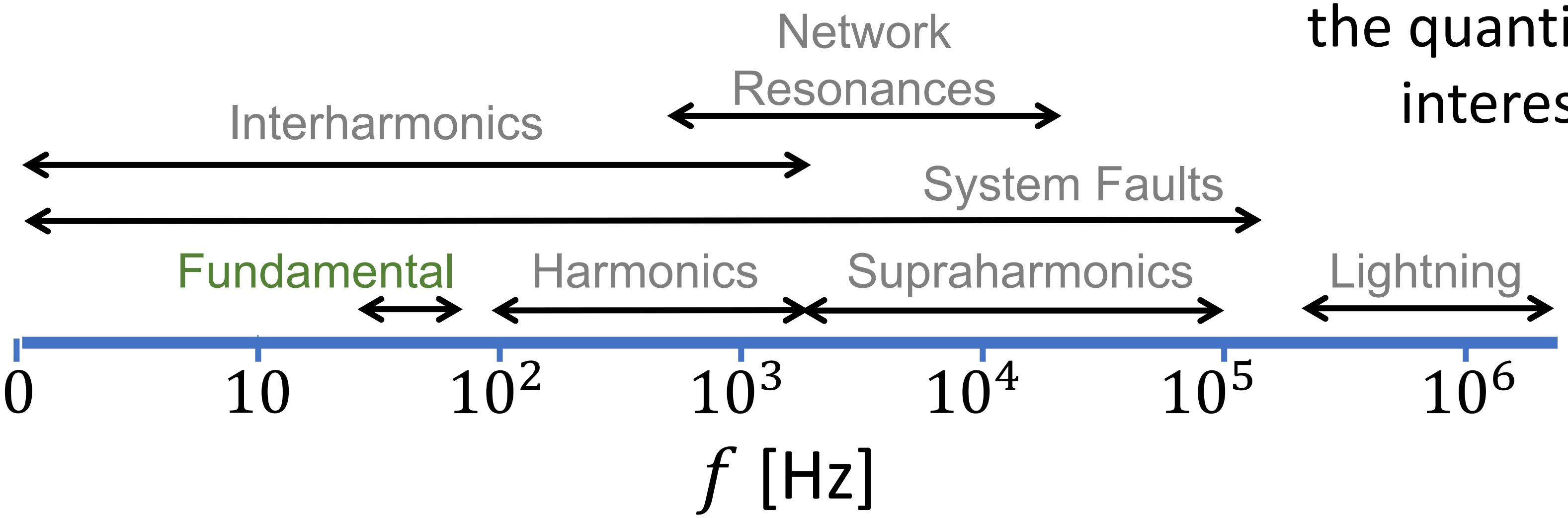


Measured quantities (AC systems)

Different measurements for different monitoring applications:

- Fundamental frequency phasors
- Harmonics and interharmonics
- Supraharmonics
- Point-of-wave
- …

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



Dynamic synchrophasor

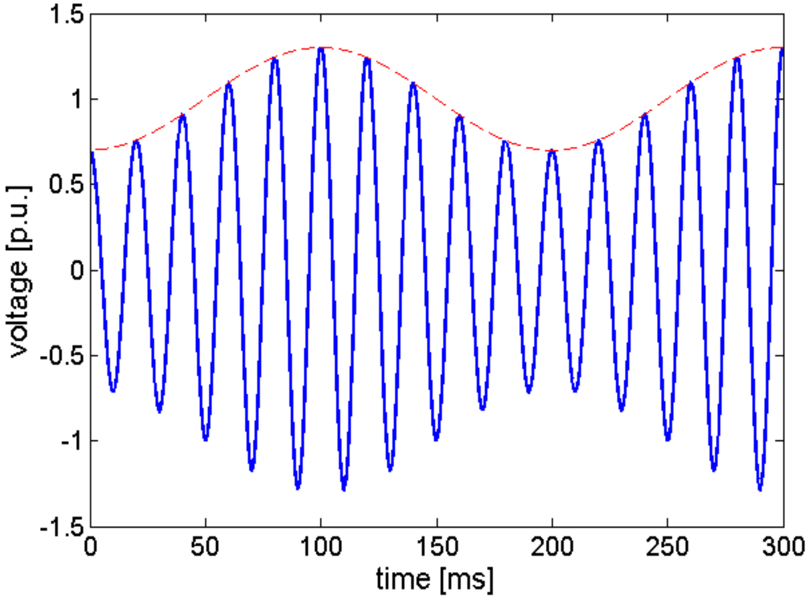
- Signal ($t_{ref} = 0$ for the sake of simplicity):

$$x(t) = X_m g(t)\cos(\omega_0 t + \varphi(t)) \qquad \text{with } \omega_0 = 2\pi f_0 \text{ (nominal)}$$

- Dynamic synchrophasor:

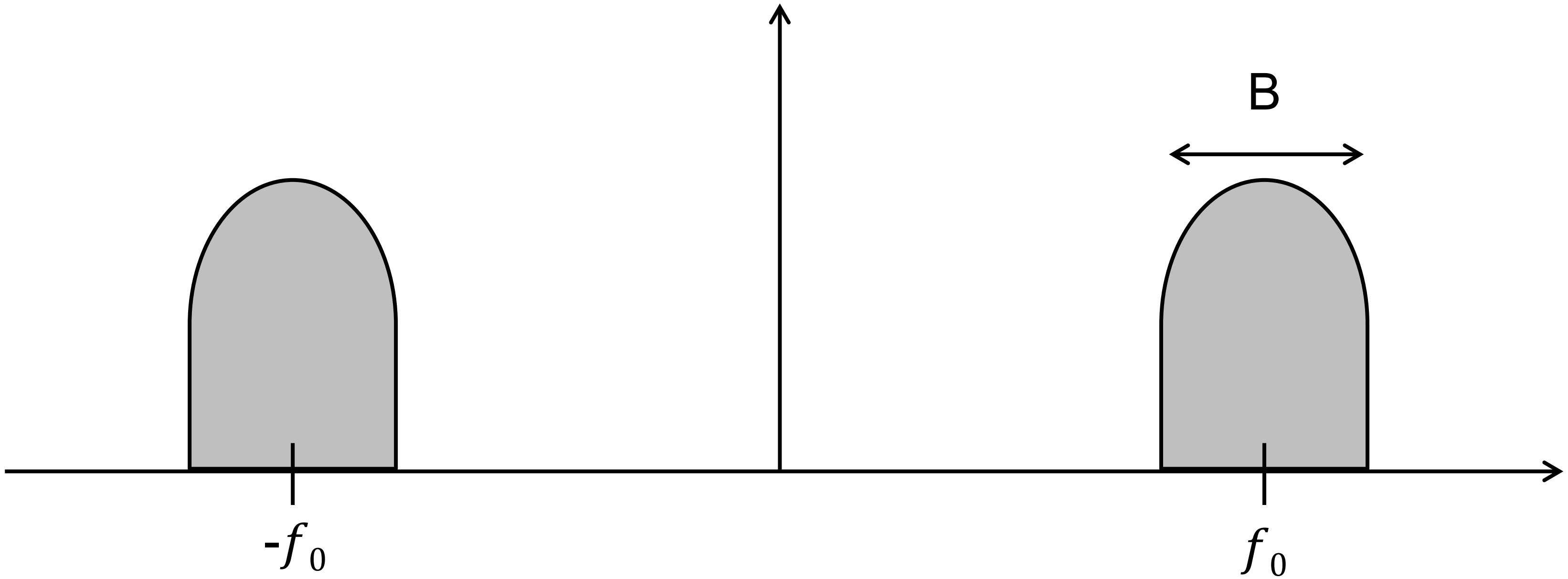
$$\bar{\mathbf{X}}(t) = a(t)e^{i\varphi(t)} = \frac{X_m g(t)}{\sqrt{2}}e^{i\varphi(t)} = X_r(t) + iX_i(t)$$

Amplitude and phase angle
are not constant
Frequency is not constant



Dynamic synchrophasor: measurand

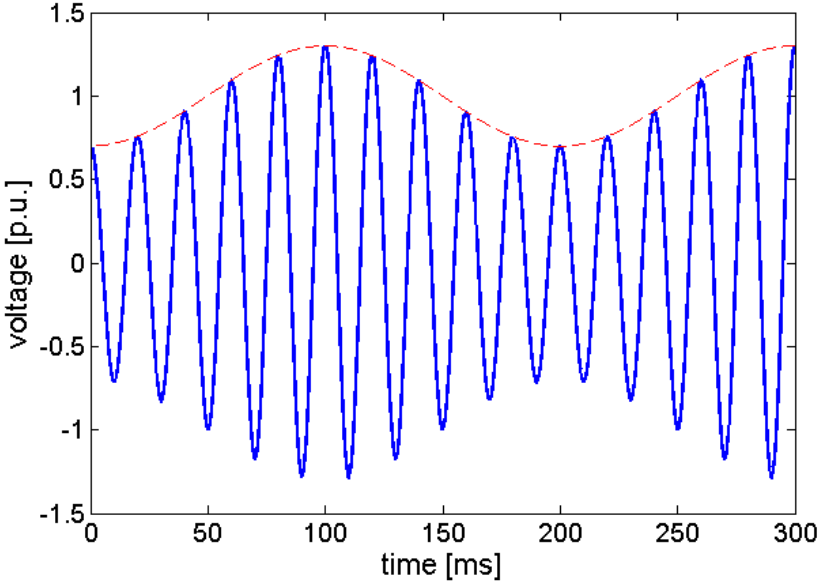
Which is the measurand under dynamic conditions?

