High Reporting Rate Measurements for Smart(er) Grids

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Technical Lecture Series

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MicroDERLab group @ UPB

- Team
- Expertise
- Projects

- [Faculty of Electrical Engineering]
- [Faculty of Automation and Control]
- [Faculty of Power Engineering]

- **Instrumentation for power systems;**
- synchronized measurements; WAMCS
- Grid integration of RES; active distribution grids
- **Microgrids** (including DC and hybrid architectures)
- **Emerging Power Quality concepts**
- Work on standardization (various IEC bodies)

member of DERlab

Nobel Grid
Smart energy for people

- **H2020 NobelGrid**
- **DCNextEve**

FLEXMETER

- **H2020 Flexmeter**

RESERVE

- **H2020 Storage4Grid**

STORAGE 4 GRID

- **ITCity (ERA Net LAC 2016), 2017-2020**

ITCity

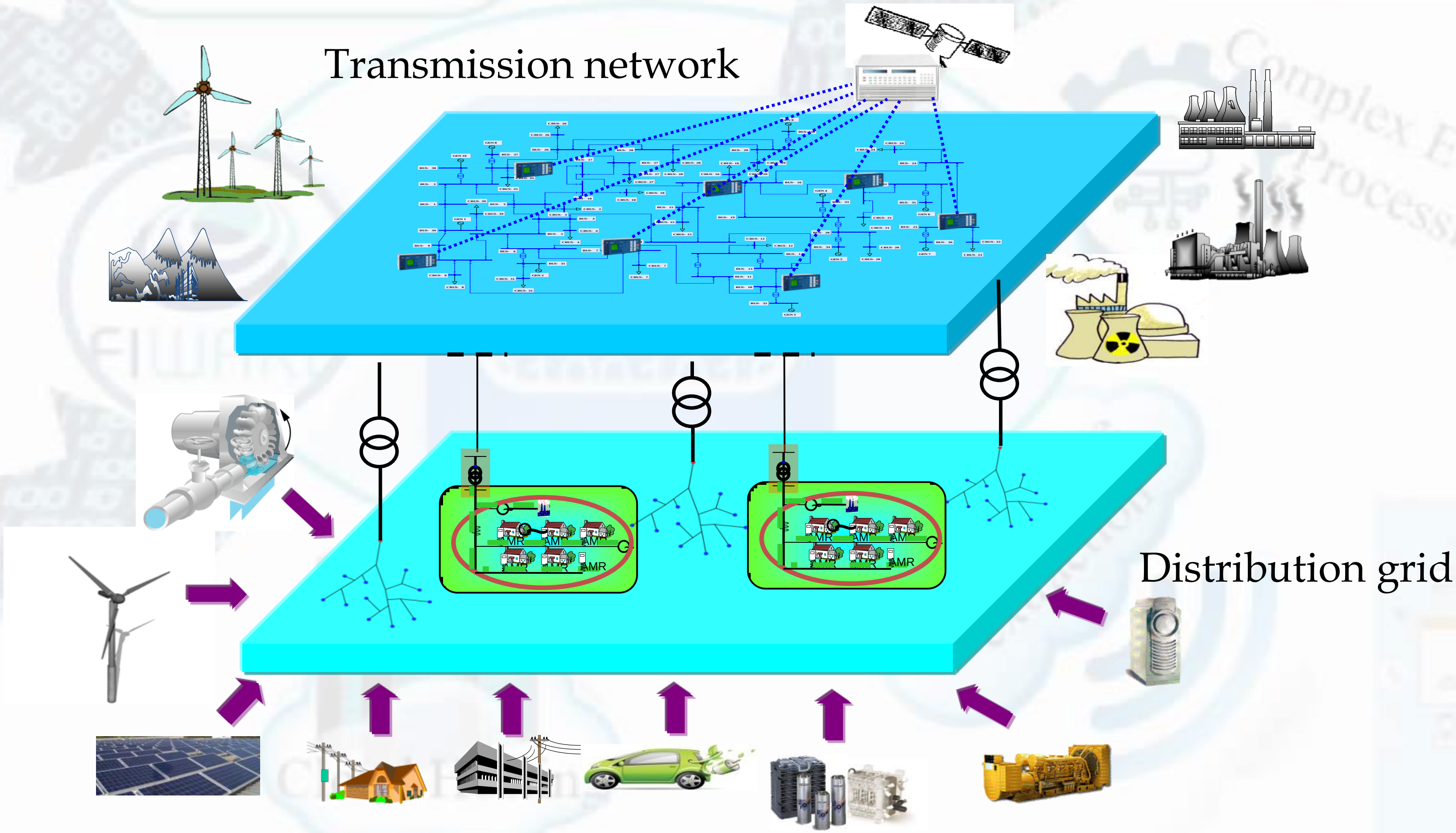
Smart Grids Plus
ERA-Net

- **FISMEP (ERA Net Smart Grids Plus), 2017-2020**

Outline

- The measurement paradigm in power systems
  - Models For the Energy Transfer
  - PQ, SCADA and PMUs
  - Time- aggregation algorithms
  - Smart metering with high reporting rate (1s). The Unbundled Smart Meter
- State estimation in electric power systems;
  - Synchronized Measurements
  - Measurement channel quality
  - Effect of the measurement weights on the state estimator (considering both the standard uncertainties associated with the measurement devices and the instrument transformers)
- Instead of Conclusions: IEEE community of I&M

POWER SYSTEMS. MODELS FOR THE ENERGY TRANSFER.



POWER SYSTEMS. MODELS FOR THE ENERGY TRANSFER

- Load and system conditions change continuously
  - ➢Quasi-steady state conditions most of the time → time aggregation
  - ➢Dynamically changing conditions occasionally → "instantaneous" measurements; protections; SCADA framework

Frequency and voltage: not anymore the ubiquitus information carriers!

(a) Wide area monitoring and control

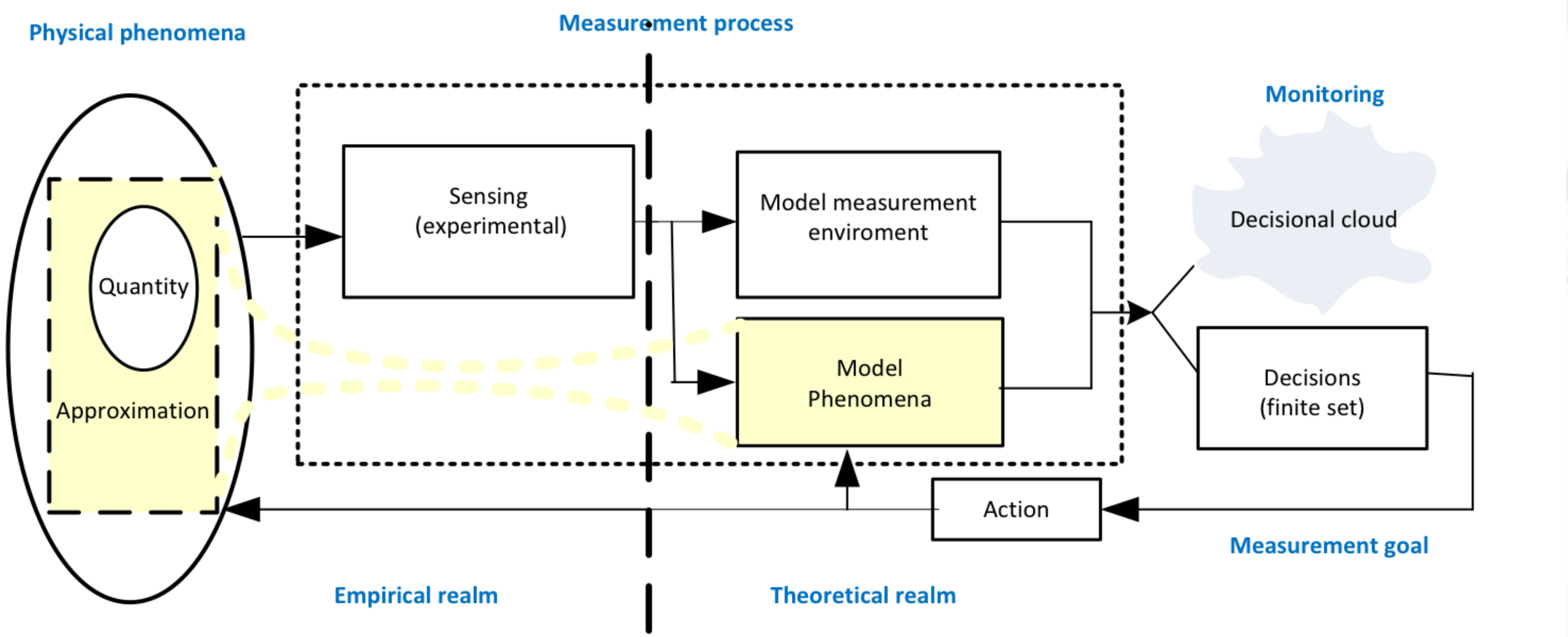
(b) More accurate modeling/validation of models

- Control and monitoring of power systems relies heavily on **measurements** dispersed throughout the system

- Need to develop information processing methodologies **to extract meaning and knowledge out of the data; data knowledge** to design software, hardware and embedded systems that operate autonomously and with system awareness

- Ultimately: **real-time decisions** in the management of large-scale, complex and safety-critical systems → **Smarter Infrastructure Networks**

THE MEASUREMENT PARADIGM IN POWER SYSTEMS



- Measurement result is meaningful *only* when the **quality of the measurement process is quantified**
- measurement is normally a **GOAL-DRIVEN PROCESS**

$$u = \sqrt{(u_M)^2 + (u_E)^2}$$

- Measurement context: the set of all entities belonging to the experimental setting with **a significant effect** on measurement result

THE MEASUREMENT PARADIGM IN POWER SYSTEMS

- **Measurement context:** [quasi-]steady state process
  - context models include definition of ⍰ measurand ⍰ standard properties ⍰ influence properties ⍰ time (implicitly included as a **hidden variable**)
  - Symmetrical/unsymmetrical three phase system (voltages)
  - Balanced/unbalanced three phase system (currents)

    symmetry ↳ single phase representation
  - Load model: constant, usually linear (P, Q)
  - Constant (time & space) frequency (system frequency)
  - Sinusoidal-waveforms → **Phasor representation**
    - Non-sinusoidal: limited frequency band; fundamental component
  - Time resolution determined by control actions → seconds
  - **Low inertia & old models**

    → significant depreciation of the information mediated by the control systems which are relying on real-time measurements

THE MEASUREMENT PARADIGM IN POWER SYSTEMS

- Typical measurement chain for electrical quantities in power systems: instrument transformers **and** the measurement device
- Specific to power systems monitoring: the **aggregator** (**inherited from analogic way of data compression**)
- newly deployed synchronized measurement units SMUs:
  - high fidelity, high accuracy, high reporting rates
- **Unequal development** pace of the models! (measurement / phenomena)

MEASUREMENT PROCESS

- A possible measure (1995, GUM): standard **uncertainty** - it "reflects the lack of knowledge of the value of the measurand" *after correcting all the systematic errors* observed during the measurement procedure.
- Two ways for evaluating the standard uncertainty of measurements:
  - Type A and Type B. In both types, the measurement is considered as a random variable.
- Any mathematical operation on measurement results → **combined uncertainty**, difficult to evaluate (compound error distributions)
- Typical measurement chain for electrical quantities in power systems: instrument transformers **and** the measurement device;
- **Any additional data processing module** contributes to an "inflation" of the uncertainty

JGCM: Evaluation of the Measurement Data - Guide to the Expression of Uncertainty in Measurement, JGCM 100:2008.

MEASUREMENT PROCESS

- from the statistical distribution of results of series of measurements (type A);

  → it can be characterized by **experimental standard deviation**.

$$u(x) = u(\overline{x}) = \sqrt{\frac{s^2(x)}{N}}$$

- from assumed probability distributions based on experience or other information: [the confidence interval is a priori known; a suitable probability distribution is assumed], (type B)

  → it can be characterized by **standard deviation;**

  → maximum entropy principle →uniform probability distribution

$$u = \frac{c_1 \times X_{max}}{100\sqrt{3}}$$

MEASUREMENT PROCESS

combined standard uncertainty: "standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities”

$$y = f(x_1, x_2, \ldots, x_N)$$

- **Uncorrelated input quantities**: $$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)$$

- **Correlated input quantities**: $$u_c^2(y) = \sum_{i=1}^{N} c_i^2 u^2(x_i) + 2\sum_{i=1}^{N-1} \sum_{j=1}^{N} c_i c_j u(x_i) u(x_j) r(x_i, x_j)$$

$$r(x_i, x_j) = \frac{u(x_i, x_j)}{u(x_i) u(x_j)}$$

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1} \sum_{j=1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)$$

MEASUREMENT PROCESS. THE MEASUREMENT PARADIGM IN POWER SYSTEMS.

