Towards Real Time Monitoring of Electric Power Systems

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Outline

- University of Cyprus and KIOS Research Center
- Our research
- Introduction to synchronized measurement technology (SMT)
- Wide area monitoring – state estimation using SMT
  - A New State Estimator: The Hybrid State Estimator
  - Line Parameter Validation and Measurement Uncertainties
  - Variable Weights in State Estimation
- Dynamic (real time) monitoring
- Conclusions

University of Cyprus

Established in 1989
7000 students (goal: 10000 by 2020)

Faculties:

- **Humanities**
- **Pure and Applied Sciences**
- **Social Sciences and Education**
- **Economics and Management**
- **Engineering** →
  - **Architecture**
  - **Civil and Environmental Eng.**
  - **Electrical & Computer Eng.**
  - **Mechanical & Manufacturing Eng.**
- **Letters**
- **Graduate Studies**
- **Medical School**

Department of Electrical and Computer Engineering

- **First students admitted in 2003**
- **Degrees in Electrical Engineering and in Computer Engineering (B.Sc., M.Sc. and Ph.D.)**
- **19 faculty members**
- **400 undergraduate students**
- **Post-graduate students (85 M.Sc. and 65 Ph.D.)**

Research areas:

- **Telecommunication Systems**
- **Systems and Control**
- **Electric Power and Renewable Energy**
- **Digital and Embedded System Design**
- **Computer Networks**
- **Microelectronics**
- **Electromagnetics**
- **Biomedical Engineering**

KIOS Research Center for Intelligent Systems and Networks

- **Founded in 2008**
  - **In Greek Mythology, “Kios” (Κοίος) was the Titan of Intelligence and the inquisitive mind**
- **Approximately 70 researchers**
- **Funded completely from external resources (70% EU funding)**
- **The leading research center in Cyprus**
- **Housed (mainly) at the KIOS Center Building, within the main UCY campus**

- **Webpage: www.kios.ucy.ac.cy**

KIOS Mission

- The KIOS Research Center for Intelligent Systems and Networks aims at contributing to the ***advancement of knowledge*** in the areas of ***computational intelligence*** and ***system design***, and apply these methodologies in ***monitoring, control and management of large-scale, complex, and safety-critical systems***
- The Center aims to instigate interdisciplinary interaction and promote collaboration between industry, academia, and research organizations in high-tech areas.

Overview of KIOS Research Center Areas

Applications *Critical Infrastructure Systems*	Methodology *Intelligent Monitoring, Control and Management*

Applications
Critical Infrastructure Systems

- **Electric Power Systems and Renewable Energy Sources**
- **Environmental Resource Management Systems (including water distribution systems)**
- **Intelligent Transportation Systems**
- **Communication Networks**

Common Characteristics/Challenges

- Safety critical systems
- Complex, Large-scale
- Data-rich environments
- Spatially distributed
- Dynamic, time-varying, uncertain

Methodology
Intelligent Monitoring, Control and Management

Characteristics of the Methodology

- Data Interpretation and Decision
- Fault Tolerant (reliable/secure)
- Self-Adapt, Self-Improve
- Distributed/Decentralized, Cooperative
- Scalable, Hierarchical
- Flexible/Interoperable, Modular
- Bio-inspired

Software
Algorithms

Software/ Hardware
Protocols, embedded systems

Hardware
Sensors, actuators, robotic systems

Our research in power systems

Wide area monitoring and control
Unit commitment and economic dispatch
Grid integration of renewables
System islanding and load shedding
Load modeling
New controllers for power electronic converters

OK, smart grids too!