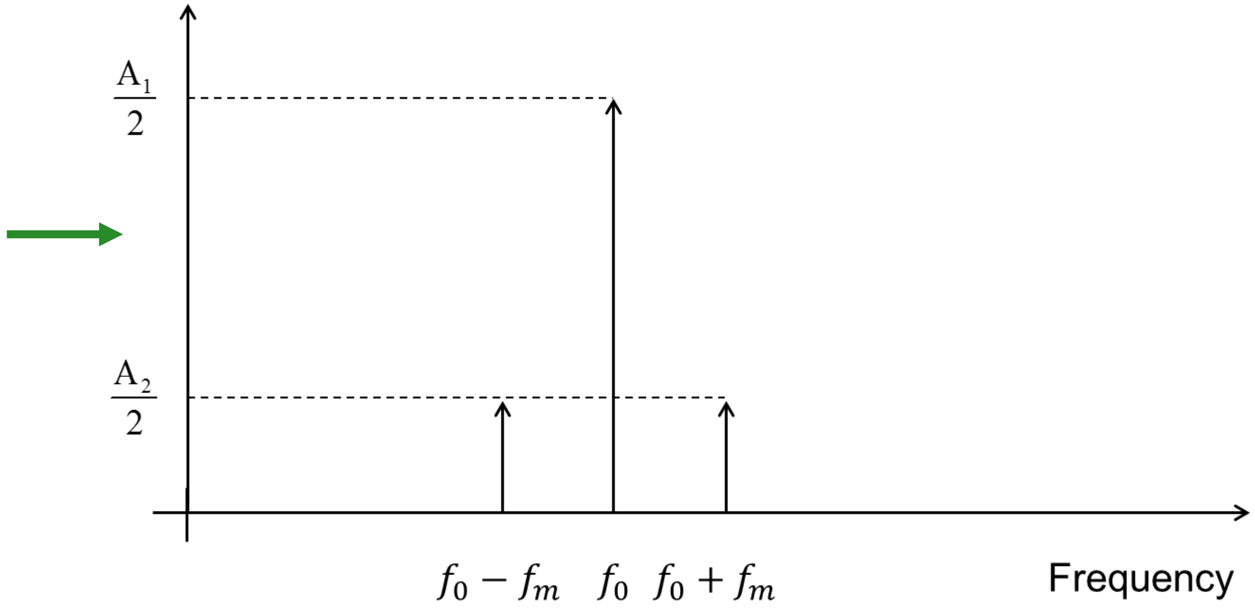


The signal of interest is a passband signal around the nominal frequency f_0

Dynamic synchrophasor: spectrum

The spectrum of interest is not a single impulse

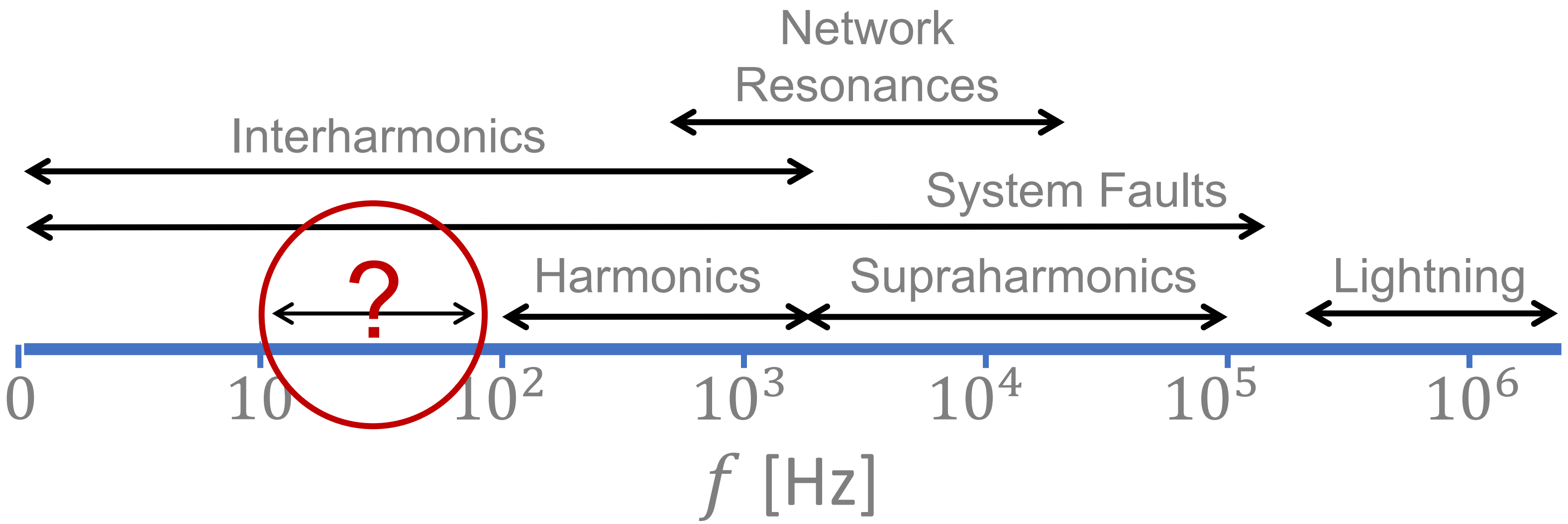




The signal of interest is a passband signal around the nominal frequency f_0

Dynamic synchrophasor: a measurement perspective

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



Measurement process

Measurement process typically involves:

- The model of the measurand
- The model of the disturbances (harmonics, interharmonics, noise, etc.)
- An observation window (an expected set of samples)
- The position of the measurement instant with respect to samples
- The algorithm to compute measurements
- The reporting rate, which influences the measurement process

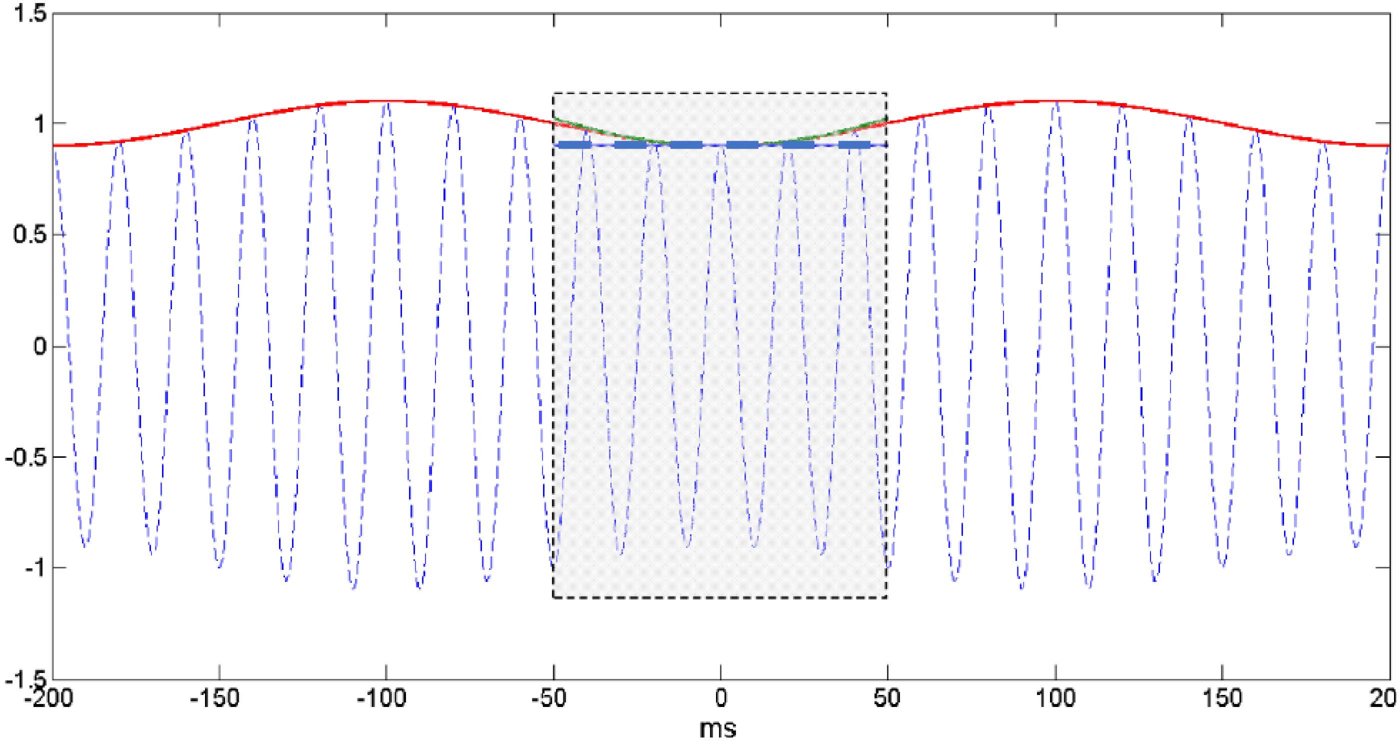
Measurement model

Paolo Attilio Pegoraro

The aim of the measurement process is **to find the model** parameters

Steady-state:

- The signal of interest is considered as perfectly sinusoidal within the observation window, with magnitude and frequency constant.
- Synchrophasor evolution is followed through sliding windows
- Result: averaging effect



P. Castello, M. Lixia, C. Muscas, P. A. Pegoraro, "Impact of the Model on the Accuracy of Synchrophasor Measurement," IEEE Transactions on Instrumentation and Measurement, vol. 61, no. 8, pp. 2179-2188, Aug. 2012.

Measurement model

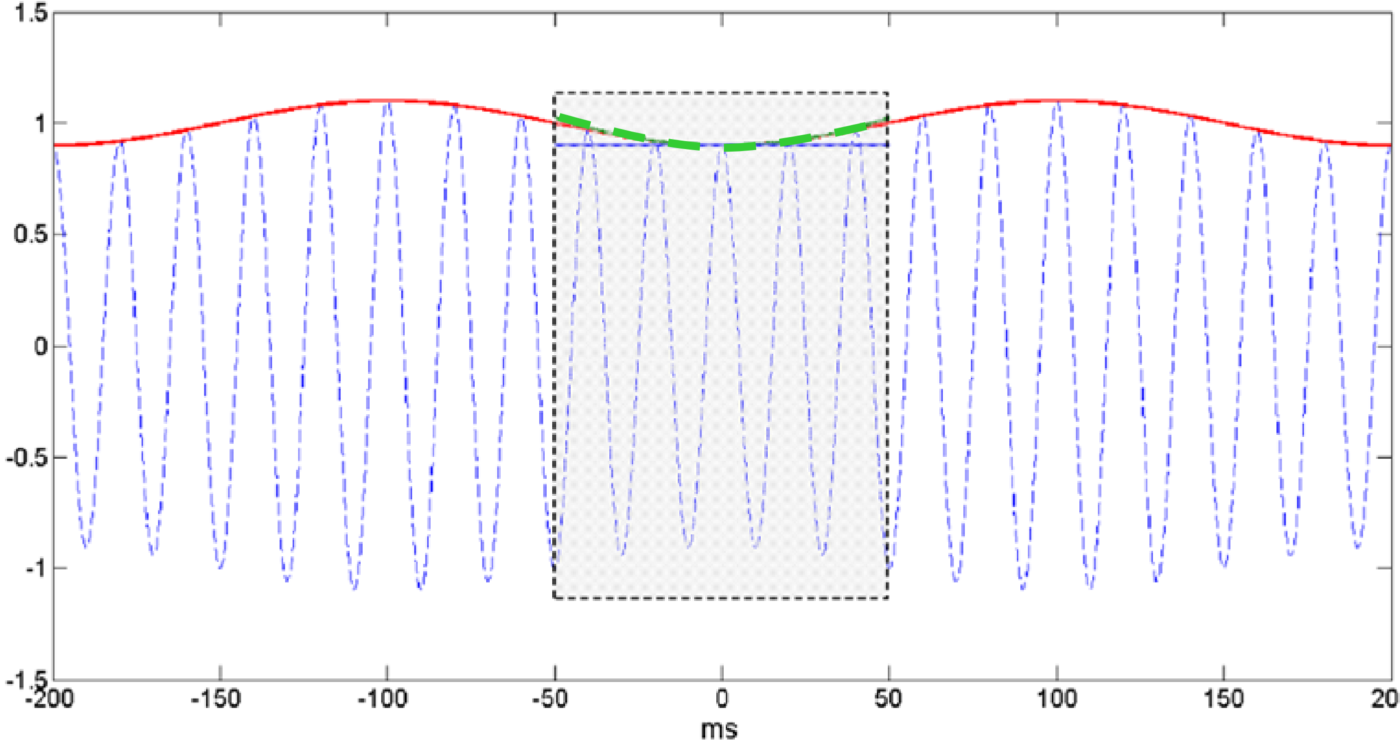
The aim of the measurement process is **to find the model** parameters

Dynamic:

- Signal parameters vary within the observation window (measurement interval).