- Specific to power systems monitoring: the [time-] **aggregator** (**inherited from analogic way of data compression**)

- Existing [series of] standards

IEC 61000-4-30 ed .3.0, Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods, Feb. 2015

- information concentrators (rms values; PQ indices) provide **data compression** capabilities while **keeping an analogue signal processing perspective**:
  - synchronous averaging (rms "*instantaneous*" values of periodic signals)
  - data aggregation (**in time**) with asynchronous averaging algorithms.

MEASUREMENT PARADIGM IN POWER SYSTEMS. INFORMATION CONCENTRATORS

Signals →information retrieved from measurements on signals

Deterministic signals → observation time window T_w: $u(t)$; u_{max}; u_{min}

Deterministic, **periodic signals → observation time window T:**

peak-to-peak voltage; mean value u; average value; **rms value;** crest factor; form factor; etc.

$$\bar{u} = \frac{1}{T} \cdot \int_{t_0}^{T+t_0} u(t)dt$$

$$\bar{u}_k = \frac{1}{N} \times \sum_{j=k}^{j=N+k-1} u[j]$$

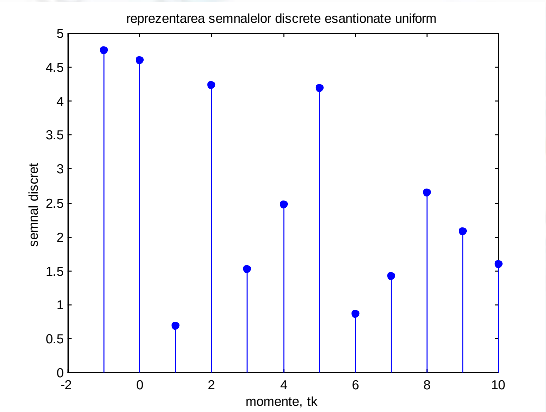
$$x(t_k) = x(k \cdot \Delta t) = x[k]$$

$$\overline{|u|} = \frac{1}{T} \cdot \int_{t_0}^{T+t_0} |u(t)| dt$$

$$\overline{|u|}_k = \frac{1}{N} \times \sum_{j=k}^{j=N+k-1} |u[j]|$$

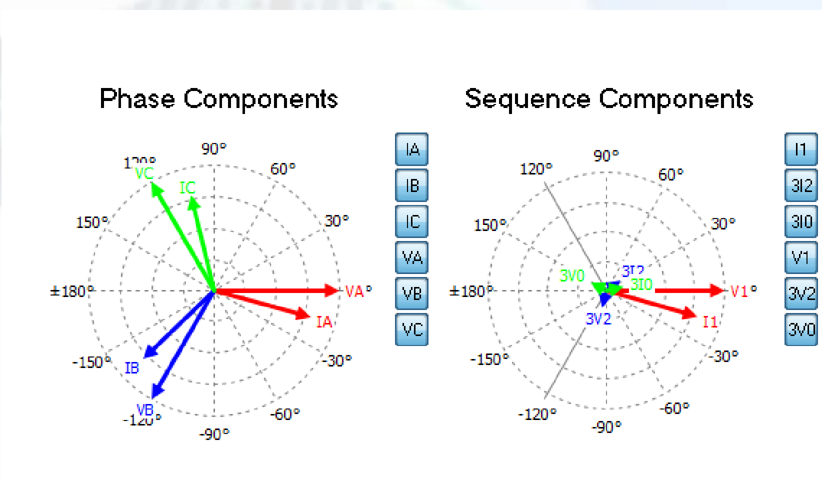
$$U = \sqrt{\frac{1}{T} \cdot \int_{t_0}^{T+t_0} [u(t)]^2 dt}$$

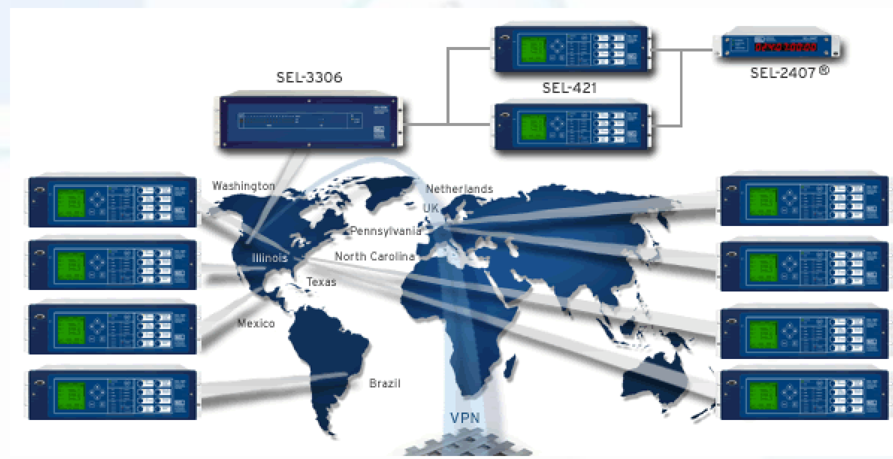
$$U_k = \sqrt{\frac{1}{N} \times \sum_{j=k}^{j=N+k-1} u^2[j]}$$



MEASUREMENTS IN POWER SYSTEMS. SYNCHRONIZED MEASUREMENTS. PMU

- The Phasor Measurement Unit (PMU) is the key element of the synchronized phasor measurement technology
- Dispersed PMUs in the power system are synchronized using a GPS signal, enabling the PMU to provide voltage and current phasor measurements.
- Synchronized phasor measurements are distinguished by their high fidelity, in comparison to the conventional measurements (i.e., real and reactive power injections and flows, voltage magnitudes)
- Still deivers an **information concentrator** only! ← → **signal model!**





MEASUREMENTS IN POWER SYSTEMS. SYNCHRONIZED MEASUREMENTS. PMU

Synchronized measurement technology has the potential of becoming the backbone for a "real-time" wide area monitoring, protection and control (WAMPAC) system.

PMU measurements are delivered (made available) at a high speed (30-120 samples [frames] per second);

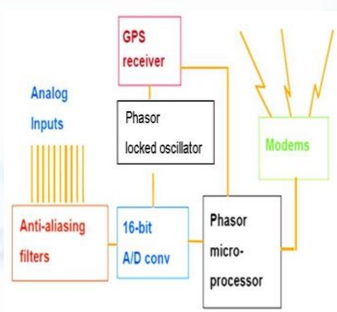
synchronized measurement system:

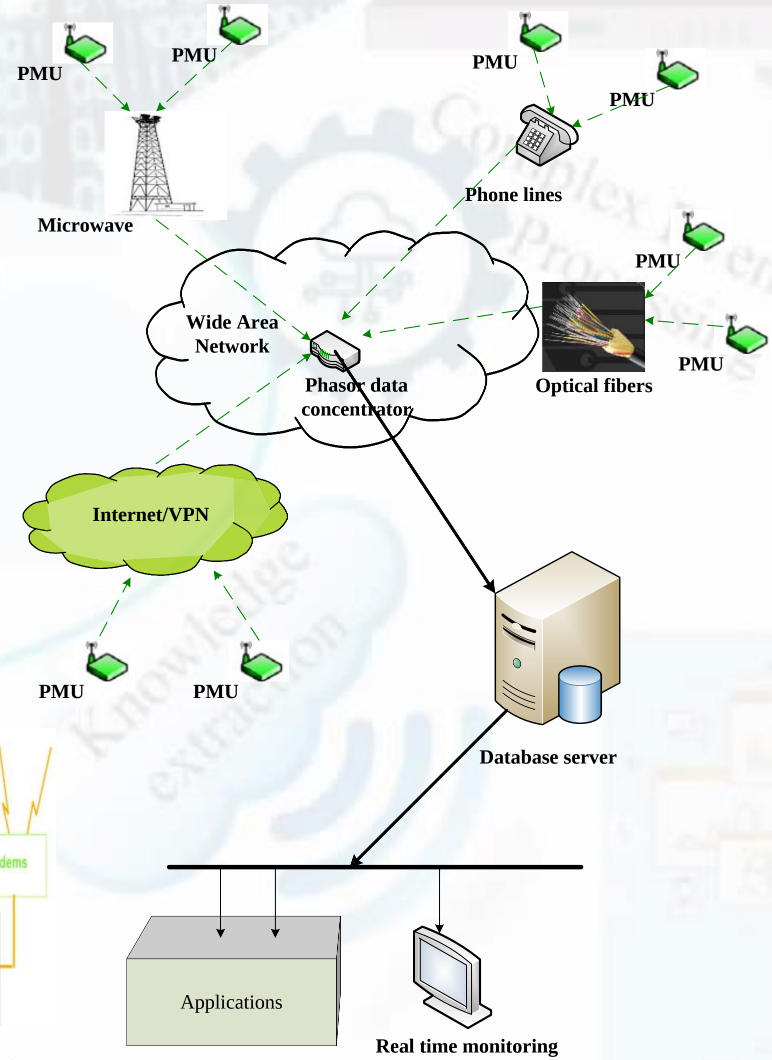
-- Synchronized measurement units (SMU), such as PMUs

-- Phasor data concentrators

-- Application software and servers

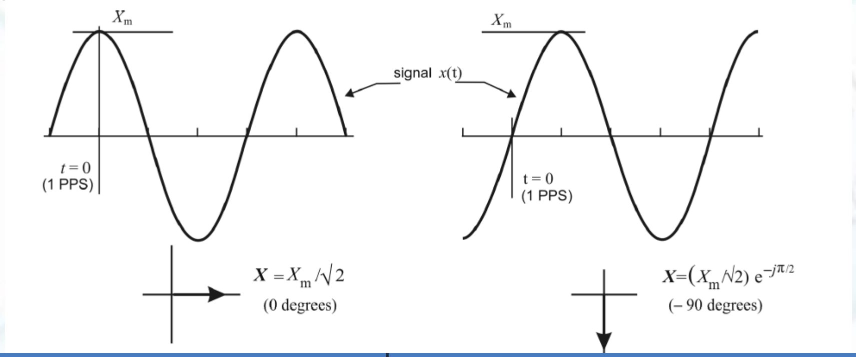
-- A wide area network





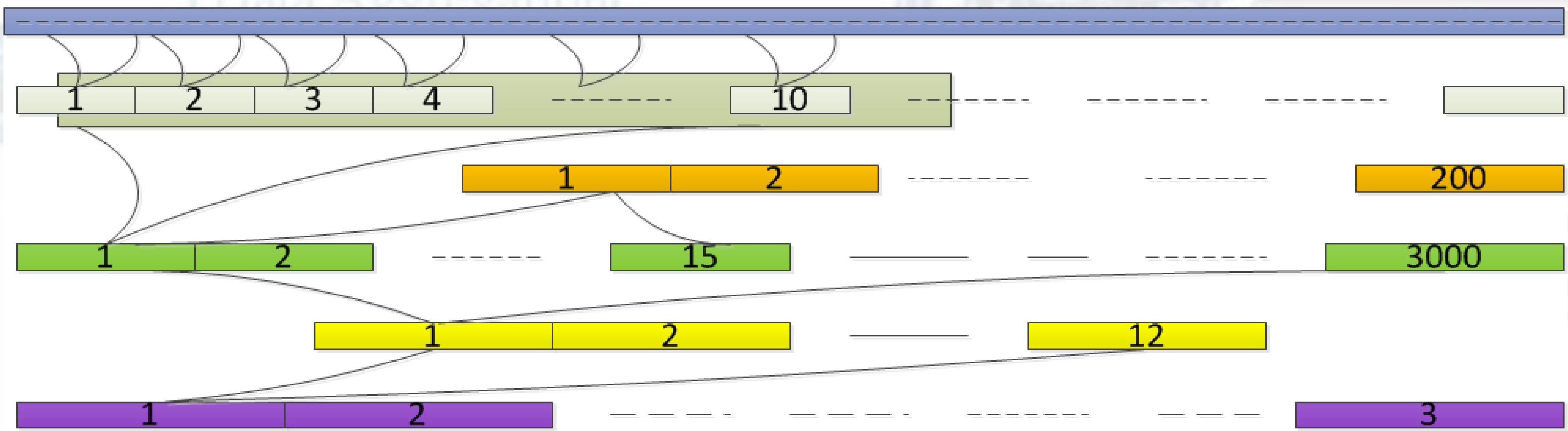
MEASUREMENTS IN POWER SYSTEMS. SYNCHRONIZED MEASUREMENTS. PMU

- **phasor:** A complex **equivalent**, in polar or rectangular form, of a **sinusoidal wave quantity**.
- **synchronized phasor or synchrophasor**: A phasor calculated from data samples using a **standard time signal as the reference** for the measurement.
- **phasor measurement unit** (PMU): a device that **measures** and **reports** synchronized phasor, frequency, and ROCOF **estimates** from voltage and/or current signals *and* a time synchronizing signal.
- **phasor data concentrator (PDC)**: **A function** that **collects** phasor data, and discrete event data from PMUs and possibly from other PDCs, and **transmits** data to other applications.