Also working on security of critical infrastructure systems (modeling of power networks and interdependencies with telecommunication and transportation networks, CIPRNet FP7 NoE)

The PV2Grid Project – Partners and Aim

A next generation grid side converter with advanced control and power quality capabilities

- **KIOS Research Center – University of Cyprus (Coordinator)**
- **Department of Energy Technology - Aalborg University**
- **Quantum Energy Corporation Ltd**

- ✓ **This project aims to advance the technology related to the seamless grid integration of photovoltaic (PV) systems.**
- ✓ **Development of next generation power electronic Grid Side Converters (GSC) with advanced capabilities and innovative operational management approaches.**

The PV2Grid Project – Objectives

- **Design and develop new generation Grid Side Converters (GSCs) equipped with advanced control capabilities and novel operational mode approaches:**
    - ✓ **providing support to the grid when needed**
    - ✓ **enhancing the power system stability**
    - ✓ **improving the power quality of the grid**
    - ✓ **reducing the network losses**
- **Design new current controllers that can accurately inject positive, negative (in case of three-phase GSCs) and harmonic-free currents under normal or abnormal voltage conditions.**
- **Develop experimental prototypes of GSCs including the current control techniques, the PQ controllers and the scheduling algorithm.**
- **Design an optimal scheduling algorithm considering a dynamic electricity-pricing environment and the presence of storage (prosumer profit maximization).**

Electric Power Systems

- **Similar to all critical infrastructure systems, power systems are crucial for everyday life and well-being**
  - ➢ **Citizens expect/rely that they will *always* be available (24/7)**
  - ➢ **Citizens expect that they will be managed efficiently (low cost)**

- **Power systems malfunction (frequently) or fail (occasionally)**
  - ➢ **Natural disasters (earthquakes, floods)**
  - ➢ **Accidental failures (equipment failures, software bugs, human error)**
  - ➢ **Malicious attacks (directly, remotely)**

- **When power systems fail, the consequences are tremendous**
  - ➢ **Societal consequences**
  - ➢ **Health hazards**
  - ➢ **Economic effects**

Electric Power Grid

- **Current electric grid: built about a century ago, and has been growing in size and capacity**
- **Transmission lines connect power sources to the grid**
  - ✓ **Technologically updated with automation and human monitoring over the last few decades**
- **Distribution lines, no significant changes**
  - ✓ **They have been mostly taken as user end-points of service**

In the last few years:

- **Steady growth of distributed generation**
- **Higher penetration of renewable energy sources**
- **Policies on electricity distribution have been supporting needs for a "smart grid"**
- **Centralized power plants have enormous economic constraints, and utilities have been trying to use their assets more efficiently**

Key Challenges for the Power Grid

- Load and system conditions change continuously
  - Quasi-steady state conditions most of the time
  - Dynamically changing conditions occasionally

- Integration of distributed energy resources (DER), renewables, microgrids

- Management of the evolving integrated infrastructure including its ties/interdependencies with massively deployed sensors, communication infrastructure and intelligent software agents

- Ensure system stability, robustness, reliability, security and efficiency

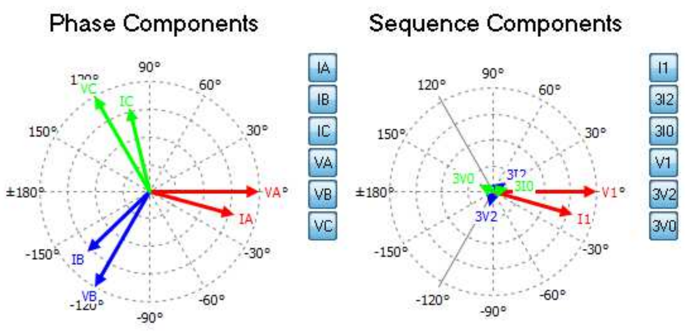
How?