For example, the phasor can be described through a polynomial expansion around the measurement instant (timestamp)

- Result: dynamics matching

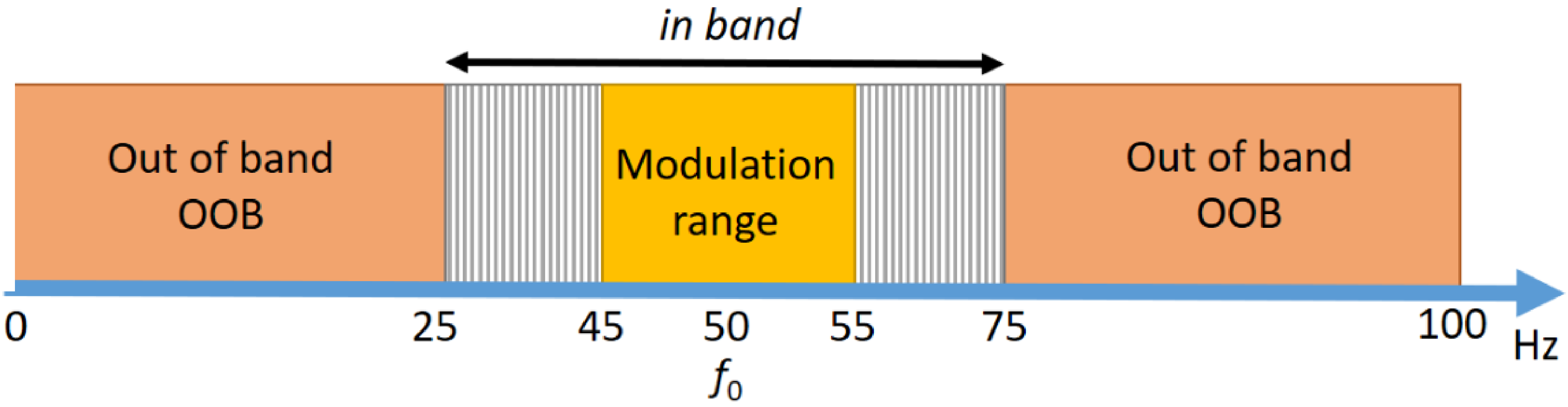


P. Castello, J. Liu, C. Muscas, P. A. Pegoraro, F. Ponci and A. Monti, “A Fast and Accurate PMU Algorithm for P+M Class Measurement of Synchrophasor and Frequency,” IEEE Transactions on Instrumentation and Measurement, vol. 63, no. 12, pp. 2837-2845, Dec. 2014.

Which is the signal of interest?

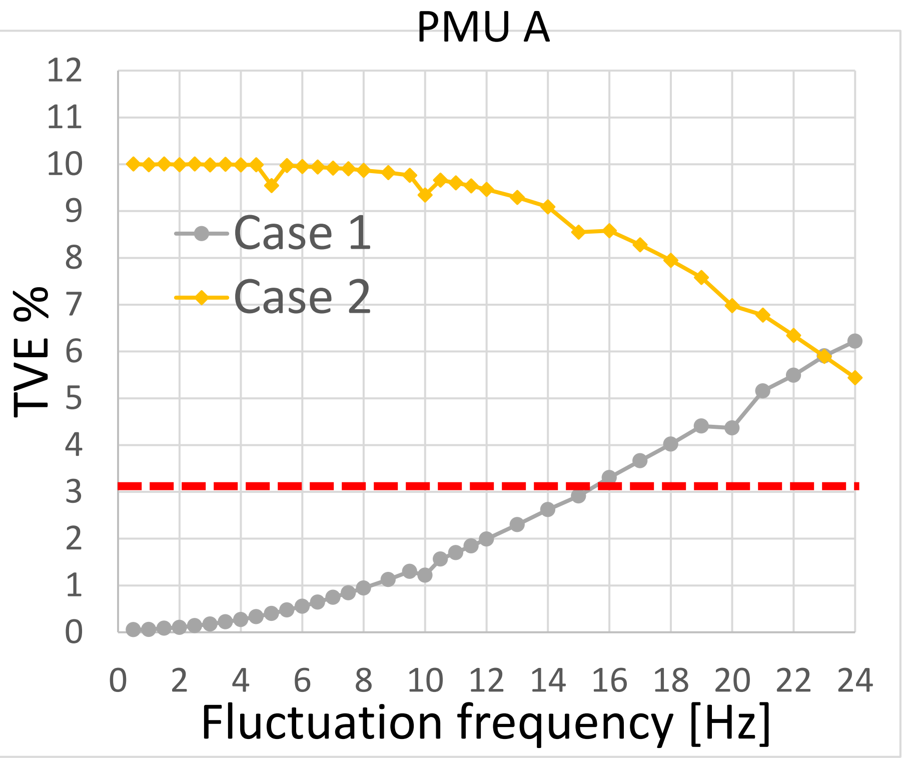
What is a disturbance?

M class
$\mathrm{RR} = 50$ fps
$f_0 = 50$ Hz



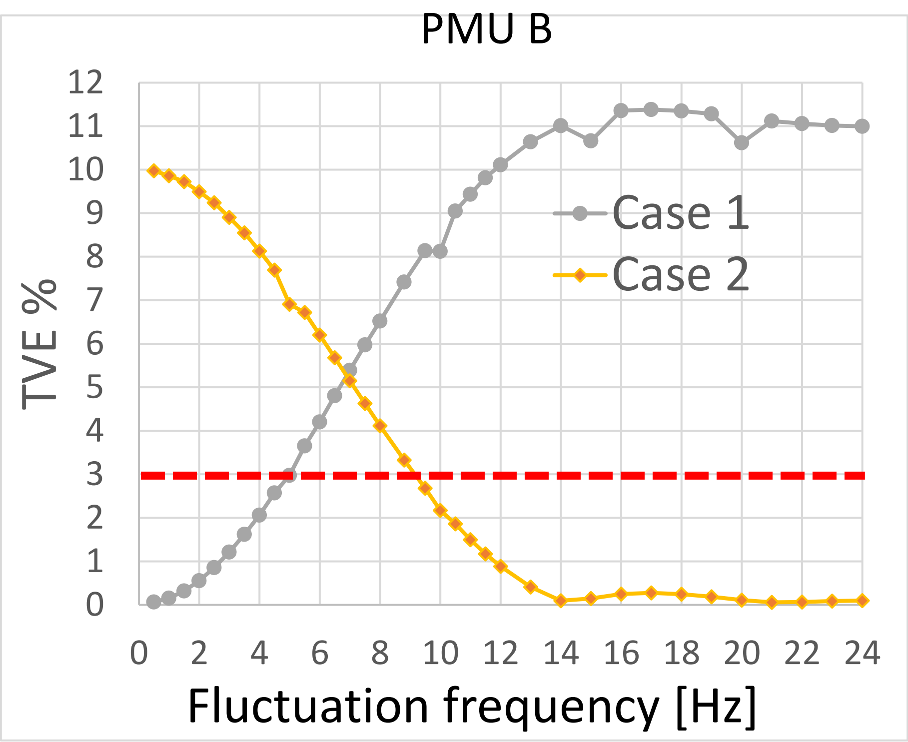
PMU specifications

Measurement model and process



Two PMUs from different vendors: **same class, different behaviour**

Case 1: fluctuation tracking
Case 2: fluctuation rejection



Voltage fluctuations (Flickermeter standard 61000-4-15)

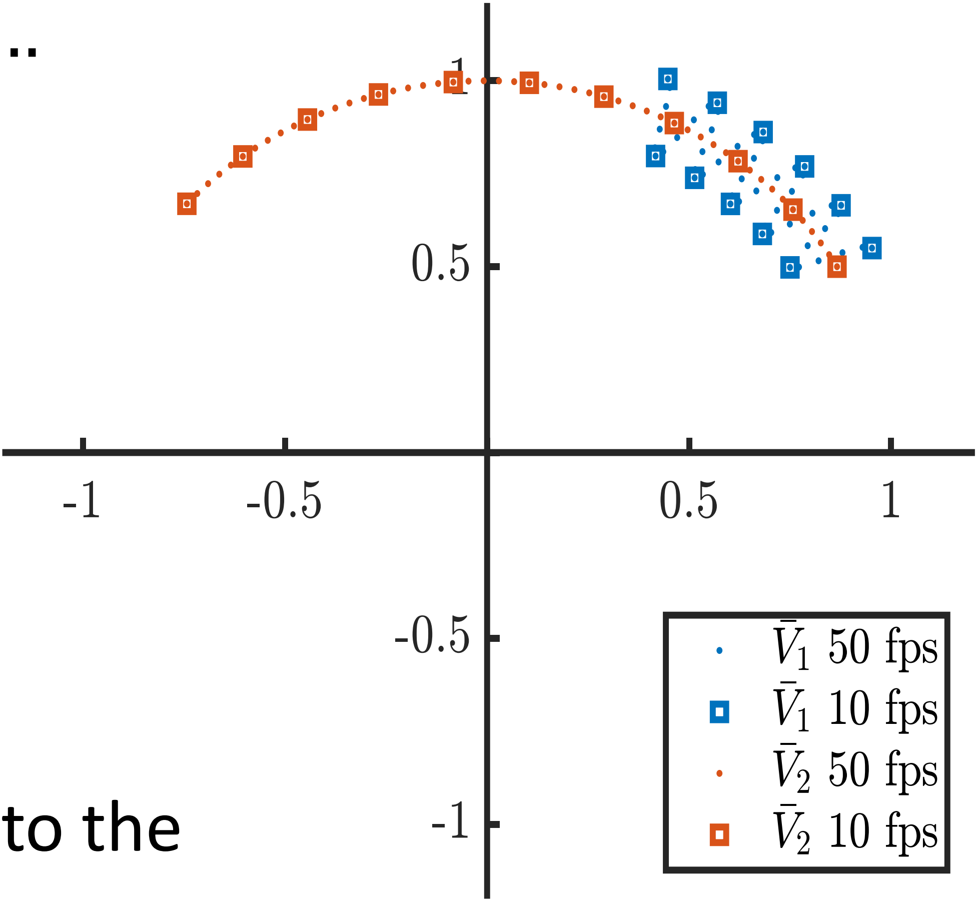
P. Castello, C. Muscas, P. A. Pegoraro, S. Sulis, “PMU’s behavior with flicker-generating voltage fluctuations: An experimental analysis,” Energies, 12 (17), 2019.