f_s	50 Hz				60 Hz						
fps	.. 1	10	25	50	.. 1	10	12	15	20	30	60

MEASUREMENT PARADIGM IN POWER SYSTEMS. AGGREGATION IN TIME DOMAIN



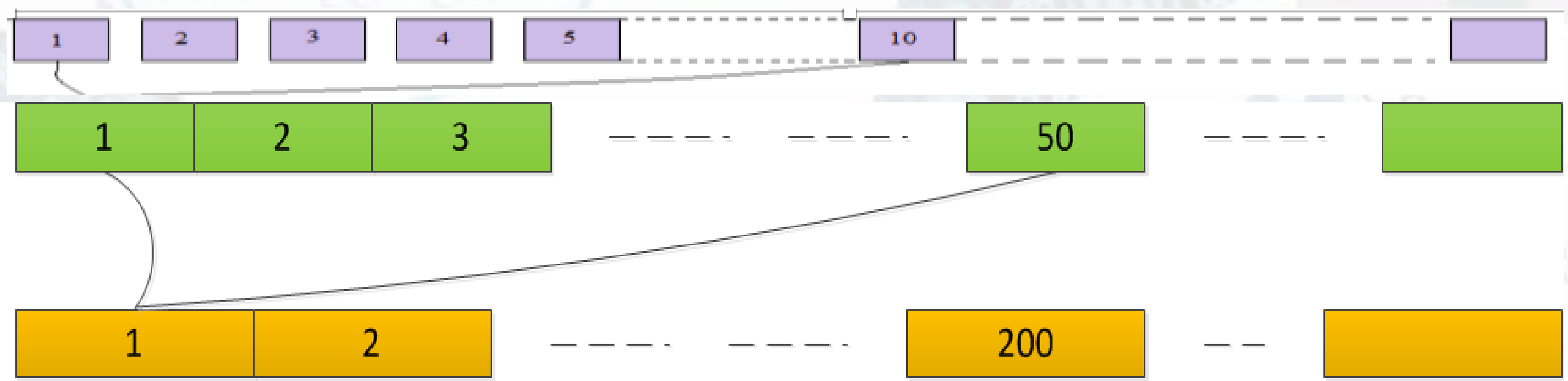
IEC 61000-4-30 ed2.0, Electromagnetic compatibility (EMC) Part 4-30: Testing and measurement techniques - Power quality measurement methods, 2008 (preserved in ed.3, 2015)

- Original signal
- RMS computed every period
- RMS computed every 200 ms
- RMS computed every 3s
- RMS computed every 10 minutes
- RMS computed every 2 hours

$$X^{A}_{(L_P+1)} = \sqrt{\frac{\sum_{k=1}^{M_{L_P}} \left(X^{2}_{(L_P)}\right)_k}{M_{L_P}}}$$

Phenomena – measurement: Signal (waveform) – [sampling] – compression – reporting (time granularity) → **knowledge**

MEASUREMENT PARADIGM IN POWER SYSTEMS. AGGREGATION IN TIME DOMAIN



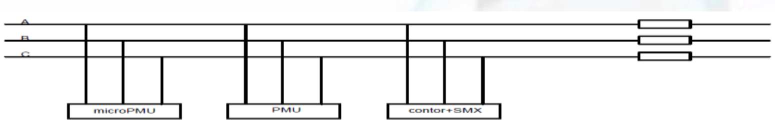
Original signal f[k]

Average over 10 cycles – 200ms

Average over 10s

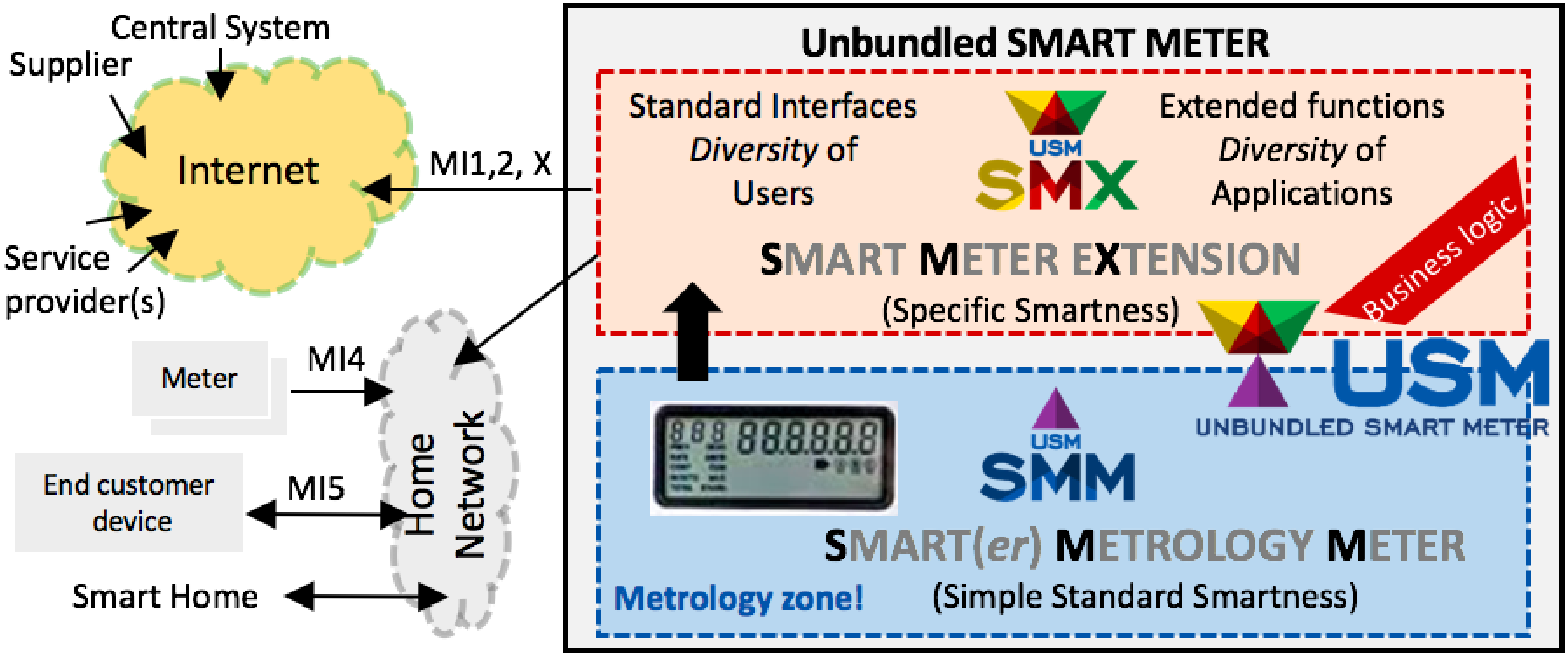
$$f_{(L_P+1)} = \frac{M_{L_P}}{M_{L_P}} \sum_{k=1} T_k^{L_P}$$

IEC 61000-4-30 ed2.0, Electromagnetic compatibility (EMC) Part 4-30: Testing and measurement techniques - Power quality measurement methods, 2008 (preserved in ed.3, 2015)

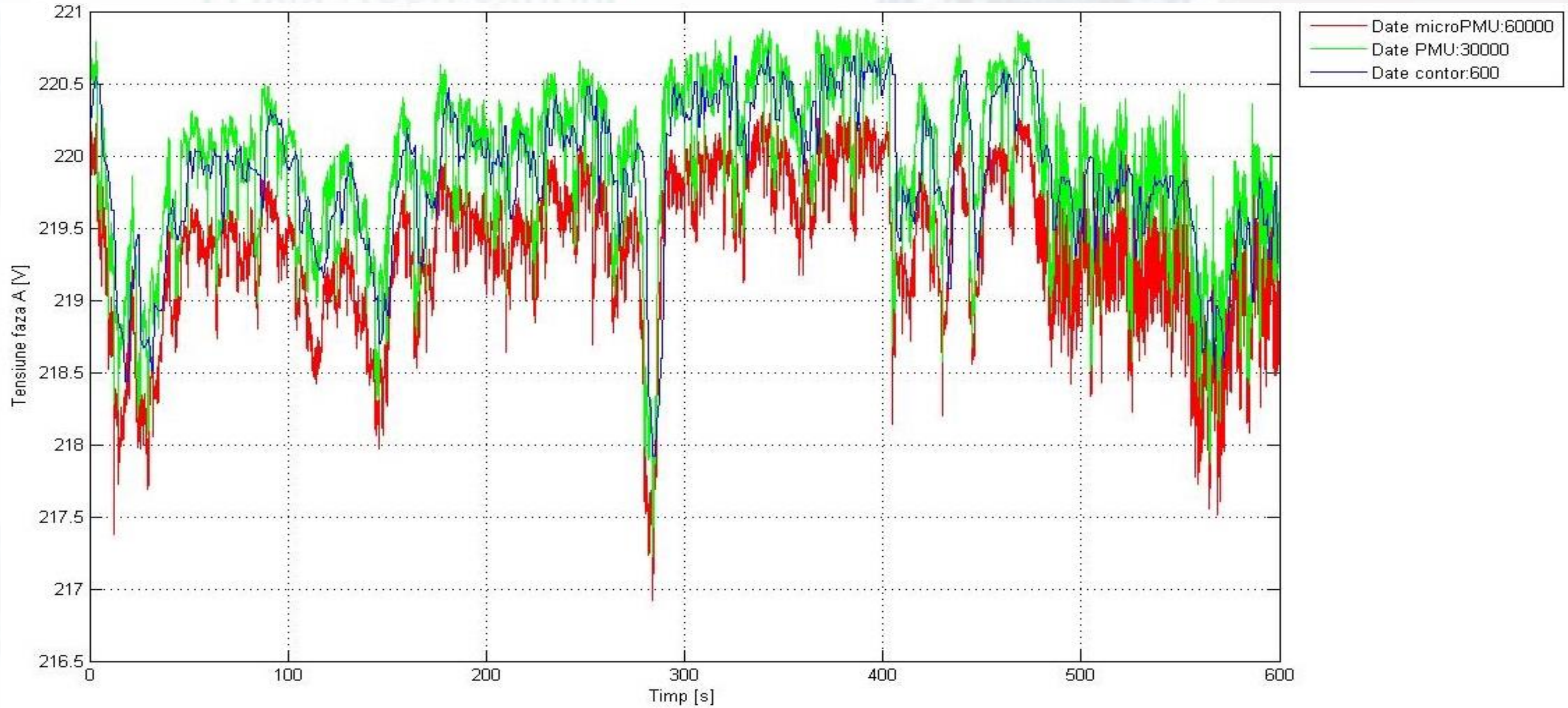


Smart Meters/ The unbundled Smart Meter

NobelGrid project



VOLTAGE MEASUREMENT AND REPORTING



microPMU (100 frames/s), PMU (50 frames/s), smart meter (1 frame/s)
15.03.2017, 09:00 - 09:10 UTC