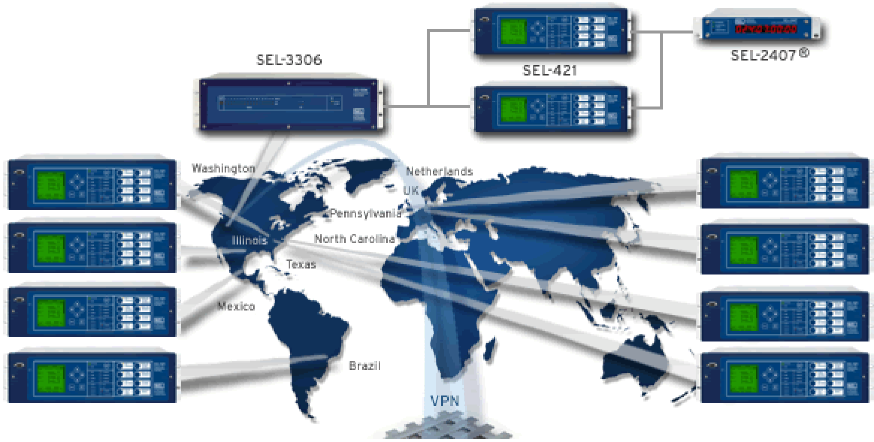
(a) Wide area monitoring and control

(b) More accurate modeling/validation of models

Synchronized Phasor Measurements

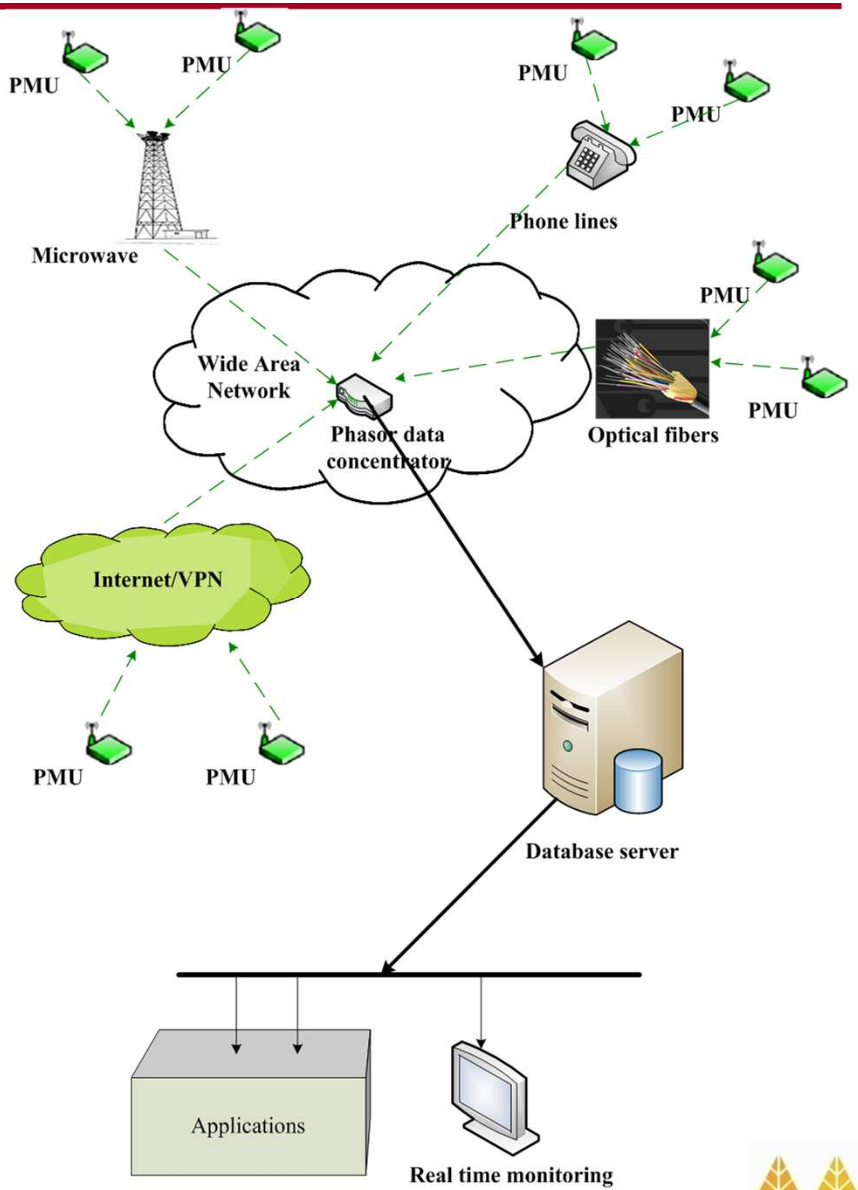
- **The Phasor Measurement Unit (PMU) is the key element of the synchronized phasor measurement technology**
- **PMU measurements are time-aligned to a common reference via a GPS signal. Thus, voltage and current phasor measurements at dispersed locations may be sampled simultaneously.**
- **Synchronized 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)**