Reporting instants

$$\bar{X}(nT) = a(nT)e^{i\phi(nT)} \quad n = 0,1,\ldots$$

- T is the time **reporting interval**
  typically, multiple of the fundamental cycle
  $\rightarrow 20 \text{ ms for } f_0 = 50 \text{ Hz}$
- A PMU can work at $10, 25, 50, 100$ measures per second (frames per second, fps)
  $\rightarrow T = 100 \text{ ms}, 40 \text{ ms}, 20 \text{ ms}, 10 \text{ ms}$

At design stage it is possible to imagine T equal to the sampling interval (T_s) of the acquisition system.

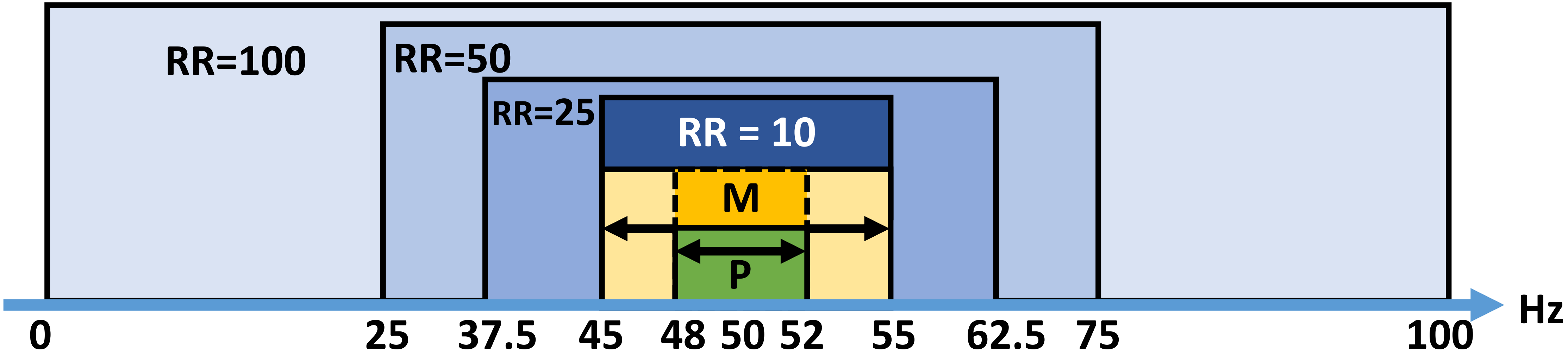


Reporting rate and measurement model

Paolo Attilio Pegoraro

Different reporting rates (RRs) mean different requirements (aliasing).

How to compare them? Different quantities are measured



PMU specifications – Class P and M

Reporting rate and tracking

Paolo Attilio Pegoraro

Tracking error (TrE):

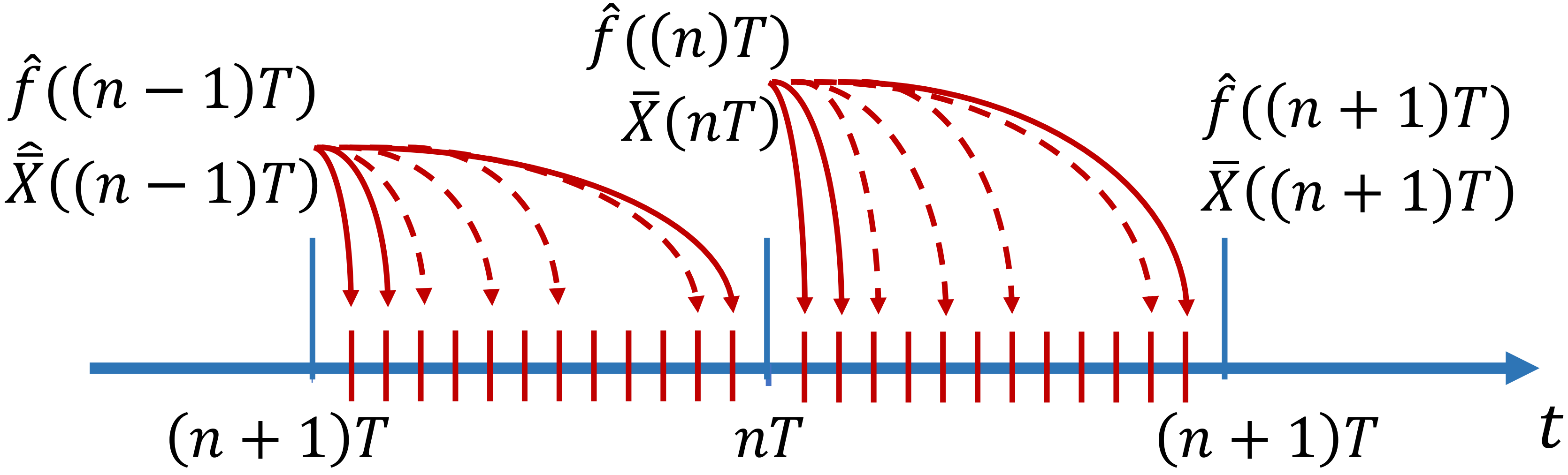
measured values at RR → f_s ↑ RR → sample-by-sample comparison with references

Interpolation of
$\hat{\bar{X}}, \hat{f}, \widehat{\mathbf{ROCOF}}$

Tracking errors

$\mathrm{TrE}_{\mathrm{TVE}}$ $\mathrm{TrE}_{\mathrm{FE}}$ $\mathrm{TrE}_{\mathrm{RFE}}$

Interpolation or prediction

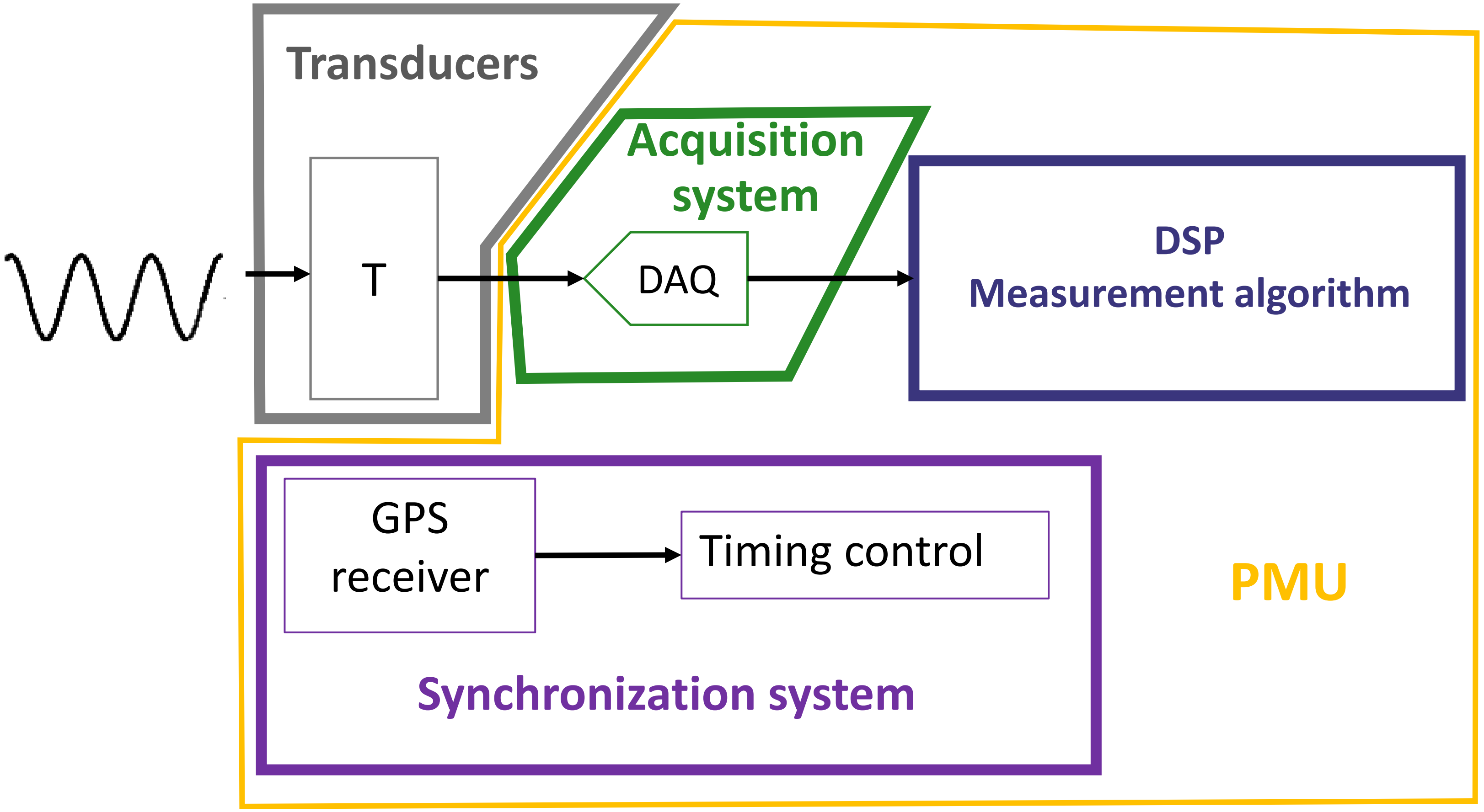


G. Frigo, P. A. Pegoraro and S. Toscani, “Tracking Power Systems Events: PMU, Reporting Rate, Interpolation,” 2022 International Conference on Smart Grid Synchronized Measurements and Analytics (SGSMA), 2022.

Measurement chain

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

The measurement method and the instrument accuracy do not guarantee 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.