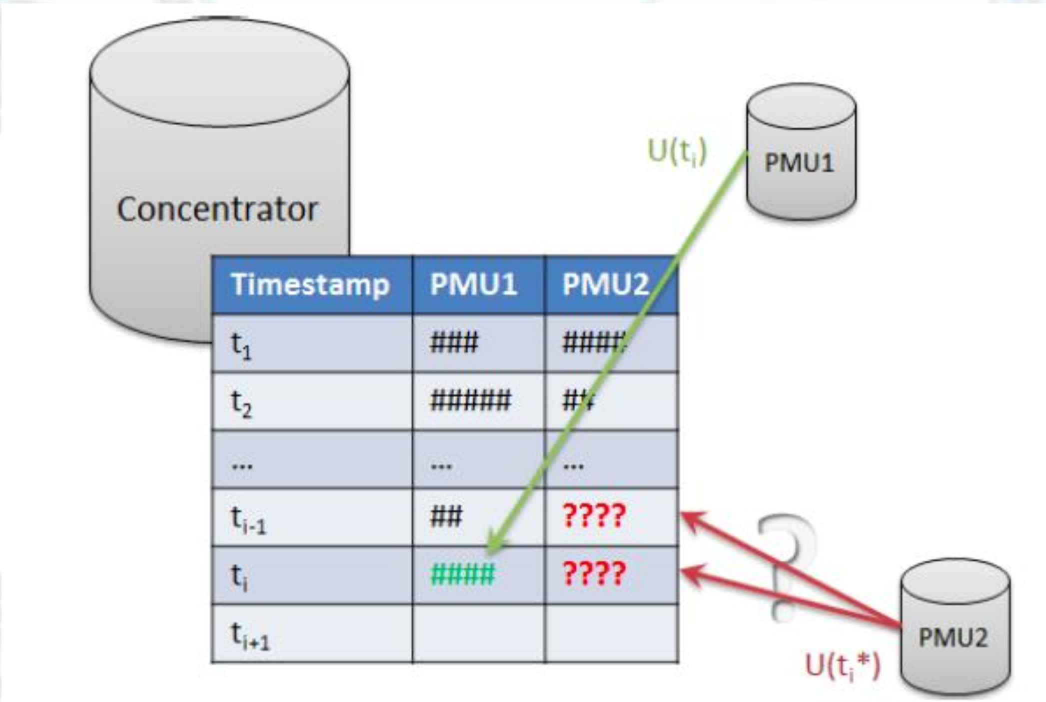
VOLTAGE MEASUREMENT AND REPORTING. LOSS OF INFORMATION

15/03/2017 09^{00}-09^{10}	15/03/2017 10^{55}-11^{55}	15/03/2017 18^{00}-18^{10}	19/03/2017 09^{00}-09^{10}	20/04/2017 02^{30}-02^{40}	22/05/2017 08^{25}-08^{35}	22/05/2017 08^{35}-08^{45}	22/05/2017 09^{00}-09^{10}	22/05/2017 09^{10}-09^{20}	22/05/2017 09^{20}-09^{30}	Minim	Maxim
Eroarea relativa a agregarii tensiunii furnizata de microPMU pe 200 ms [%]											
0,03337	0,02463	0,04142	0,02531	0,04414	0,05431	0,02783	0,04472	0,02334	0,03969	0,02334	0,05431
Eroarea relativa a agregarii tensiunii furnizata de microPMU pe 3 s [%]											
0,07808	0,06379	0,07989	0,06144	0,05942	0,11028	0,08075	0,06048	0,03860	0,04649	0,03860	0,11028
Eroarea relativa a agregarii tensiunii furnizata de microPMU pe 10 min [%]											
0,24217	0,19998	0,20002	0,14777	0,11749	0,18238	0,15397	0,22607	0,14047	0,09146	0,09146	0,24217
Eroarea relativa a agregarii tensiunii furnizata de PMU pe 200 ms [%]											
0,03411	0,03195	0,04021	0,02994	0,03212	0,04576	0,02420	0,03215	0,01782	0,02922	0,01782	0,04576
Eroarea relativa a agregarii tensiunii furnizata de PMU pe 3 s [%]											
0,10629	0,08890	0,10644	0,09212	0,05869	0,10987	0,08048	0,05946	0,03796	0,04632	0,03796	0,10987
Eroarea relativa a agregarii tensiunii furnizata de PMU pe 10 min [%]											
0,25782	0,21353	0,22220	0,17402	0,11548	0,20393	0,14946	0,22358	0,13201	0,09346	0,09346	0,25782
Eroarea relativa a agregarii tensiunii furnizata de contor pe 3 s [%]											
0,06174	0,04963	0,05955	0,04510	0,03739	0,08600	0,07204	0,03998	0,03213	0,02865	0,02865	0,08600
Eroarea relativa a agregarii tensiunii furnizata de contor pe 10 min [%]											
0,23893	0,19735	0,19517	0,14329	0,10898	0,16962	0,14447	0,22216	0,13416	0,08251	0,08251	0,23893

10 data sets

microPMU (100 frames/s; 0,01%), PMU (50 frames/s, 0,02%), smart meter (1 frame/s, 0,5%)

MEASUREMENTS IN POWER SYSTEMS. SYNCHRONIZED MEASUREMENTS. PMUs



Timestamp	PMU1	PMU2
t_1	###	####
t_2	#####	##
...	...	...
t_{i-1}	##	????
t_i	####	????
t_{i+1}		

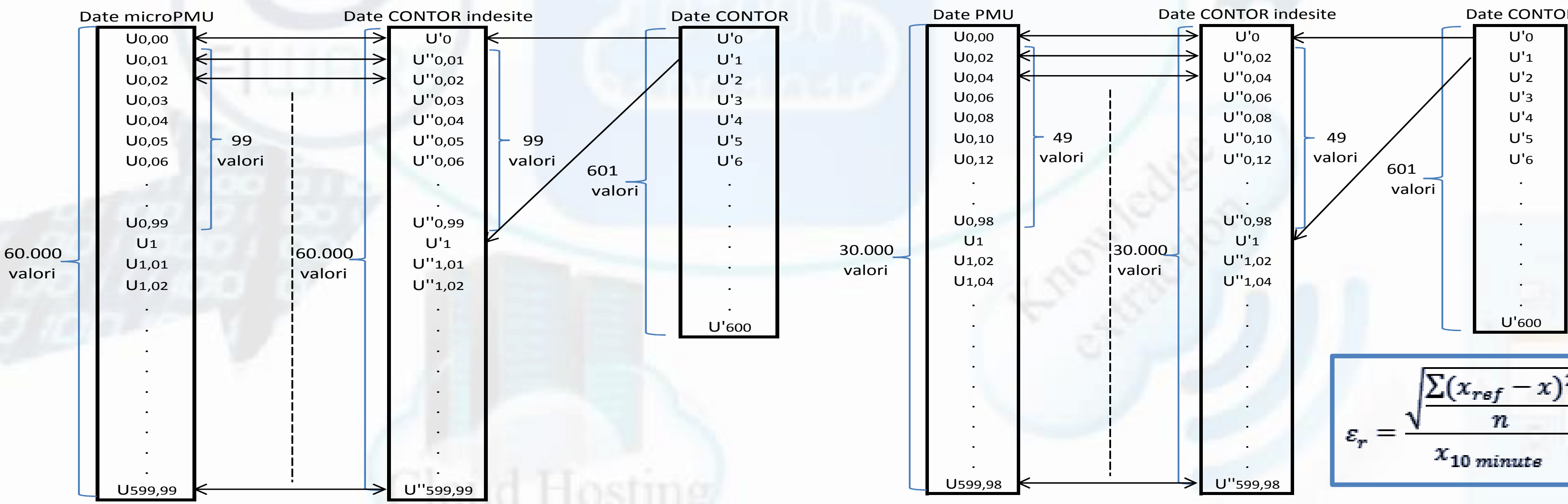
Time alignment decision algorithm for heterogenous reporting rates

Heterogenous Data Reporting. Resampling

State estimation: U, P, Q → microPMU → PMU / Smart meter / meter

→ PMU → meter / Smart meter

Evaluation of 4 resampling algorithms



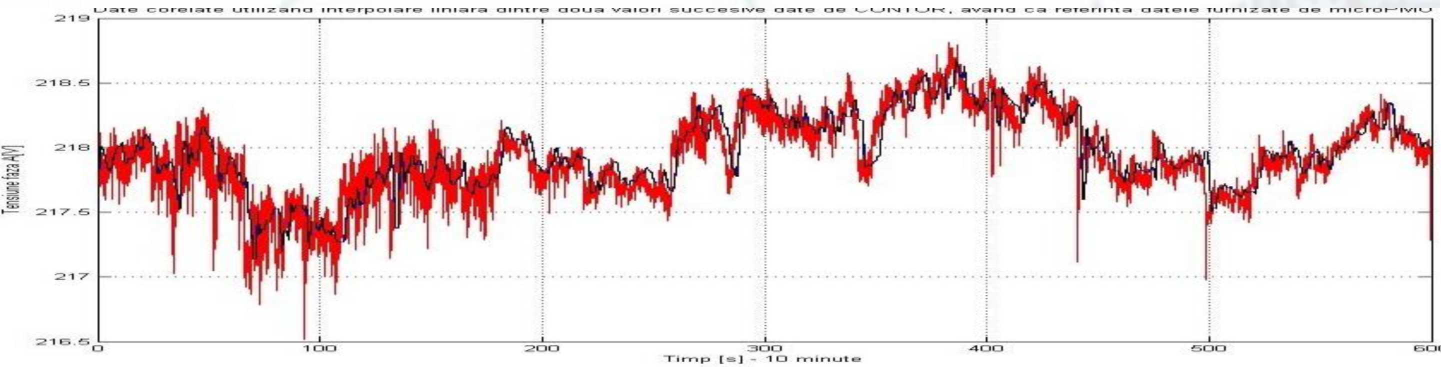
$$\varepsilon_r = \frac{\sqrt{\frac{\Sigma(x_{ref} - x)^2}{n}}}{x_{10\ minute}}$$

HETEROGENOUS DATA REPORTING. RESAMPLING

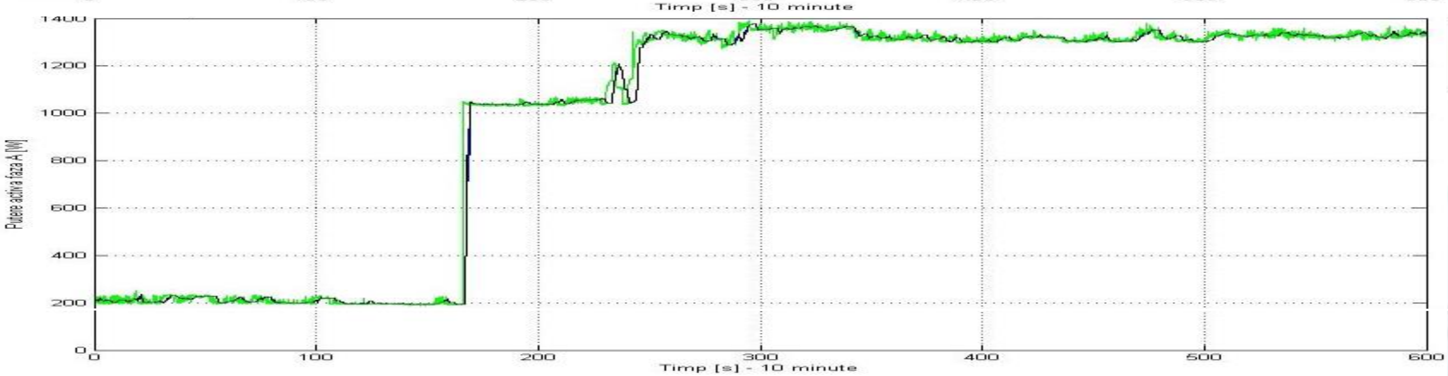
Reference:
PMU

	Medie aritmetică	Medie patratică	Re-eşantionare simplă	Interpolare liniară	Concluzii	
	εr_U [%]				Minim	Metoda
15/03/2017, 09:00-09:10	0,17953	0,17953	0,19718	0,18210	0,17953	Medie aritmetică / pătratică
15/03/2017, 10:55-11:05	0,15283	0,15283	0,16729	0,15469	0,15283	Medie aritmetică / pătratică
15/03/2017, 18:00-18:10	0,18812	0,18813	0,20280	0,19007	0,18812	Medie aritmetică
19/03/2017, 09:00-09:10	0,15330	0,15330	0,16126	0,15492	0,15330	Medie aritmetică / pătratică
20/04/2017, 02:30-02:40	0,10259	0,10258	0,11061	0,10383	0,10258	Medie pătratică
22/05/2017, 08:25-08:35	0,48786	0,48784	0,49696	0,48966	0,48784	Medie pătratică
22/05/2017, 08:35-08:45	0,56774	0,56772	0,57168	0,56896	0,56772	Medie pătratică
22/05/2017, 09:00-09:10	0,55468	0,55467	0,55578	0,55501	0,55467	Medie pătratică
22/05/2017, 09:10-09:20	0,54231	0,54230	0,54340	0,54250	0,54230	Medie pătratică
22/05/2017, 09:20-09:30	0,53783	0,53782	0,53849	0,53802	0,53782	Medie pătratică
	εr_P [%]				Minim	Metoda
22/05/2017, 08:25-08:35	5,06482	4,94021	5,88136	5,12414	4,94021	Medie pătratică
22/05/2017, 08:35-08:45	0,69925	0,69932	0,75805	0,71108	0,69925	Medie aritmetică
22/05/2017, 09:00-09:10	0,52383	0,52389	0,55911	0,53502	0,52383	Medie aritmetică
22/05/2017, 09:10-09:20	0,27431	0,27439	0,29929	0,27689	0,27431	Medie aritmetică
22/05/2017, 09:20-09:30	0,26594	0,26598	0,28097	0,26956	0,26594	Medie aritmetică
	εr_Q [%]				Minim	Metoda
22/05/2017, 08:25-08:35	7,36797	7,36422	7,90071	7,42357	7,36422	Medie pătratică
22/05/2017, 08:35-08:45	6,63738	6,64254	6,80790	6,66512	6,63738	Medie aritmetică
22/05/2017, 09:00-09:10	6,51664	6,52223	6,62679	6,54807	6,51664	Medie aritmetică
22/05/2017, 09:10-09:20	6,09992	6,10145	6,15051	6,10653	6,09992	Medie aritmetică
22/05/2017, 09:20-09:30	6,19497	6,19668	6,23276	6,20517	6,19497	Medie aritmetică