Synchronized Measurement Technology

PMU measurements are sampled at a high speed (30-120 samples per second); measurements from conventional technology meters are sampled once every 4 seconds.

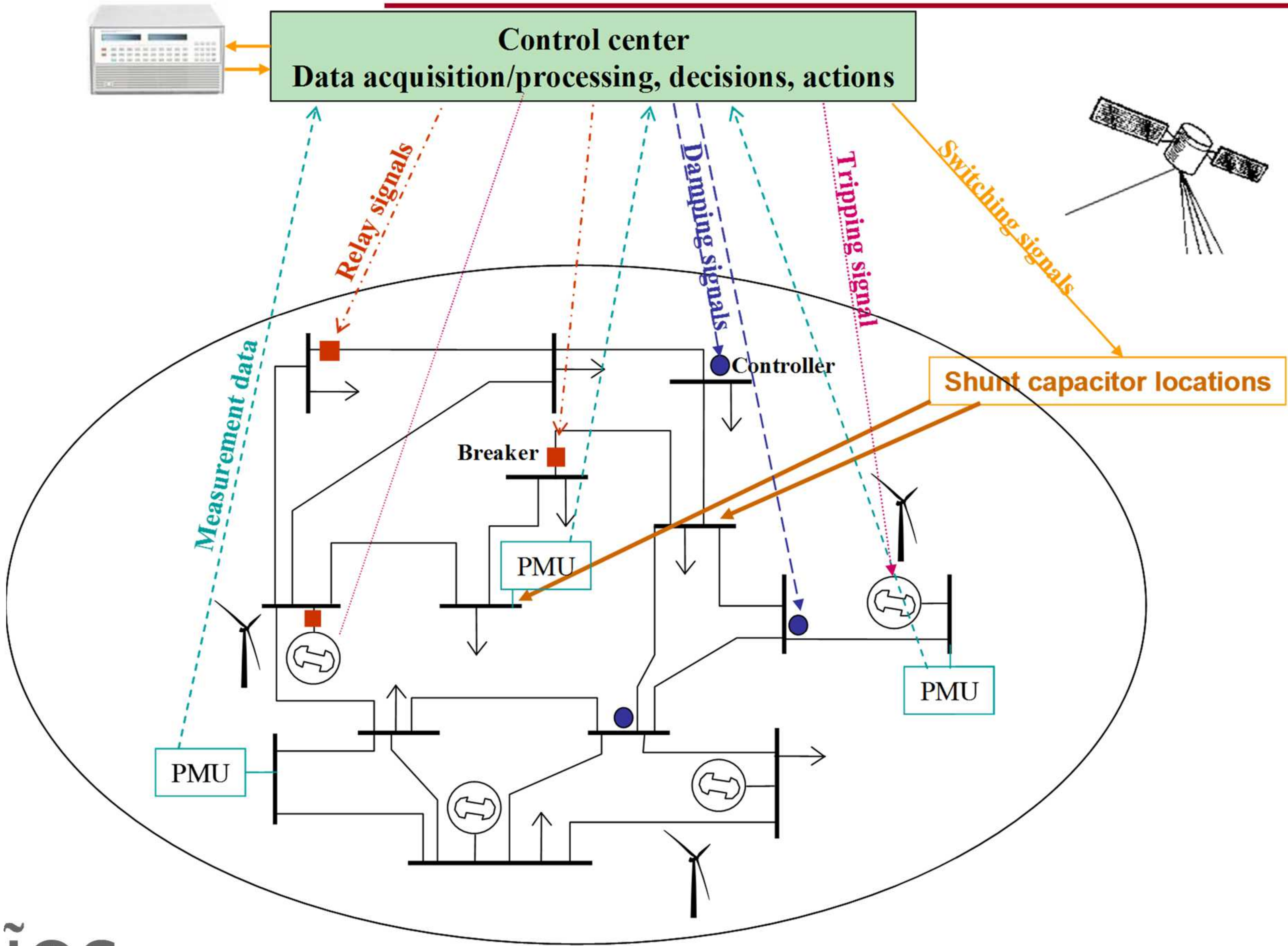


Main parts of a synchronized measurement system:
-- Synchronized measurement units (SMU), such as PMUs
-- Phasor data concentrators
-- Application software and servers
-- A wide area network

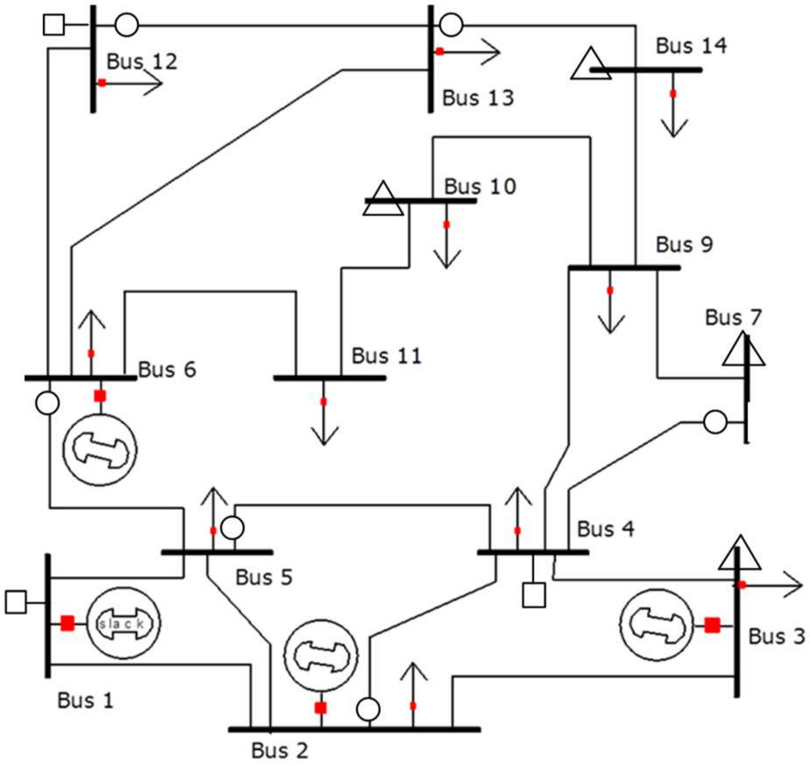
Why do we Need Synchronized Measurements?

- **Investigation for the cause of the recent blackouts found the following:**
  - **Lack of wide area visibility**
  - **Lack of time-synchronized data**
  - **Inability to monitor system dynamic behavior in real-time**
- **Phasor technology addresses these shortcomings**
- **Phasor technology facilitates the move from wide area measurement systems to wide area control systems**

The Vision


Control center
Data acquisition/processing, decisions, actions
Relay signals
Damping signals
Tripping signal
Switching signals
Measurement data
Controller
Shunt capacitor locations
Breaker
PMU
PMU
PMU

State Estimation in Electric Power Systems



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

Measurements every 5-30 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.