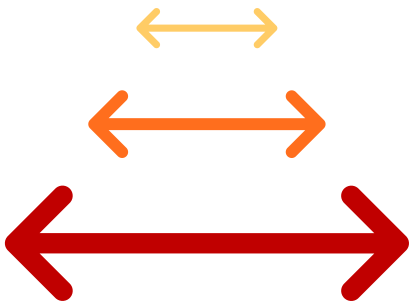
Measurement chain: transducers

Paolo Attilio Pegoraro

Transducers are a major source of measurement error

For example, an uncompensated Class 0.5 VT has:

- 0.5 % maximum ratio error
- 6 mrad maximum phase displacement error



Instrument Transformer

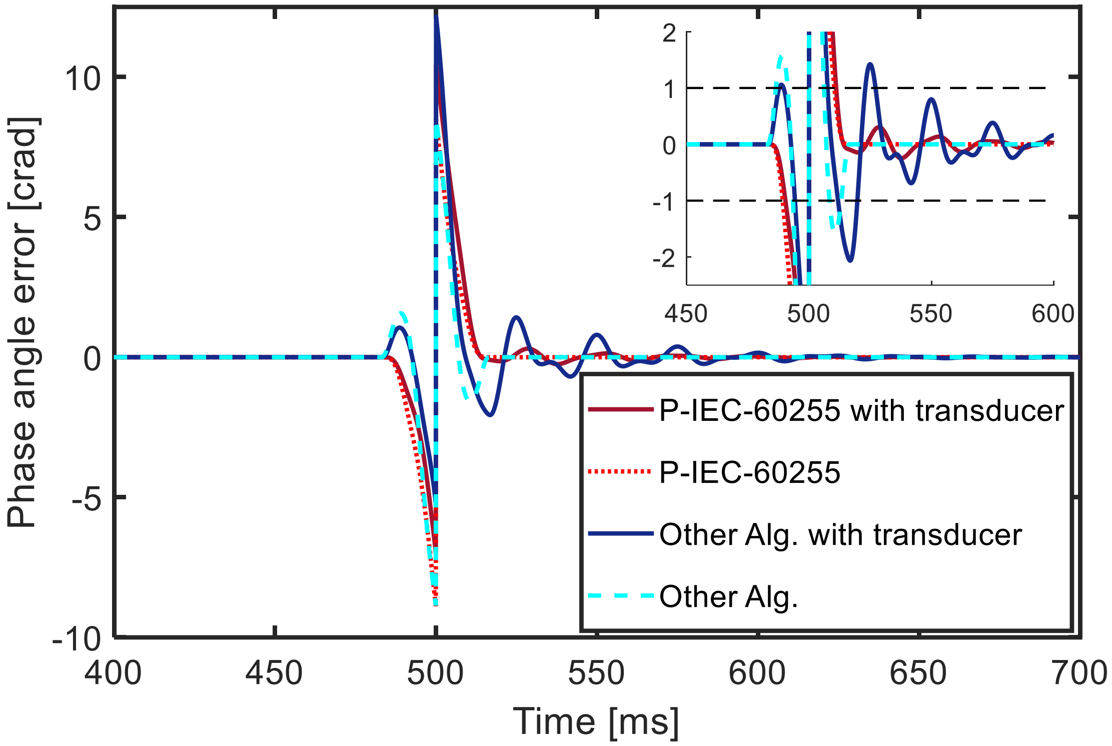
Instrument

Overall chain

For example, IEC/IEEE 60255-118-1
requires PMU error < 1%
under steady-state conditions

- P. A. Pegoraro, C. Sitzia, A. V. Solinas and S. Sulis, “PMU-Based Estimation of Systematic Measurement Errors, Line Parameters, and Tap Changer Ratios in Three-Phase Power Systems,” IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-12, 2022.
- P. A. Pegoraro, K. Brady, P. Castello, C. Muscas and A. von Meier, “Compensation of Systematic Measurement Errors in a PMU-Based Monitoring System for Electric Distribution Grids,” IEEE Transactions on Instrumentation and Measurement, vol. 68, no. 10, pp. 3871-3882, Oct. 2019.

Measurement chain: transducers and dynamics

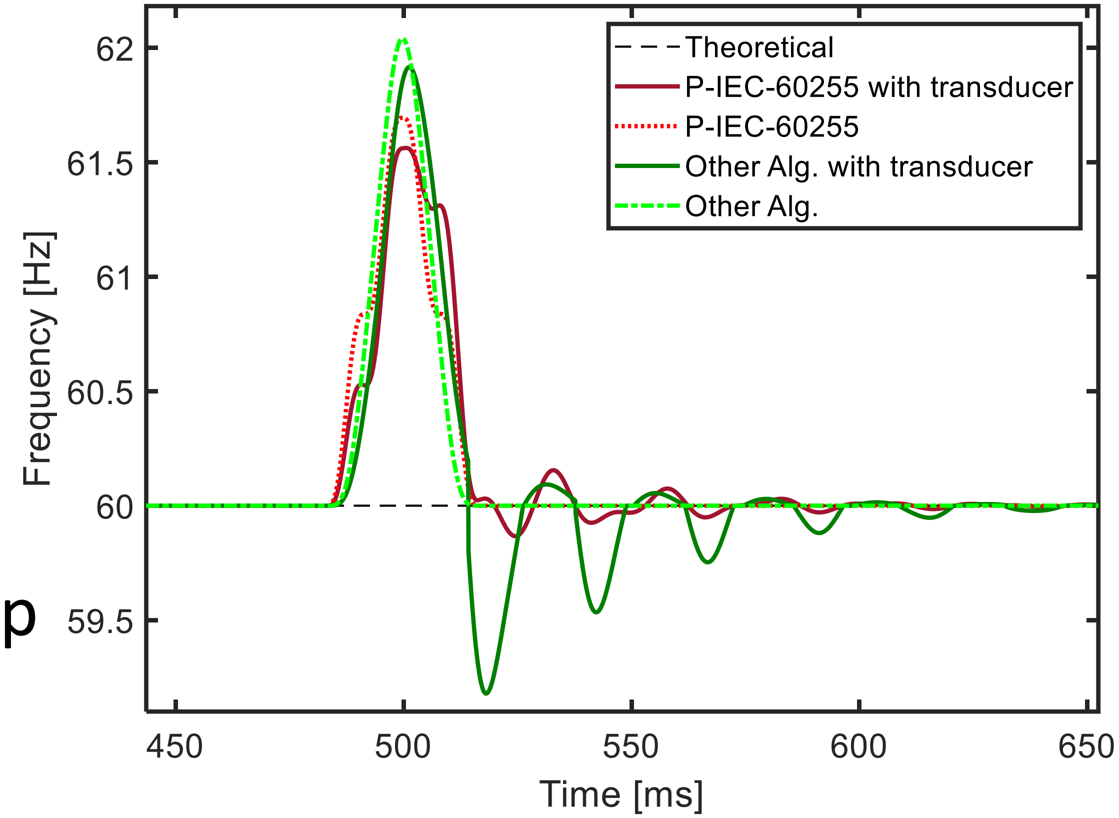


CVT

+

phase angle step

+10°



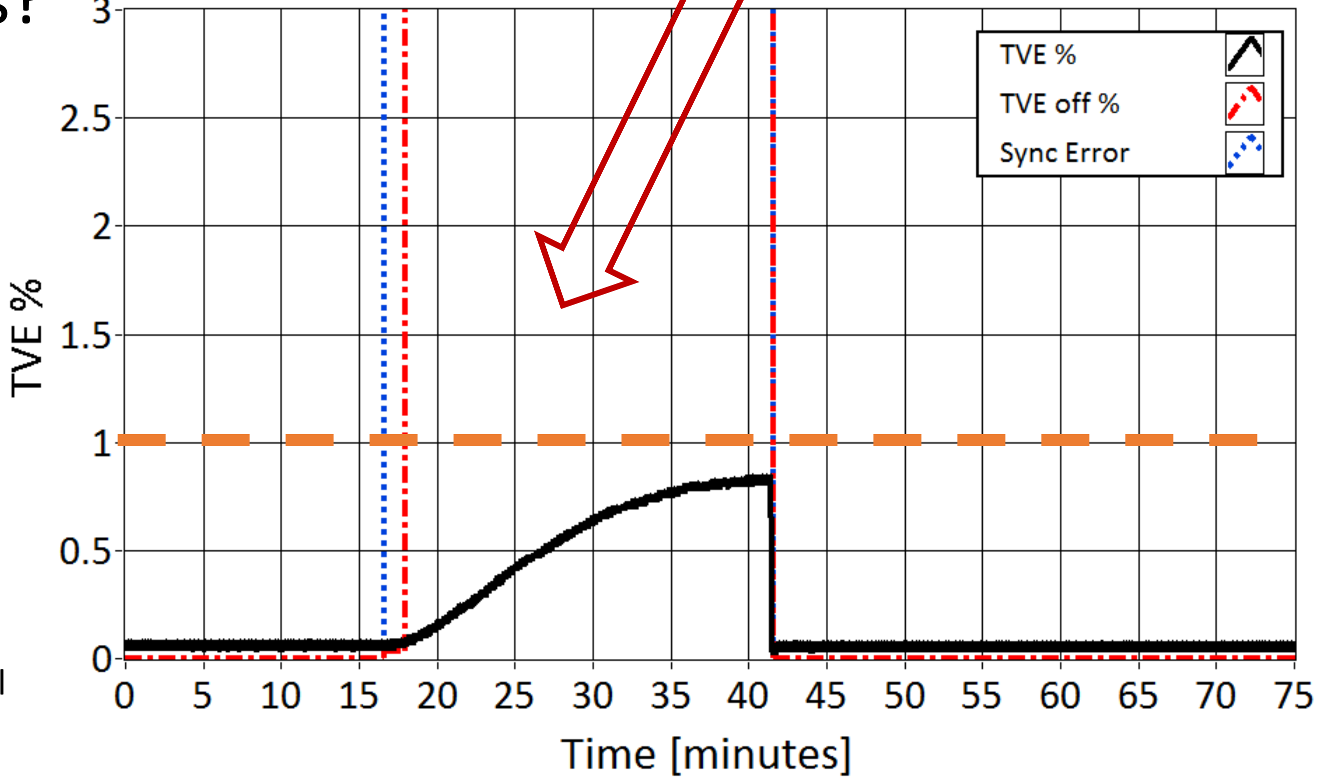
R. Ferrero, <u>P. A. Pegoraro</u>, S. Toscani, “Impact of Capacitor Voltage Transformers on Phasor Measurement Units Dynamic Performance,” IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS 2018), Bologna, Sept. 2018.