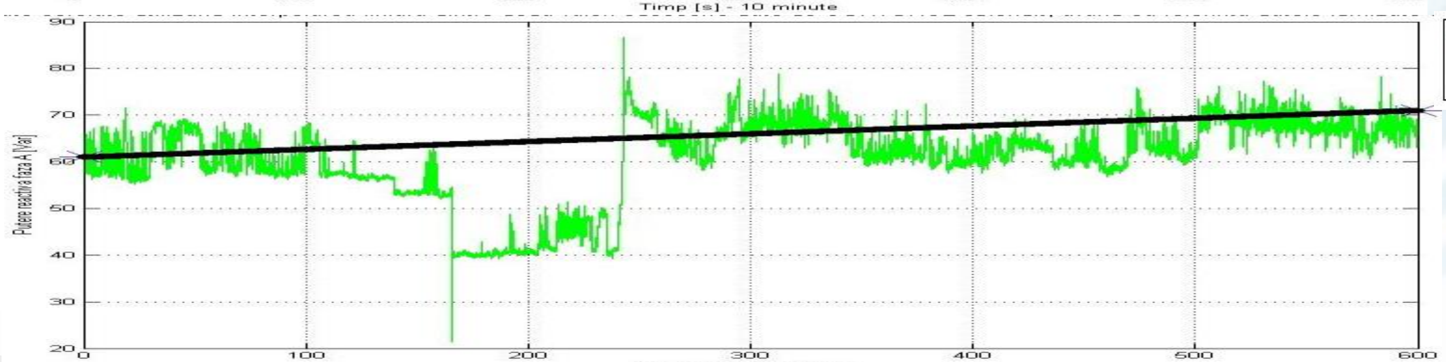
Heterogenous Data Reporting. Resampling



Voltage resampling: smart meter / microPMU (reference)



Active power resampling: smart meter / PMU (reference)



reactive power resampling: meter / PMU (reference)

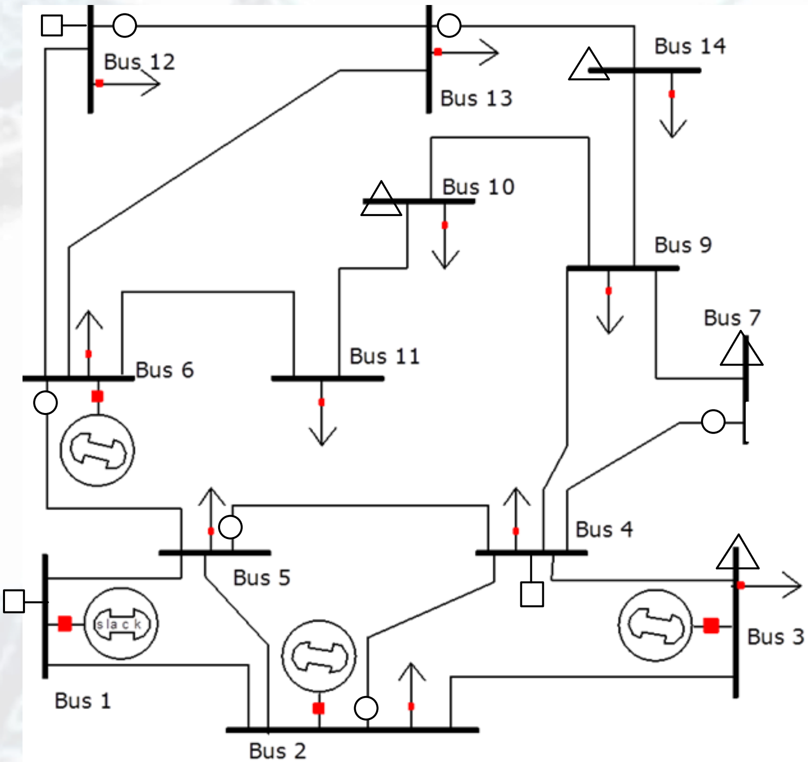
State Estimation

Measurements every 2-30 s
Not synchronized

State Estimation (SE) **executed every 1-5 min using asynchronous measurements**

Goal of state estimation: Obtain an estimate of the "state" of the system (V and δ at every bus)

When the state is known, all MW and MVAr flows can be calculated.

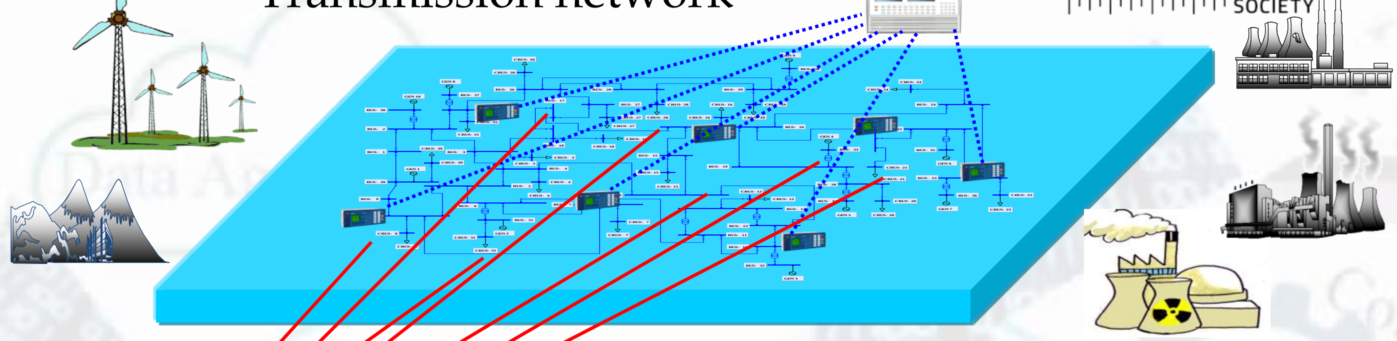


○ Active/reactive power flow measurement
□ Active/reactive injection measurement
△ Voltage magnitude measurement

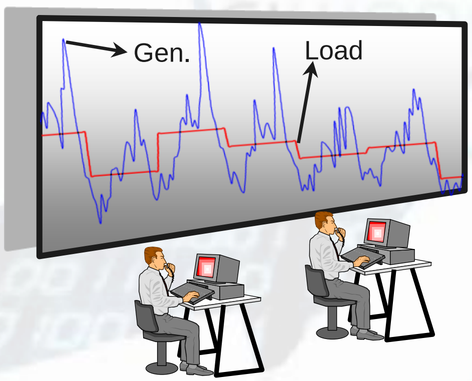
SE assumptions:

- **Balanced system**
- **Line parameters perfectly known**
- **No time-skew between measurements**
- **Topology known**

Transmission network



Measurements:
U, θ, P, Q



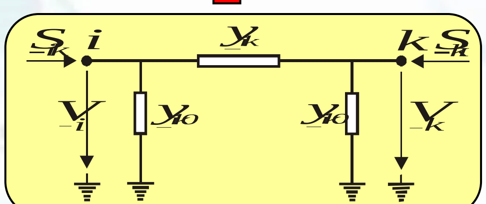
$$\begin{bmatrix} \underline{I}_1 \\ \cdots \\ \underline{I}_k \\ \cdots \\ \underline{I}_k \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \cdots & \underline{Y}_{1k} & \cdots & \underline{Y}_{nk} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \underline{Y}_{k1} & \cdots & \underline{Y}_{kk} & \cdots & \underline{Y}_{nk} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \underline{Y}_{n1} & \cdots & \underline{Y}_{nk} & \cdots & \underline{Y}_{nn} \end{bmatrix} \begin{bmatrix} \underline{U}_1 \\ \cdots \\ \underline{U}_k \\ \cdots \\ \underline{U}_n \end{bmatrix}$$

Voltage level

Estimated $U_{min} \le U_k \le U_{max}$

Power flow

$S_{ik} \le S_{ik,adm}$



R, X

G_0, B_0

CONVENTIONAL STATE ESTIMATION

Model of the state estimator $\mathbf{z} = \mathbf{h}(\mathbf{x}) + \mathbf{e}$

$$\begin{bmatrix} P_{flow} \\ Q_{flow} \\ P_{inj} \\ Q_{inj} \\ V \end{bmatrix} = \begin{bmatrix} P_{ij} = V_i^{\,2}(g_{si} + g_{ij}) - V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}) \\ Q_{ij} = -V_i^{\,2}(b_{si} + b_{ij}) - V_i V_j (g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}), \\ P_i = V_i \sum_{j\in\aleph_i} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ Q_i = V_i \sum_{j\in\aleph_i} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \\ V_i \end{bmatrix} + \mathbf{e}$$

Estimation of the state vector x using the WLS methodology

$$Min: \; J(x) = [z - h(x)]R^{-1}[z - h(x)]$$

z is the measurement vector
h(x) is the vector containing equations that
Relates measurements to system states
R is measurement error covariance matrix

Solution:

$$x^{k+1} = x^k + [G(x^k)]^{-1} H^T(x^k) R^{-1} [z - h(x^k)]$$

where,

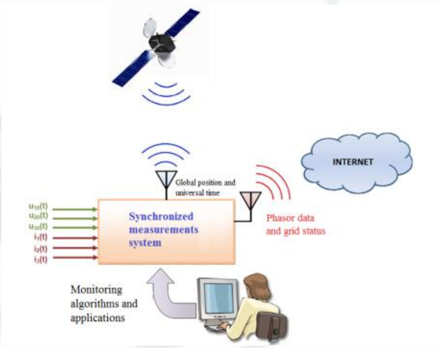
$$H(x) = \frac{\partial h(x)}{\partial x}$$ Jacobian matrix

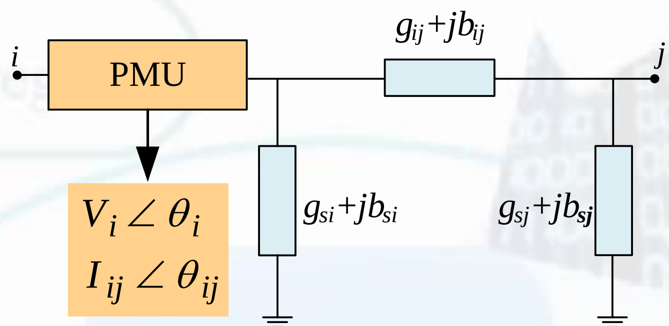
$$G(x^k) = H^T(x^k) R^{-1} H(x^k)$$ Gain matrix

$$H(x) = \begin{bmatrix} \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial Q_{flow}}{\partial \theta} & \frac{\partial Q_{flow}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \end{bmatrix}$$

The iterative process stops when the element of Δx with the maximum value is smaller than a predefined threshold

LINEAR STATE ESTIMATION





$$V_i^{meas} \angle \theta_i^{meas} = \underbrace{V_i \cos\theta_i}_{V_{real}^{meas}} + j\underbrace{V_i \sin\theta_i}_{V_{imag}^{meas}}$$

$$I_{real}^{meas} = V_i \cos\theta_i (g_{si} + g_{ij}) - V_i \sin\theta_i (b_{si} + b_{ij}) + b_{ij} V_j \sin\theta_j - g_{ij} V_j \cos\theta_j$$

$$I_{imag}^{meas} = V_i \cos\theta_i (b_{si} + b_{ij}) + V_i \sin\theta_i (g_{si} + g_{ij}) - b_{ij} V_j \cos\theta_j - g_{ij} V_j \sin\theta_j$$