SE assumptions:

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

Model of the state estimator

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

⇓

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

Conventional State Estimation

Estimation of the state vector x using the Weighted Least Squares (WLS) methodology

Problem formulation

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

where,

z **is the measurement vector**

h(x) **is the vector containing equations that relates measurements to system states**

R **is measurement error covariance matrix**

$$z = \begin{bmatrix} P_{flow} \\ P_{inj} \\ Q_{flow} \\ Q_{inj} \\ V_i \end{bmatrix}$$

Conventional State Estimation

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**

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

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

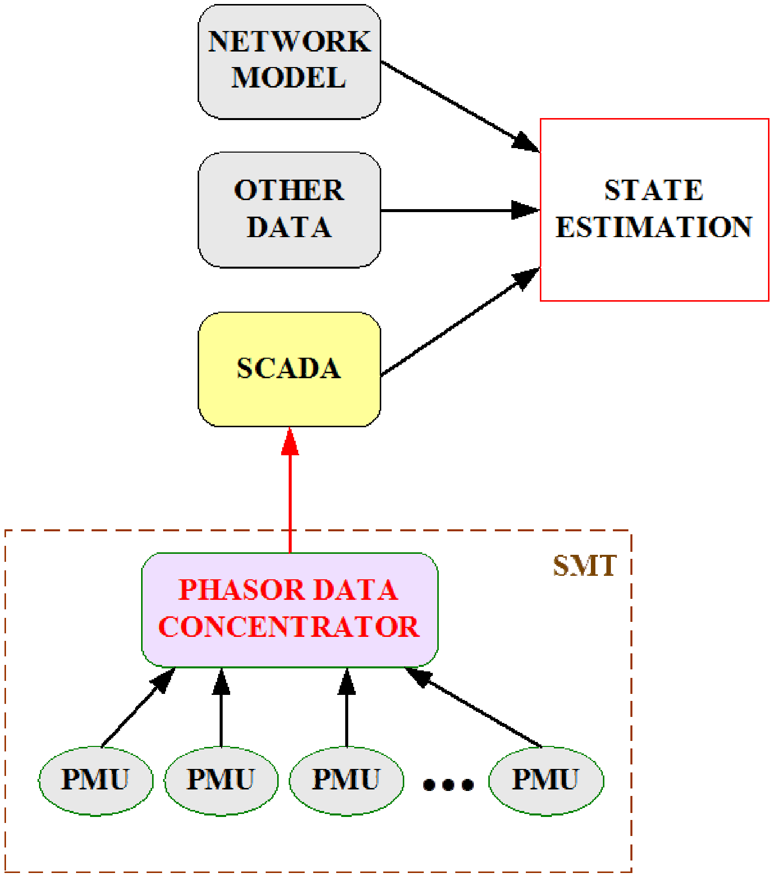
The iterative process stops when the element of Δx with the maximum value is smaller than a predefined threshold

Hybrid State Estimation (version 1)

Idea: Take advantage of voltage and current phasor measurements from PMUs

Incorporate these measurements into the existing state estimator

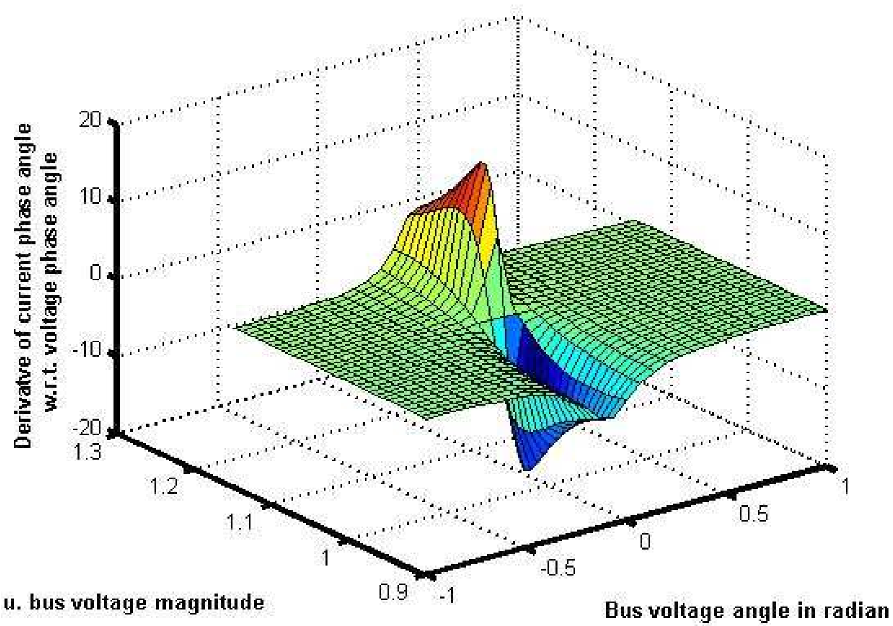
Emergence of a new state estimator: The Hybrid State Estimator