Measurement chain: synchronization

Paolo Attilio Pegoraro

Synchronization error directly affects measurement accuracy

Can information about synchronization be refined and used by applications?



worst case info about time error

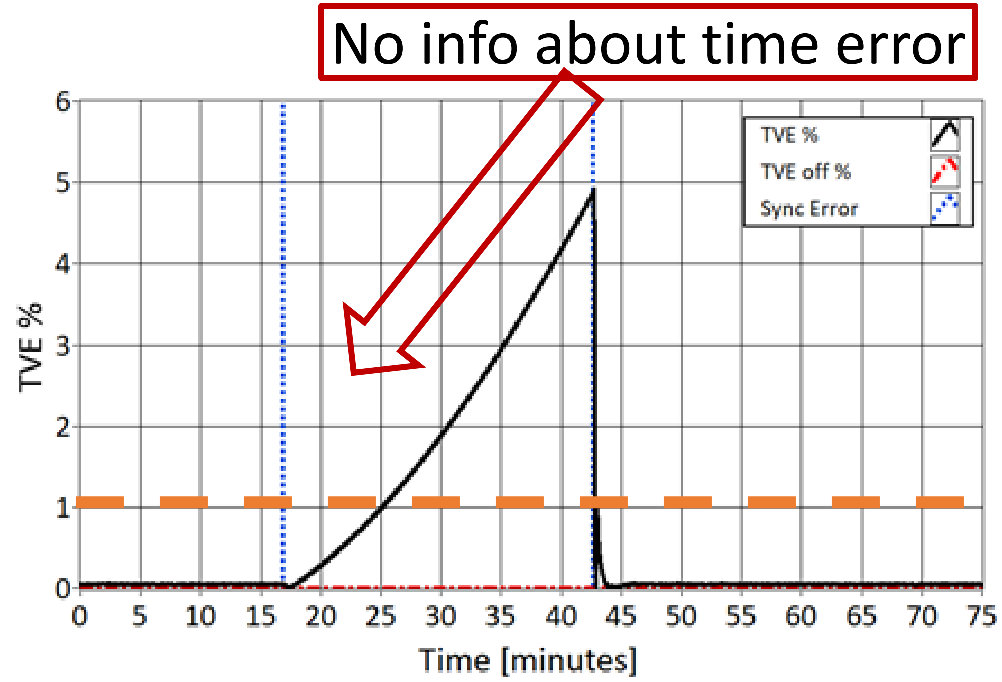
Equivalent TVE due to Sync Error

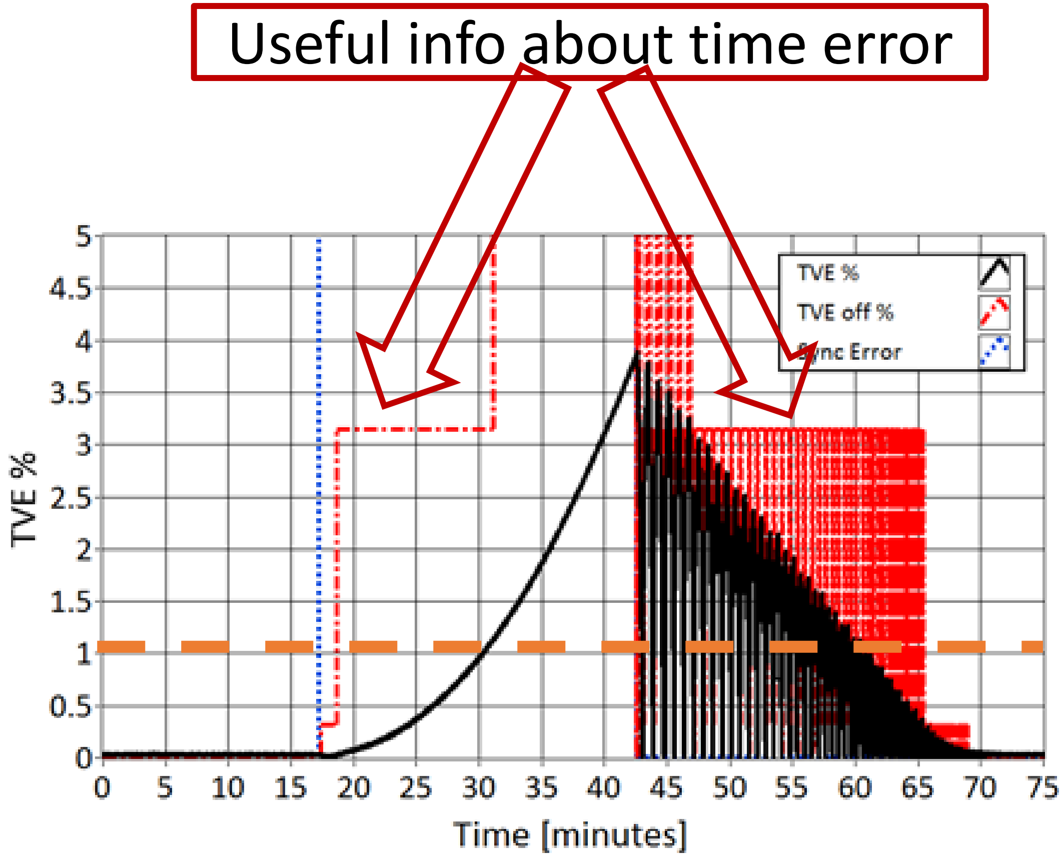
P. Castello, C. Muscas, P. A. Pegoraro, S. Sulis, “Trustworthiness of PMU data in the presence of synchronization issues,” 2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Houston, TX, USA, May 2018, pp. 1-5.

Measurement chain: synchronization

Different clock behaviours and different time quality awareness levels

- Accuracy is important
- Information about accuracy is important


No info about time error


Useful info about time error

Measurement chain: data acquisition system

DAQ system is a source of uncertainty

- Quantization
- Acquisition noise
- Internal transducer (particularly for current channels)
- Delays

Measurement chain: the algorithm

The algorithm is essential

Measurement errors depend on:

- Input signal conditions
- Noise and disturbance reduction
- Reporting rate

Measurement error assessment

Measurement accuracy can be quantified through indexes:

- Relative Amplitude Error:

$$\mathrm{RAE} \triangleq \frac{\hat{a} - \boxed{a}}{a} = \frac{\Delta a}{a}$$

- Phase angle Error:

$$\mathrm{PhE} \triangleq (\hat{\phi} - \boxed{\phi}) = \Delta\phi$$

- Total Vector Error:

$$\mathrm{TVE} \triangleq \frac{\left|\hat{\bar{X}} - \boxed{\bar{X}}\right|}{|\bar{X}|} = \sqrt{\frac{(\hat{X}_r - X_r)^2 + (\hat{X}_i - X_i)^2}{(X_r + X_i)^2}}$$

- Frequency error:

$$\mathrm{FE} \triangleq \hat{f} - f = \widehat{\Delta f} - \boxed{\Delta f}$$

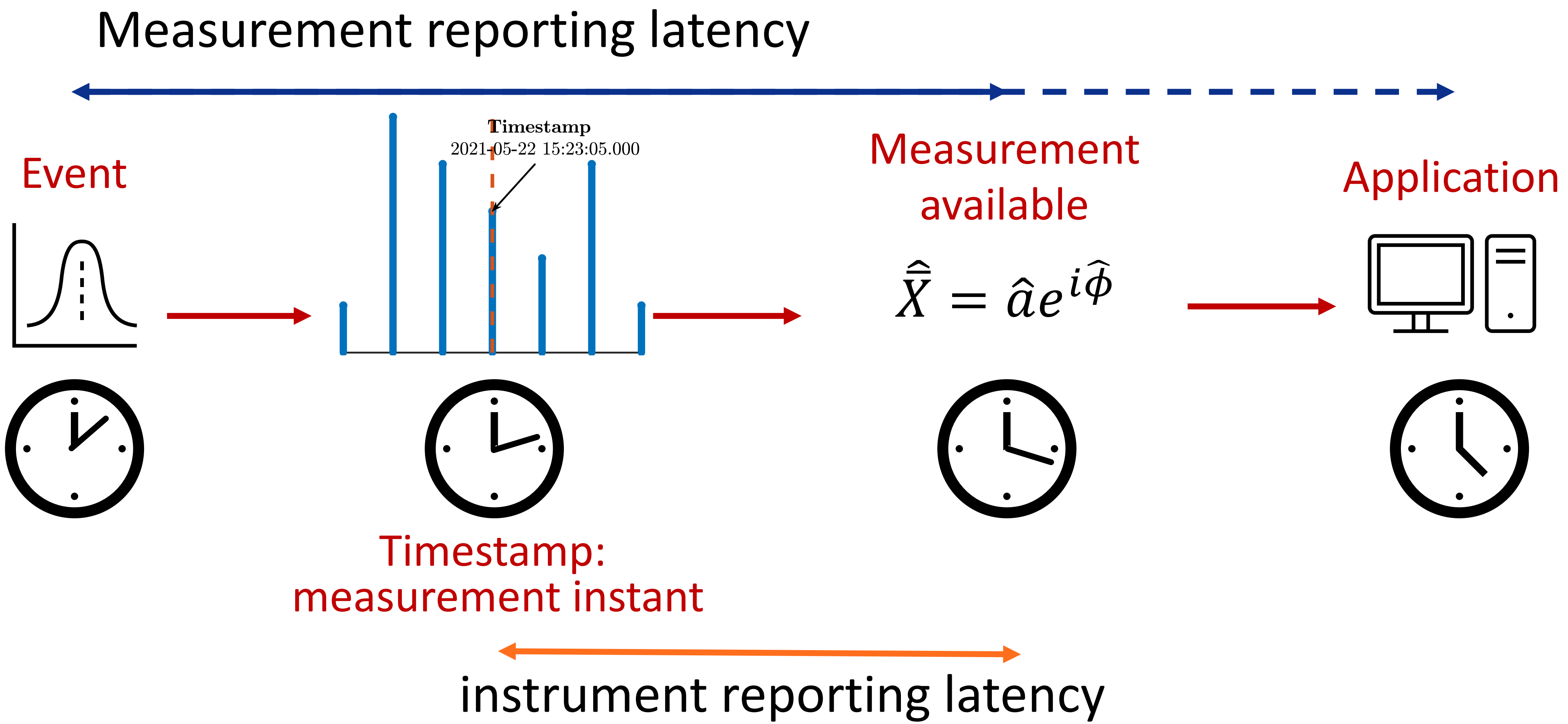
- ROCOF error:

$$\mathrm{RFE} \triangleq \widehat{\mathrm{RFE}} - \boxed{\mathrm{RFE}}$$

Reference values are known only under **controlled environment**

\- Tests -

Latency



Measurement reporting latency

Event

Measurement available

$$\hat{\hat{X}} = \hat{a}e^{i\hat{\phi}}$$

Application

Timestamp: measurement instant

instrument reporting latency

Latency

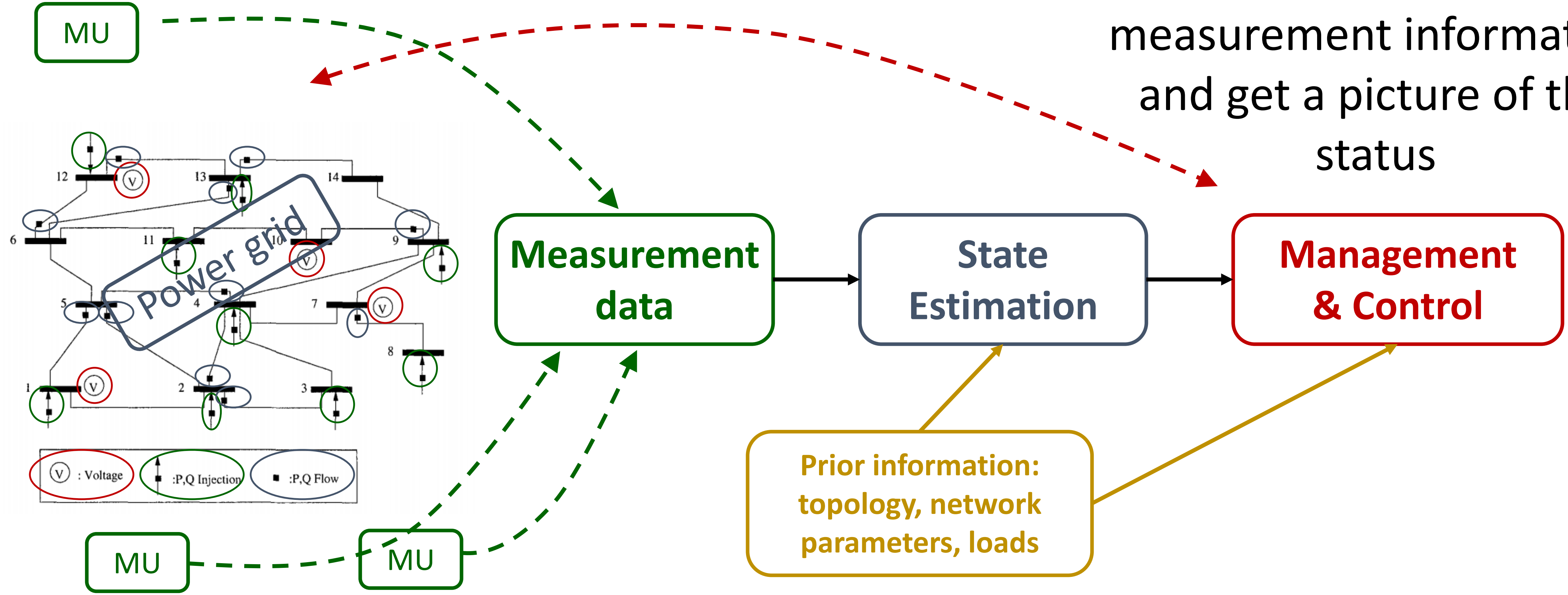
The instrument reporting latency is due to:

- The algorithm: where is the time instant w.r.t. the window of samples?
- The reporting rate: different reporting rates have different requirements and thus different algorithm latencies
- Processing time: algorithm computational burden, hardware, etc.
- Transmission time: the data are available when the packet containing them appears on the network link

- P. Castello, C. Muscas, P. A. Pegoraro, S. Sulis, “Automated test system to assess reporting latency in PMUs,” Proceedings of 2016 IEEE Instrumentation and Measurement Technology Conference (I2MTC). Taipei, Taiwan, May 2016.
- 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,” 12th IEEE International Workshop on Applied Measurements for Power Systems (AMPS 2022), Cagliari, Italy, Sept. 2022.

State estimation

State estimation to merge measurement information and get a picture of the status



MU

MU

MU

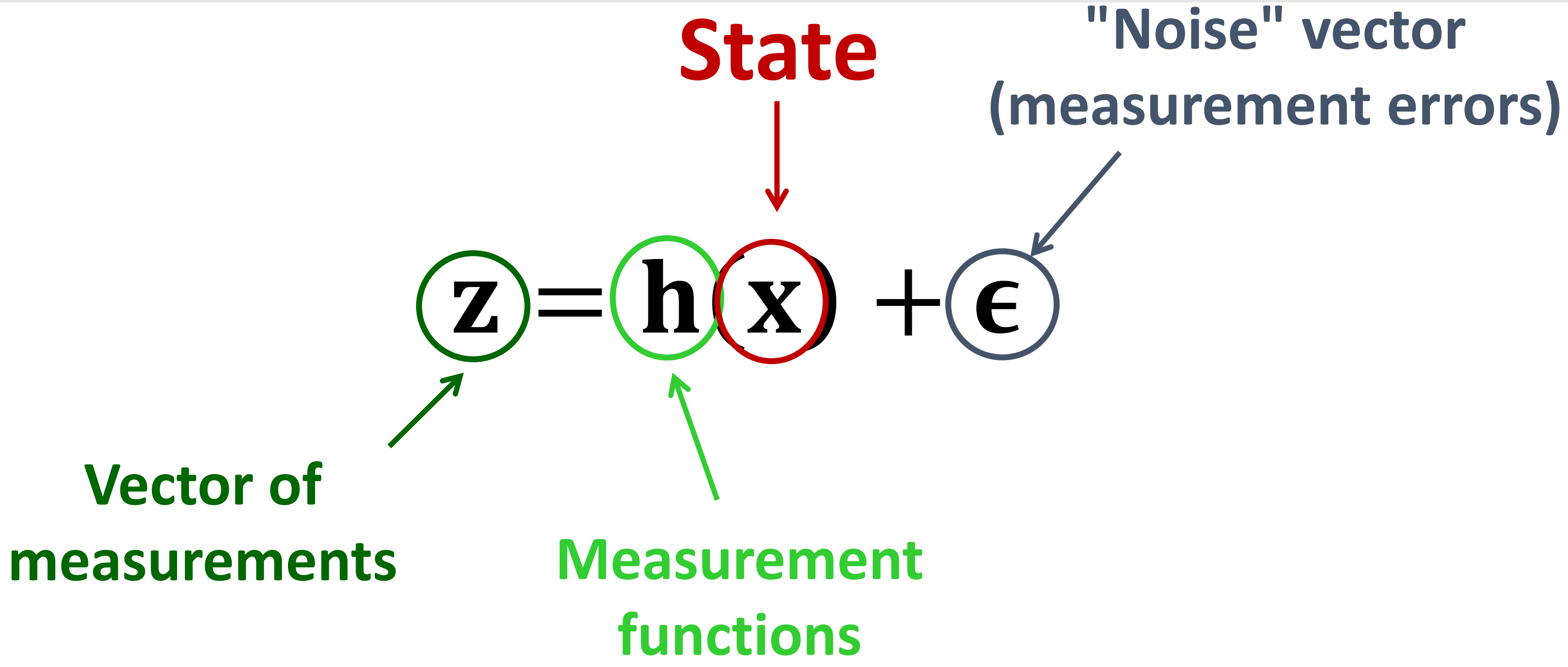
Measurement data

State Estimation

Management & Control

Prior information: topology, network parameters, loads

State estimation



State

"Noise" vector (measurement errors)

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + \boldsymbol{\epsilon}$$

Vector of measurements

Measurement functions

State: voltages (typical), currents, powers

Measurements $\mathbf{z}$: voltage/current magnitudes, phasors, active/reactive power

Measurement functions: commonly nonlinear

Vector of the measurement uncertainties: e.g., Gaussian, zero mean

State estimation solution

Classic solution: weighted least squares (WLS)

Linear case →

$$\mathbf{H}^{\mathrm{T}}\mathbf{W}\mathbf{H}\hat{\mathbf{x}} = \mathbf{H}^{\mathrm{T}}\mathbf{W}\mathbf{z}$$

Jacobian Matrix

Estimated State

Weight Matrix $\mathbf{W} = \boldsymbol{\Sigma}_{\mathbf{z}}^{-1}$

Each measurement has its own weight: more accurate measurements are more “reliable”.

M. Pau, P. A. Pegoraro and S. Sulis, “Efficient Branch-Current-Based Distribution System State Estimation Including Synchronized Measurements,” IEEE Transactions on Instrumentation and Measurement, vol. 62, no. 9, pp. 2419-2429, Sept. 2013.

State estimation and dynamics: accuracy

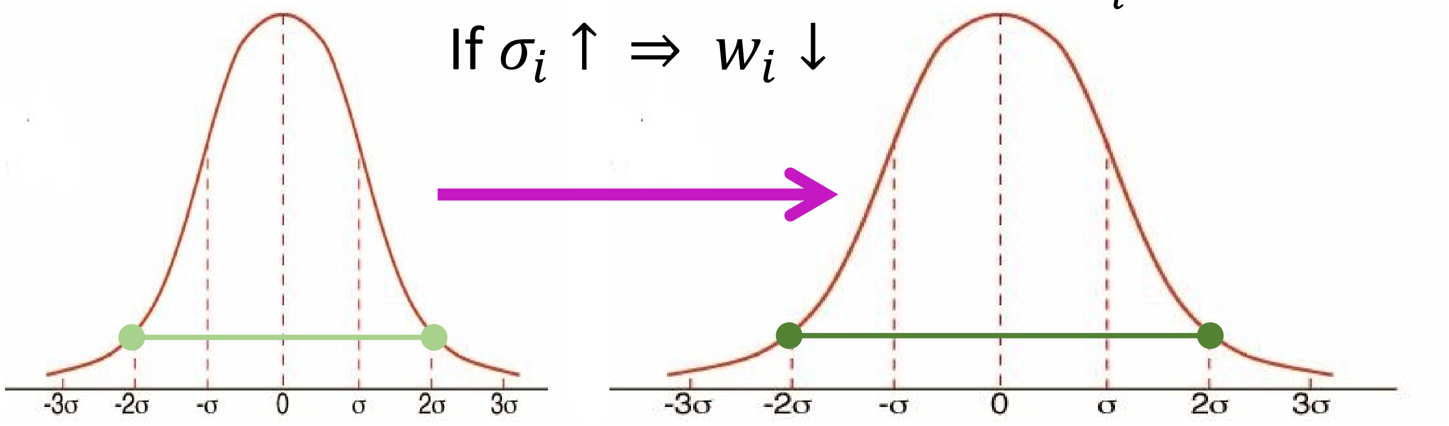
When dynamics occur measurement accuracy degrades

e.g., TVE of PMUs 1 % → **3 % TVE**

$$\mathbf{W} = \begin{bmatrix} \frac{1}{\sigma_1^2} & & & & \\ & \ddots & & & \\ & & \boxed{\frac{1}{\sigma_i^2}} & & \\ & & & \ddots & \\ & & & & \frac{1}{\sigma_M^2} \end{bmatrix} \longleftarrow w_i = \frac{1}{\sigma_i^2}$$