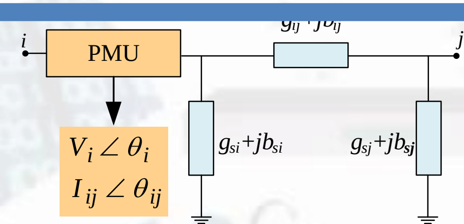
$$\mathbf{z} = \mathbf{H}\mathbf{x} + \mathbf{e} = \begin{bmatrix} \mathbf{V}_{real}^{meas} \\ \mathbf{V}_{imag}^{meas} \\ \mathbf{I}_{real}^{meas} \\ \mathbf{I}_{imag}^{meas} \end{bmatrix} = \begin{bmatrix} \partial\mathbf{V}_r/\partial\mathbf{V}_r & \partial\mathbf{V}_r/\partial\mathbf{V}_i \\ \partial\mathbf{V}_i/\partial\mathbf{V}_r & \partial\mathbf{V}_i/\partial\mathbf{V}_i \\ \partial\mathbf{I}_r/\partial\mathbf{V}_r & \partial\mathbf{I}_r/\partial\mathbf{V}_i \\ \partial\mathbf{I}_i/\partial\mathbf{V}_r & \partial\mathbf{I}_i/\partial\mathbf{V}_i \end{bmatrix} \begin{bmatrix} \mathbf{V}_r \\ \mathbf{V}_i \end{bmatrix} + \mathbf{e}$$

Weighted Least Squares

$$\Rightarrow \mathbf{x} = (\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{R}^{-1} \mathbf{z}$$

Linear State Estimation

$$\overline{V}_j = \left(\frac{\overline{V}_i - \overline{I}_{ij}\overline{Z}_c}{2}\right) e^{\overline{\gamma} l} + \left(\frac{\overline{V}_i + \overline{I}_{ij}\overline{Z}_c}{2}\right) e^{-\overline{\gamma} l}$$



$$A = \left[V_i\left(e^{\gamma_r l}\cos\varphi_1 + e^{-\gamma_r l}\cos\varphi_2\right) - I_{ij}Z_c\left(e^{\gamma_r l}\cos\varphi_3 - e^{-\gamma_r l}\cos\varphi_4\right)\right]/2$$

$$B = \left[V_i\left(e^{\gamma_r l}\sin\varphi_1 + e^{-\gamma_r l}\sin\varphi_2\right) - I_{ij}Z_c\left(e^{\gamma_r l}\sin\varphi_3 - e^{-\gamma_r l}\sin\varphi_4\right)\right]/2$$

$$\left.\begin{matrix} \varphi_1 = \theta_i + \gamma_i l; \quad \varphi_2 = \theta_i - \gamma_i l \\ \varphi_3 = \theta_{ij} + \theta_z + \gamma_i l; \quad \varphi_4 = \theta_{ij} + \theta_z - \gamma_i l \end{matrix}\right\}.$$

$$\overline{V}_j = A + jB;$$

$$V_j = \sqrt{A^2 + B^2} = f_{V_j}\left(V_i, q_i, I_{ij}, q_{ij}\right)$$

$$q_j = \tan^{-1}\left(B/A\right) = f_{q_j}\left(V_i, q_i, I_{ij}, q_{ij}\right)$$

$$\mathbf{p} = \left(V_i, q_i, I_{ij}, q_{ij}\right)$$

$u\left(\mathbf{p}(k)\right)$: standard uncertainty in $\mathbf{p}(k)$

$$u\left(\mathbf{p}(k)\right) = \frac{D\mathbf{p}(k)}{\sqrt{3}}$$

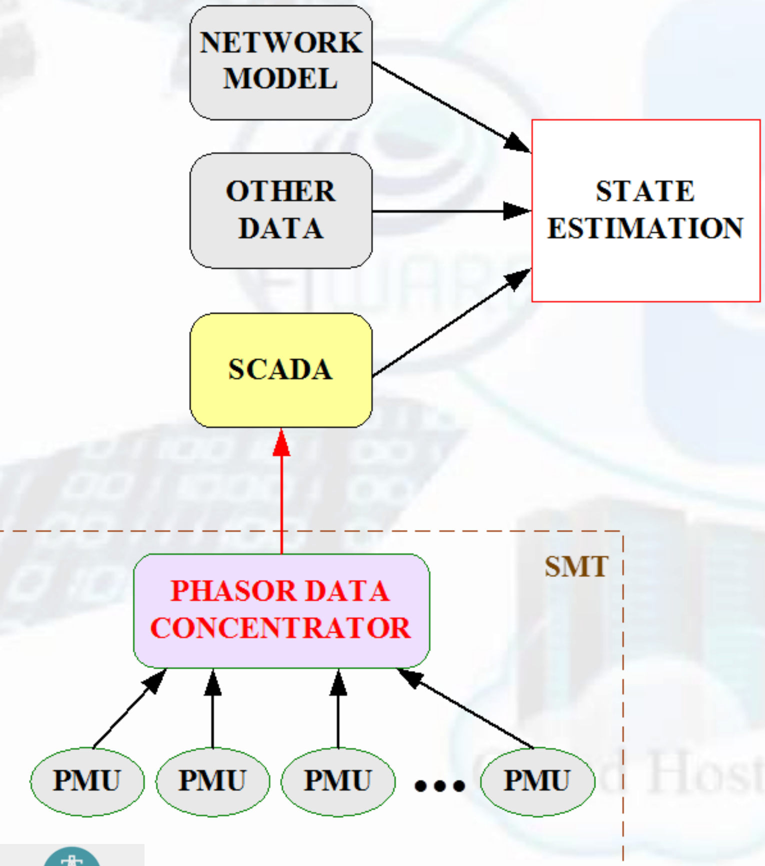
$$u(V_j) = \sqrt{\sum_{k=1}^{4}\left[\partial V_j/\partial \mathbf{p}(k)\right]^2\left[u\left(\mathbf{p}(k)\right)\right]^2}$$

$$u(\theta_j) = \sqrt{\sum_{k=1}^{4}\left[\partial \theta_j/\partial \mathbf{p}(k)\right]^2\left[u\left(\mathbf{p}(k)\right)\right]^2}$$

Hybrid State Estimation

Take advantage of voltage **and** current phasor measurements from PMUs

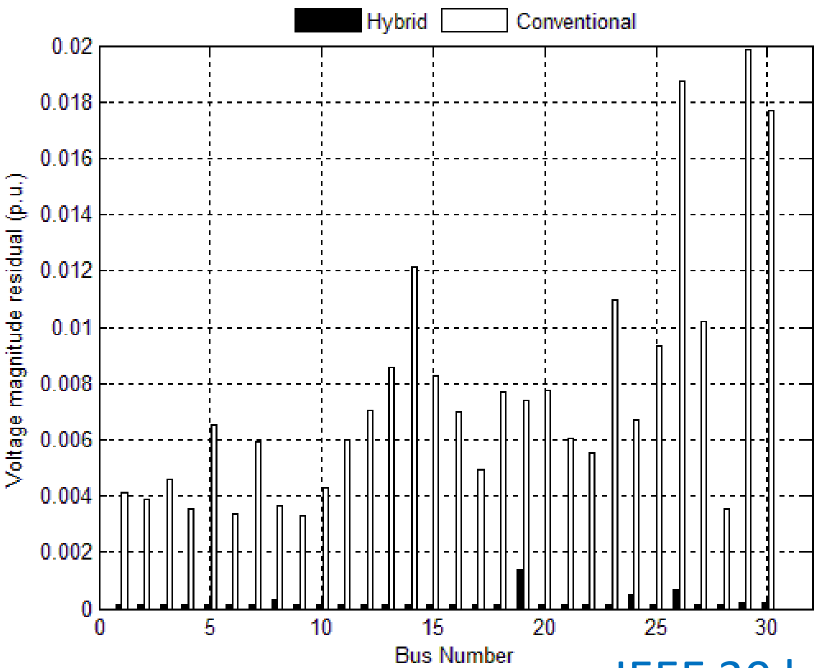
Incorporate these measurements into the existing state estimator

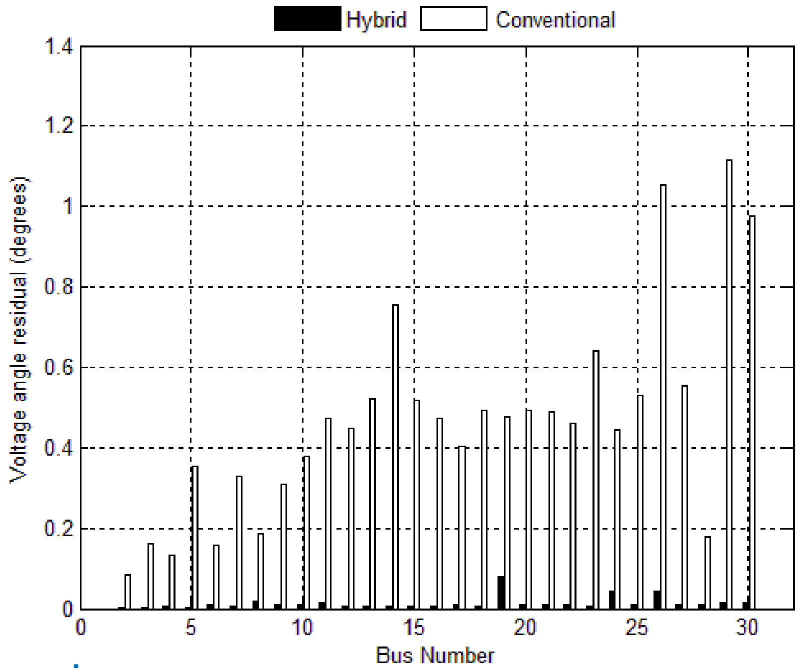


$$z_{hyb} = \begin{bmatrix} P_{flow} \\ P_{inj} \\ Q_{flow} \\ Q_{inj} \\ \theta_{Vpmu} \\ V_{pmu} \\ \theta_{Ipmu} \\ I_{pmu} \end{bmatrix}$$

$$H_{hyb}(x) = \begin{bmatrix} \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial Q_{flow}}{\partial \theta} & \frac{\partial Q_{flow}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \\ \frac{\partial \theta_{Vpmu}}{\partial \theta} & \frac{\partial \theta_{Vpmu}}{\partial V} \\ \frac{\partial V_{pmu}}{\partial \theta} & \frac{\partial V_{pmu}}{\partial V} \\ \frac{\partial \theta_{Ipmu}}{\partial \theta} & \frac{\partial \theta_{Ipmu}}{\partial V} \\ \frac{\partial I_{pmu}}{\partial \theta} & \frac{\partial I_{pmu}}{\partial V} \end{bmatrix}$$

HYBRID VS. CONVENTIONAL STATE ESTIMATOR





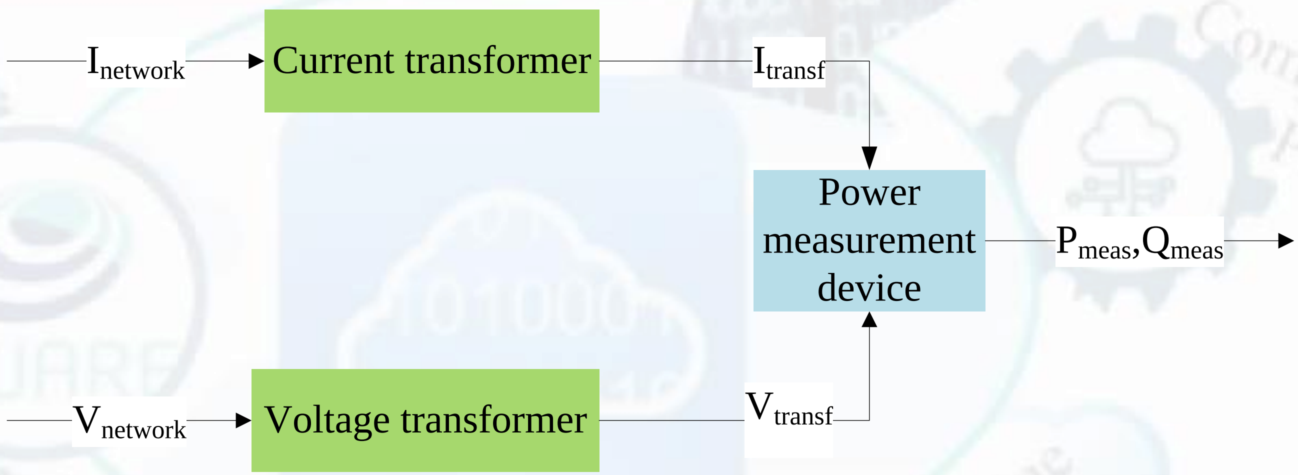
IEEE 30 bus system

Flow measurements locations (bus # - bus #)	Injection measurements locations (bus #)	PMU locations (bus #)
1-3, 2-6, 2-4, 5-7, 4-6, 6-28, 6-8, 6-9, 6-10, 12-13, 12-15, 16-17, 10-20, 10-17, 14-15, 15-23, 15-18, 25-26, 25-27, 28-27, 29-30	1, 2, 4, 6, 10, 11,12, 15, 18, 19, 24, 25,27, 30	1, 5, 10, 12, 15, 27