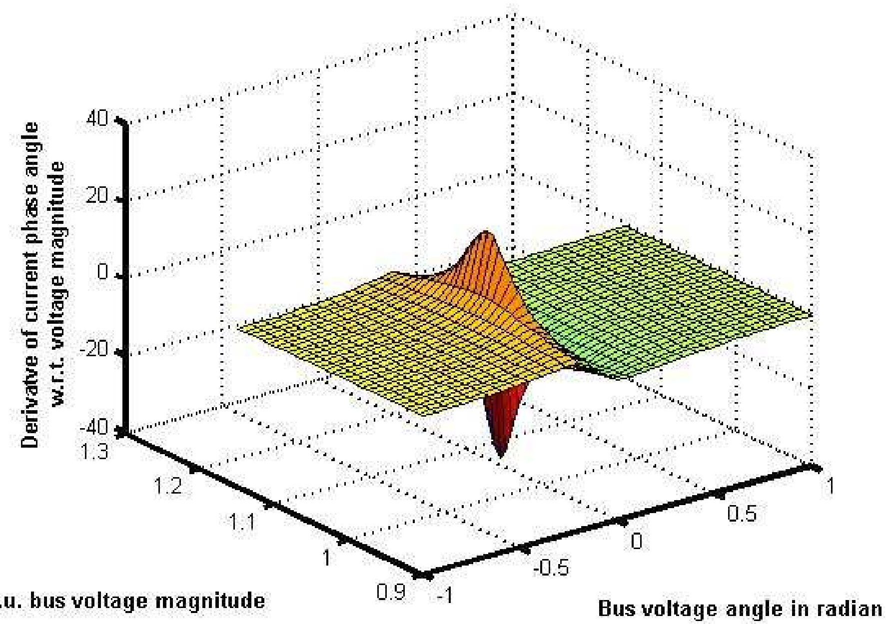


$$z_{hyb} = \begin{bmatrix} P_{flow} \\ P_{inj} \\ Q_{flow} \\ Q_{inj} \\ \theta_{Vpmu} \\ V_{pmu} \\ \theta_{Ipmu} \\ I_{pmu} \end{bmatrix} \qquad H_{hyb}(x) = \begin{bmatrix} \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial P_{inj}}{\partial \theta}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

Convergence Issues

- **The previous hybrid state estimation scheme may face convergence problems during the iterative process**
- **The elements of the Jacobian matrix take relatively large values for specific values of the voltage magnitude and the voltage angle**





*** S. Chakrabarti, E. Kyriakides, G. Ledwich, and A. Ghosh, "Inclusion of PMU current phasor measurements in a power system state estimator," *IET Generation, Transmission, and Distribution*, vol. 4, no. 10, pp. 1104-1115, Sep. 2010.**