z_i has standard deviation $\sigma_i \rightarrow w_i = \frac{1}{\sigma_i^2}$

If $\sigma_i \uparrow \; \Rightarrow \; w_i \downarrow$



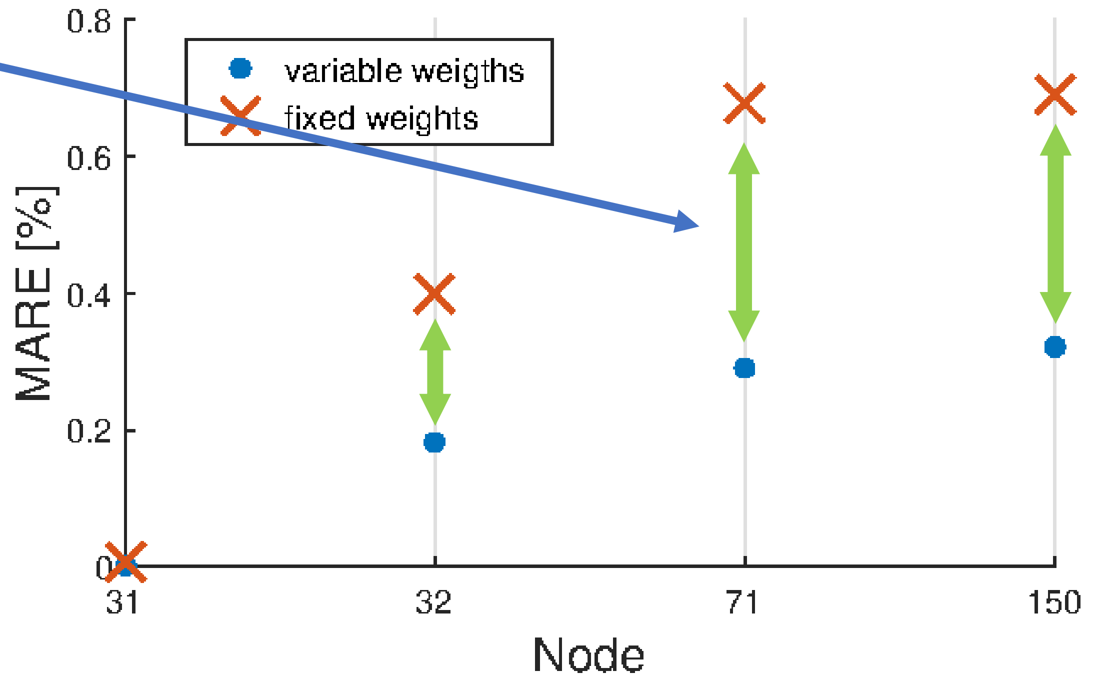
$$\mathbf{H}^{\mathrm{T}} \boxed{\mathbf{W}_{\mathrm{dyn}}} \mathbf{H}\,\hat{\mathbf{x}} = \mathbf{H}^{\mathrm{T}} \boxed{\mathbf{W}_{\mathrm{dyn}}} \mathbf{z}$$

New weights are needed

State estimation and dynamics: accuracy

Adaptive weights improve the estimation significantly

Dynamics may affect mainly some nodes



Example: Distribution System State Estimation voltage magnitude estimation

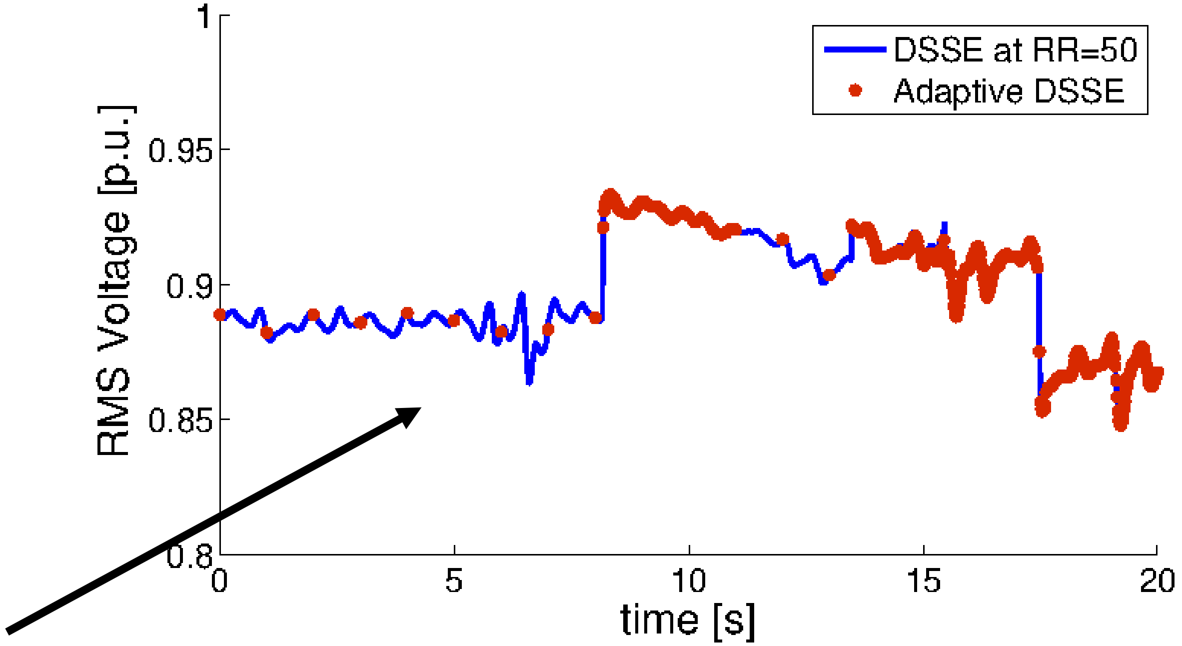
P. A. Pegoraro, A. Meloni, L. Atzori, P. Castello and S. Sulis, “PMU-Based Distribution System State Estimation with Adaptive Accuracy Exploiting Local Decision Metrics and IoT Paradigm,” IEEE Transactions on Instrumentation and Measurement, vol. 66, no. 4, pp. 704-714, Apr. 2017.

State estimation and dynamics: adaptive rate

State estimation can be triggered by significant variations:

- Virtualization of the instruments
- Variable measurement reporting rate
- Thresholds to trigger estimation
- ON/OFF criteria
- Bandwidth and storage saving

Distribution System State Estimation:
Magnitude estimation at a specific node
(e.g., thresholds on voltage rms and ROCOF)

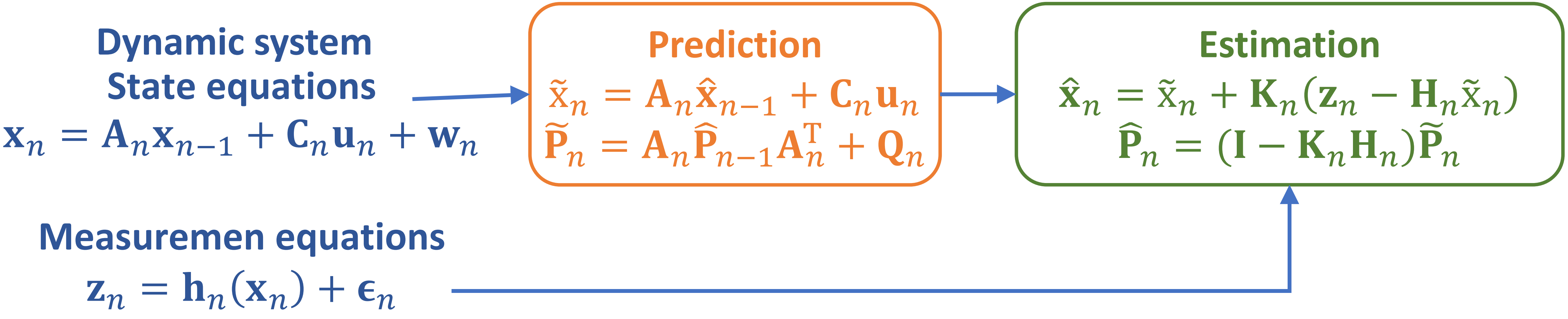


A. Meloni, P. A. Pegoraro, L. Atzori, A. Benigni, S. Sulis, "Cloud-based IoT solution for state estimation in smart grids: Exploiting virtualization and edge-intelligence technologies," Computer Networks, vol. 130, pp. 156-165, 2018.

State estimation and dynamics: frequency measurement

Kalman filtering is often used for forecasting aided state estimation

$$\mathbf{x} = [\theta_1, \ldots, \theta_N, V_1, \ldots, V_N]^{\mathrm{T}}$$



Dynamic system
State equations

$$\mathbf{x}_n = \mathbf{A}_n \mathbf{x}_{n-1} + \mathbf{C}_n \mathbf{u}_n + \mathbf{w}_n$$

Prediction

$$\tilde{\mathbf{x}}_n = \mathbf{A}_n \hat{\mathbf{x}}_{n-1} + \mathbf{C}_n \mathbf{u}_n$$
$$\widetilde{\mathbf{P}}_n = \mathbf{A}_n \widehat{\mathbf{P}}_{n-1} \mathbf{A}_n^{\mathrm{T}} + \mathbf{Q}_n$$

Estimation

$$\hat{\mathbf{x}}_n = \tilde{\mathbf{x}}_n + \mathbf{K}_n (\mathbf{z}_n - \mathbf{H}_n \tilde{\mathbf{x}}_n)$$
$$\widehat{\mathbf{P}}_n = (\mathbf{I} - \mathbf{K}_n \mathbf{H}_n) \widetilde{\mathbf{P}}_n$$

Measuremen equations

$$\mathbf{z}_n = \mathbf{h}_n(\mathbf{x}_n) + \boldsymbol{\epsilon}_n$$

Add frequency measurements to $\mathbf{z}_n$ → help angle prediction → improve SE

C. Muscas, P. A. Pegoraro, S. Sulis, M. Pau, F. Ponci and A. Monti, "New Kalman Filter Approach Exploiting Frequency Knowledge for Accurate PMU-Based Power System State Estimation," IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 9, pp. 6713-6722, Sept. 2020.

Final considerations

- Dynamic conditions require new measurements and ask for accuracy, synchronization, tracking etc.
- Measurement process requires the **definition of the measurand**
- Synchronized measurements under dynamics require **specific models**
- Measurement procedures must reflect the **defined models**
- **Measurement errors** can arise at **every stage of the measurement process** (synchronization, acquisition, processing, etc.)
- Knowing what to expect from the instruments allows better exploiting them and allows building **applications** that are more **accuracy aware**
- Applications should give **requirements and targets for the measurement process**

Thank you for your attention!

for any additional question or further discussion,

please contact me at:

paolo.pegoraro@unica.it