State Estimation and the Measurement Chain

- **Uncertainties in the measurement chain – effect on weighting matrix**
  - Measurement uncertainty: The standard deviation of a set of measurements of the same quantity, for which a specified distribution is assumed. ("Guide to the Expression of Uncertainty in Measurement, JGCM 100:2008")
- **Approximation of network model (e.g., errors in line parameters)**
  - Surveys have shown that the stored parameter values in control center databases could deviate from the real ones by as much as 30%
- **In practice, usually only the measurement device accuracy is used for measurement weighting**
- **Important to look at the whole measurement chain**

Conventional measurement chain



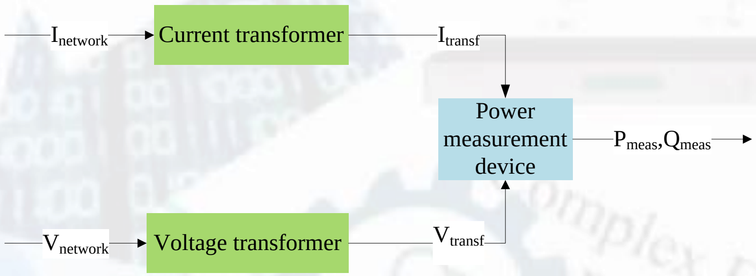
The measurement weights are based on the combined uncertainty introduced to the measurement by both instrument transformers (ITs) and measurement devices

Maximum measurement uncertainties

Real/reactive power injection (p.u.)	Real/reactive power flow (p.u)	Voltage magnitude PMU (p.u)	Current magnitude PMU (p.u)	Phase angle PMU (degrees)
3/100	3/100	0.02/100	0.03/100	0.01

STATE ESTIMATION AND THE MEASUREMENT CHAIN

Conventional measurement chain



$$V_{meas} = V_{network} + N(0, u_{VT}^{V}) + N(0, u_{MU}^{V})$$

$$I_{meas} = I_{network} + N(0, u_{CT}^{I}) + N(0, u_{MU}^{I})$$

$$q_{meas}^{V} = q_{network}^{V} + N(0, u_{VT}^{q_V}) + N(0, u_{MU}^{q_V})$$

$$q_{meas}^{I} = q_{network}^{I} + N(0, u_{CT}^{q_I}) + N(0, u_{MU}^{q_I}),$$

$$u_{VT}^{q_V} = \frac{\overline{e}_{VT}^{q_V}}{1.96} \qquad u_{CT}^{q_I} = \frac{\overline{e}_{CT}^{q_I}}{1.96}$$

$$u_{MU}^{q_V} = \frac{\overline{e}_{MU}^{q_V}}{1.96} \qquad u_{MU}^{q_I} = \frac{\overline{e}_{MU}^{q_I}}{1.96}$$

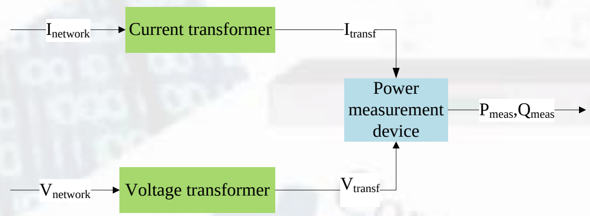
$$u_{meas}^{V} = \sqrt{(u_{VT}^{V})^2 + (u_{MU}^{V})^2}$$

$$u_{meas}^{q_V} = \sqrt{(u_{VT}^{q_V})^2 + (u_{MU}^{q_V})^2}$$

$$u_{VT}^{V} = \frac{\overline{e}_{VT}^{V}}{1.96}\left|V_{meas}\right| \qquad u_{CT}^{I} = \frac{\overline{e}_{CT}^{I}}{1.96}\left|I_{meas}\right|$$

$$u_{MU}^{V} = \frac{\overline{e}_{MU}^{V}}{1.96}\left|V_{meas}\right| \qquad u_{MU}^{I} = \frac{\overline{e}_{MU}^{I}}{1.96}\left|I_{meas}\right|,$$

Conventional measurement chain



$$P_{meas} = V_{transf} I_{transf} \cos(\theta^{V}_{transf} - \theta^{I}_{transf}) \qquad Q_{meas} = V_{transf} I_{transf} \sin(\theta^{V}_{transf} - \theta^{I}_{transf}).$$

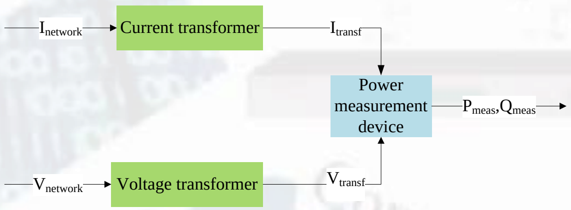
$$\frac{u_{IT}^{P_{meas}}}{P_{meas}} = \sqrt{\frac{1}{(P_{meas})^2} \sum_{k=1}^{4} \left[\frac{\partial (P_{meas})}{\partial \boldsymbol{\pi}_{tr}(k)}\right]^2 .[u(\boldsymbol{\pi}_{tr}(k))]^2} \qquad \frac{u_{IT}^{Q_{meas}}}{Q_{meas}} = \sqrt{\frac{1}{(Q_{meas})^2} \sum_{k=1}^{4} \left[\frac{\partial (Q_{meas})}{\partial \boldsymbol{\pi}_{tr}(k)}\right]^2 .[u(\boldsymbol{\pi}_{tr}(k))]^2},$$

$$\frac{u_{IT}^{P_{meas}}}{P_{meas}} = \sqrt{\left(\frac{u_{VT}^{V}}{V}\right)^2 + \left(\frac{u_{CT}^{I}}{I}\right)^2 + \left(u_{VT}^{\theta_V} \tan \Delta\theta\right)^2 + \left(u_{CT}^{\theta_I} \tan \Delta\theta\right)^2}$$

$$\frac{u_{IT}^{Q_{meas}}}{Q_{meas}} = \sqrt{\left(\frac{u_{VT}^{V}}{V}\right)^2 + \left(\frac{u_{CT}^{I}}{I}\right)^2 + \left(\frac{u_{VT}^{\theta_V}}{\tan \Delta\theta}\right)^2 + \left(\frac{u_{CT}^{\theta_I}}{\tan \Delta\theta}\right)^2} \qquad \tan \Delta\theta = \frac{Q_{meas}}{P_{meas}}$$

State Estimation and the Measurement Chain

Conventional measurement chain



$$P_{meas} = V_{transf} I_{transf} \cos(\theta^{V}_{transf} - \theta^{I}_{transf}) \qquad Q_{meas} = V_{transf} I_{transf} \sin(\theta^{V}_{transf} - \theta^{I}_{transf}).$$

$$u(P_{meas}, Q_{meas}) = \sqrt{\sum_{k=1}^{4} \left[\frac{\partial P_{meas}}{\partial \mathbf{p}_{tr}(k)} \quad \frac{\partial Q_{meas}}{\partial \mathbf{p}_{tr}(k)} \right] [u(\mathbf{p}_{tr}(k))]^2}$$

$$\mathbf{p}_{tr}(k) = [V_{transf}, I_{transf}, \theta^{V}_{transf}, \theta^{I}_{transf}] \qquad u(\mathbf{p}_{tr}) = \left[u^{V}_{VT} \quad u^{I}_{CT} \quad u^{\theta_V}_{VT} \quad u^{\theta_I}_{CT} \right]$$

$$u^{P,Q}_{meas} = \sqrt{(u_{IT})^2 + (u^{P,Q}_{MU})^2}, \qquad u^{P,Q}_{MU} = \frac{\bar{e}^{P,Q}_{MU}}{1.96}(P_{meas}, Q_{meas}).$$

MicroDERLab

IEEE INSTRUMENTATION & MEASUREMENT SOCIETY

IEEE

State Estimation and the Measurement Chain

PMU measurement chain → linear estimator

$V_{network}$ / $I_{network}$ → **Instrument transformer** → V_{transf} / I_{transf} → **Measurement device** → V_{meas} / I_{meas} →

$$V_{meas}\angle\theta^{V}_{meas} = \underbrace{V_{meas}\cos(\theta^{V}_{meas})}_{V_r} + j\underbrace{V_{meas}\sin(\theta^{V}_{meas})}_{V_i} \qquad I_{meas}\angle\theta^{I}_{meas} = \underbrace{I_{meas}\cos(\theta^{I}_{meas})}_{I_r} + j\underbrace{I_{meas}\sin(\theta^{I}_{meas})}_{I_i}.$$

$$S_V = [V_r \quad V_i] \quad S_I = [I_r \quad I_i]$$

$$u(\mathbf{S}_V) = \sqrt{\sum_{k=1}^{2} [\partial(\mathbf{S}_V)/\partial\mathbf{p}_V(k)]^2.[u(\mathbf{p}_V(k))]^2}$$

$$u(\mathbf{S}_I) = \sqrt{\sum_{k=1}^{2} [\partial(\mathbf{S}_I)/\partial\mathbf{p}_I(k)]^2.[u(\mathbf{p}_I(k))]^2},$$

$$\mathbf{p}_V = \begin{bmatrix} V_{meas} & q^{V}_{meas} \end{bmatrix} \quad \mathbf{p}_I = \begin{bmatrix} I_{meas} & q^{I}_{meas} \end{bmatrix}$$

$$u(\mathbf{p}_V) = \begin{bmatrix} u^{V}_{meas} & u^{q_V}_{meas} \end{bmatrix} \quad u(\mathbf{p}_I) = \begin{bmatrix} u^{I}_{meas} & u^{q_I}_{meas} \end{bmatrix}.$$

$$u(V_i, V_r) = u(V_r, V_i) = \sqrt{\sum_{k=1}^{2} \frac{\partial V_r}{\partial\mathbf{p}_V(k)}\frac{\partial V_i}{\partial\mathbf{p}_V(k)}[u(\mathbf{p}_V(k))]^2} \qquad u(I_i, I_r) = u(I_r, I_i) = \sqrt{\sum_{k=1}^{2} \frac{\partial I_r}{\partial\mathbf{p}_I(k)}\frac{\partial I_i}{\partial\mathbf{p}_I(k)}[u(\mathbf{p}_I(k))]^2}$$

Measurement Chain: Instrument Transformers

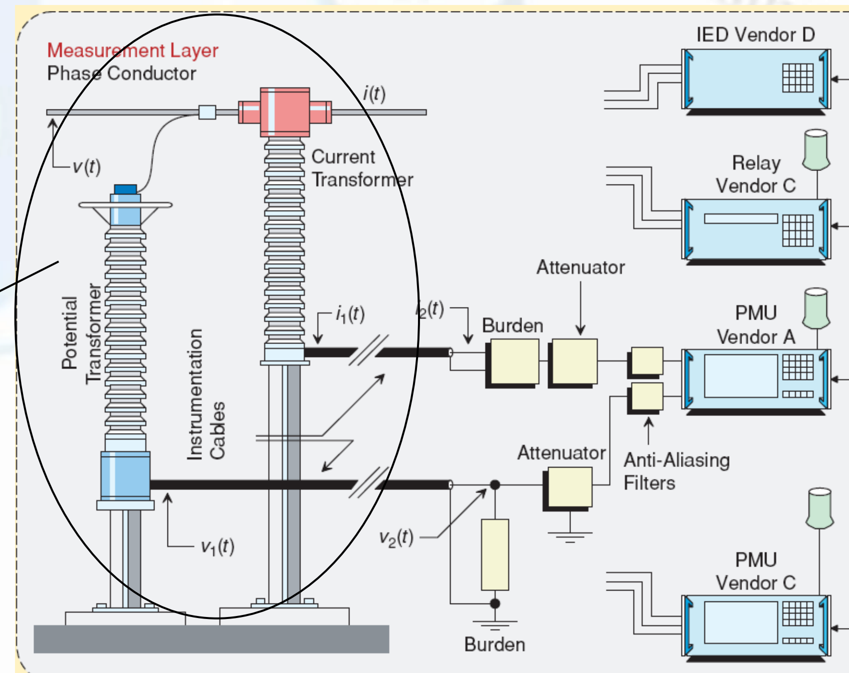
Current transformer maximum errors

Accuracy class	± Percentage of current error at percentage of rated current					± Phase displacement at percentage of rated current (degrees)				
	1	5	20	100	120	1	5	20	100	120
0.1	-	0.4	0.2	0.1	0.1	-	0.25	0.133	0.083	0.083
0.2S	**0.75**	**0.35**	**0.2**	**0.2**	**0.2**	**0.5**	**0.25**	**0.167**	**0.167**	**0.167**
0.2	-	0.75	0.35	0.2	0.2	-	0.5	0.25	0.167	0.167
0.5S	1.5	0.75	0.5	0.5	0.5	1.5	0.75	0.5	0.5	0.5
0.5	**-**	**1.5**	**0.75**	**0.5**	**0.5**	**-**	**1.5**	**0.75**	**0.5**	**0.5**
1	-	3	1.5	1	1	-	3	1.5	1	1

Voltage transformer maximum errors

Accuracy class	± Percentage of voltage magnitude error	phase displacement (degrees)
0.2S	**0.2**	**0.167**
0.5	**0.5**	**0.333**
1	1	0.667

Does the accuracy of ITs impact the accuracy provided by the PMU?



MEASUREMENT CHAIN: INSTRUMENT TRANSFORMERS

- Investigate the effect of the accuracy class of the instrument transformers on the accuracy of both the conventional and the hybrid state estimator
- Measurement chain includes instrument transformers with **good accuracy (0.2S)**
- Measurement chain includes instrument transformers with **lower accuracy (0.5)**

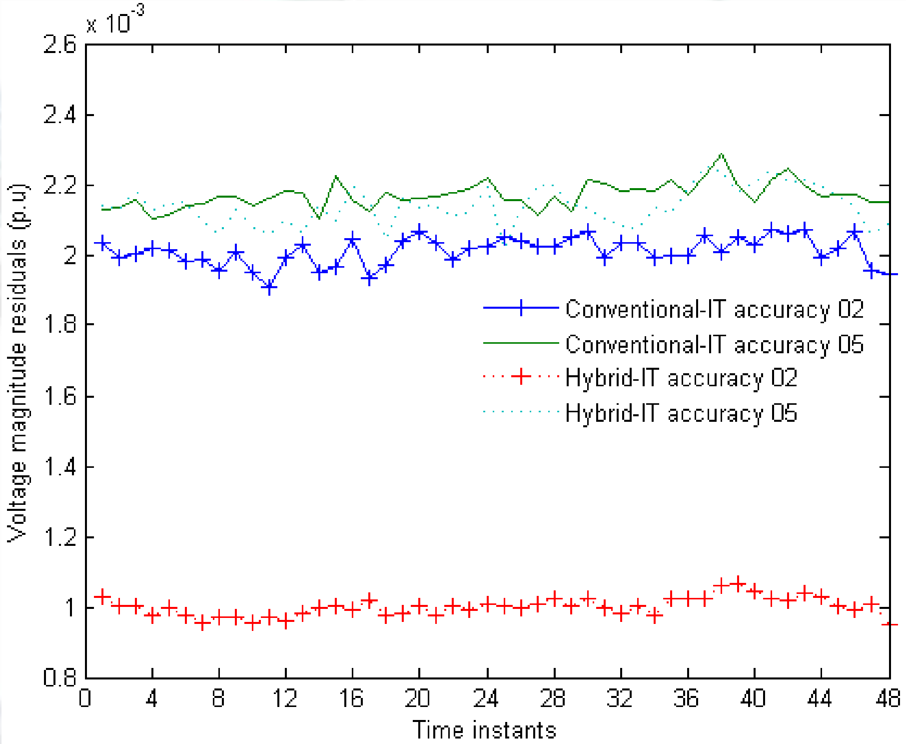
Hybrid and conventional state estimators are executed every half hour for a whole day for the IEEE 118 bus system (tests performed for other systems as well)

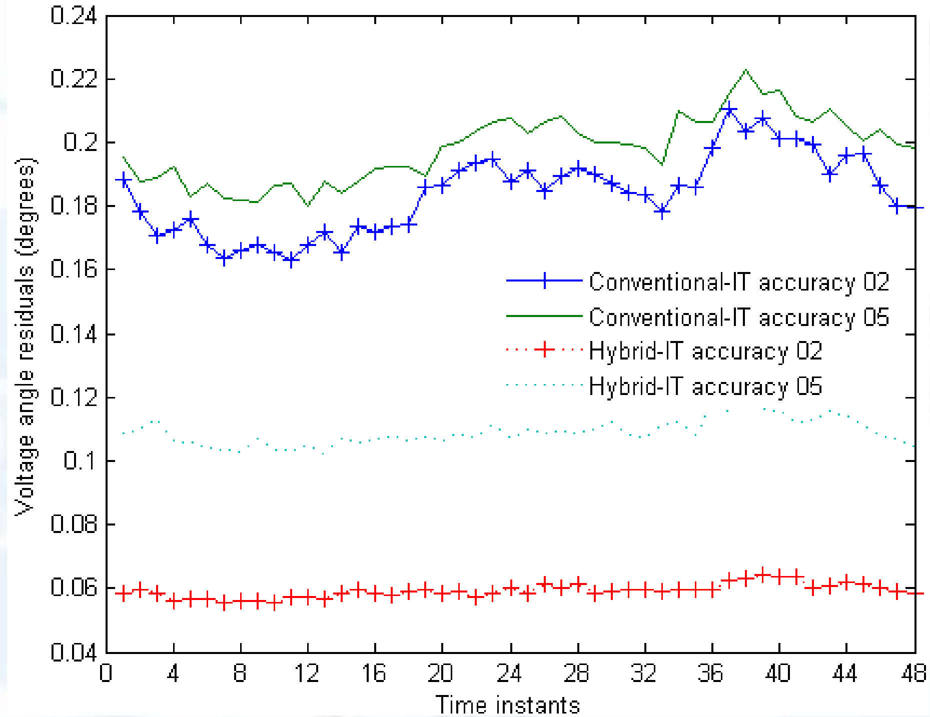
Metric of accuracy: Average sum of voltage magnitude and angle residuals

$$res_V = \frac{1}{N}\sum_{k=1}^{N}\frac{1}{M}\sum_{i=1}^{M}\left|\mathbf{V}_i(k) - \hat{\mathbf{V}}_i(k)\right| \qquad res_\theta = \frac{1}{N}\sum_{k=1}^{N}\frac{1}{M}\sum_{i=1}^{M}\left|\boldsymbol{\theta}_i(k) - \hat{\boldsymbol{\theta}}_i(k)\right|$$

N: Number of buses; *M*: Number of trials

MEASUREMENT CHAIN: INSTRUMENT TRANSFORMERS



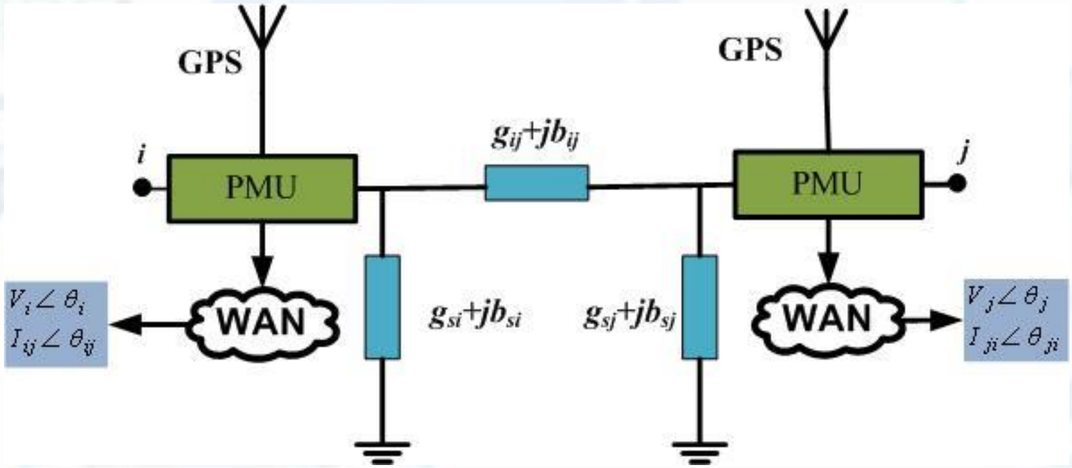


The instrument transformer accuracy class impacts only the hybrid state estimator accuracy

***M. Asprou, E. Kyriakides, and M. Albu, "The effect of instrument transformer accuracy class on the WLS state estimator accuracy," IEEE Power and Energy Society General Meeting, Vancouver, Canada, pp. 1-5, July 2013 (Best paper award).**

LINE PARAMETERS LACK OF KNOWLEDGE VS MEASUREMENT UNCERTAINTIES

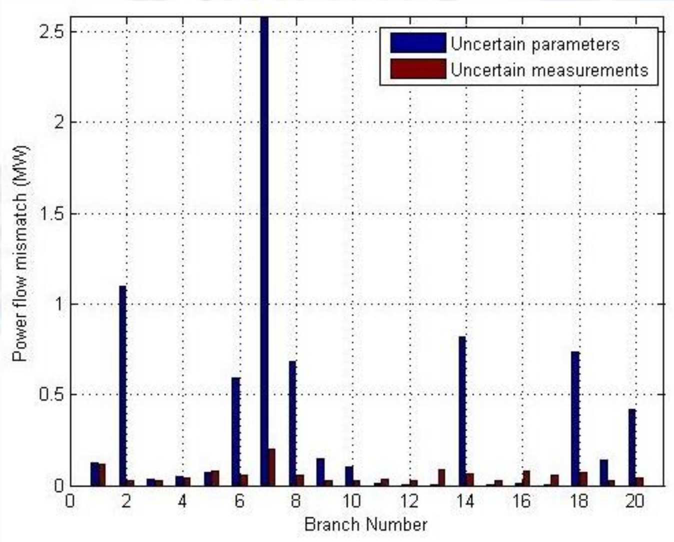
- The uncertainty of the line parameters deteriorates the accuracy of the hybrid state estimator **more** than the measurement uncertainty does.
- Important to identify and correct erroneous line parameters (take advantage of synchronized phasor measurements)
- With the knowledge of the voltage phasors at the two ends of the line and the line current phasor the line parameters can be estimated.



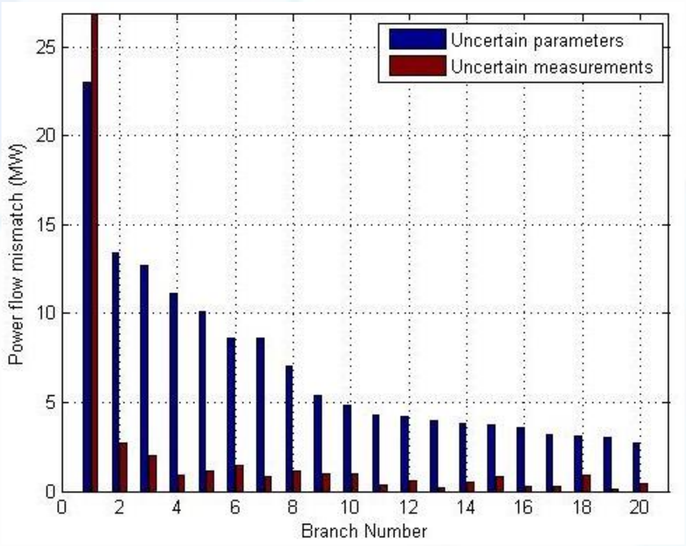
M. Asprou, E. Kyriakides, and M. Albu, "The effect of parameter and measurement uncertainties on hybrid state estimation," ***IEEE Power and Energy Society General Meeting*****, San Diego, CA, USA, pp. 1-7, July 2012**

LINE PARAMETERS LACK OF KNOWLEDGE VS MEASUREMENT UNCERTAINTIES

- Two case studies (hybrid state estimator) using the IEEE 14 and 118 bus systems
  - *Case study 1: Perfect measurements and uncertain line parameters*
  - *Case study 2: Exactly known line parameters and uncertain measurements*
- Line parameters are assumed to follow a uniform distribution spanning from (nominal value - 30%*nominal value) to (nominal value + 30%*nominal value) and a sample was taken randomly from this distribution



IEEE 14 bus system



IEEE 14 bus system

Thank you for your attention!

albu@ieee.org