Concept of Pseudo Flow Measurements

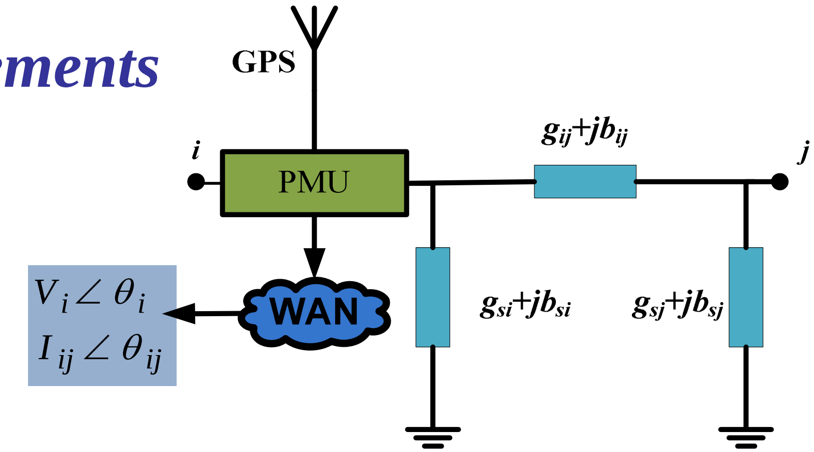
Assuming that a PMU is connected to bus *i*, the voltage phasor at bus *i*, $\overline{V_i}$, as well as the current phasor of the branch connecting bus *i* and bus *j*, $\overline{I_{ij}}$, are available.

To avoid the convergence problems, include indirectly the current phasor measurements to the measurement vector.

Pseudo flow measurements

$$P_{ij_{pseudo}} = V_i I_{ij} \cos(\theta_i - \theta_{ij})$$

$$Q_{ij_{pseudo}} = V_i I_{ij} \sin(\theta_i - \theta_{ij})$$



*** M. Asprou and E. Kyriakides, "Enhancement of hybrid state estimation using pseudo flow measurements," *IEEE Power and Energy Society General Meeting*, Detroit, MI, USA, paper no. 1022, pp. 1-7, July 2011.**

Inclusion in the Hybrid State Estimator (HSE)

$$\mathbf{z}_{hyb} = \begin{bmatrix} \mathbf{P_{flow}} \\ \mathbf{Pflow_{pse}} \\ \mathbf{P_{inj}} \\ \mathbf{Q_{flow}} \\ \mathbf{Qflow_{pse}} \\ \mathbf{Q_{inj}} \\ \boldsymbol{\theta}_{\mathbf{Vpmu}} \\ \mathbf{V_{pmu}} \end{bmatrix}$$

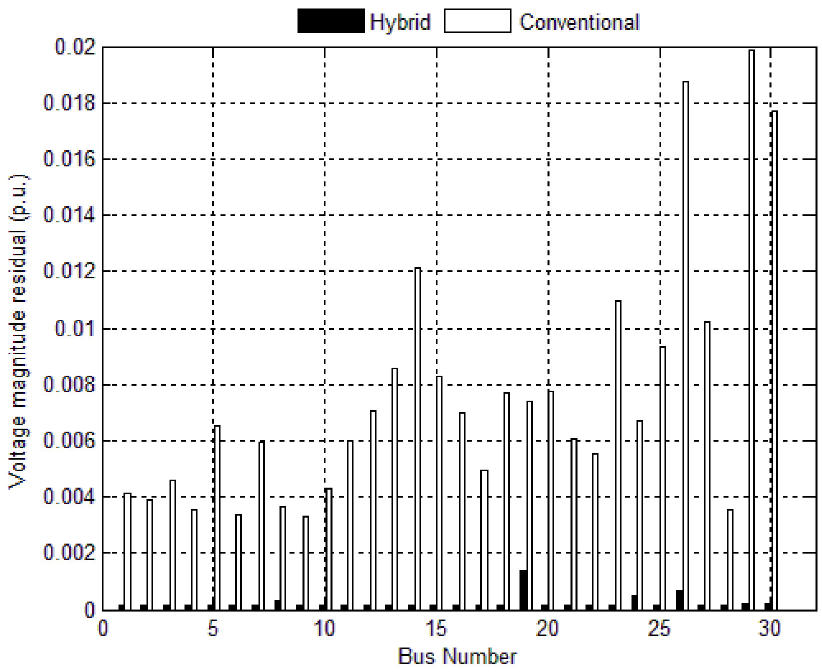
Extremely accurate measurements

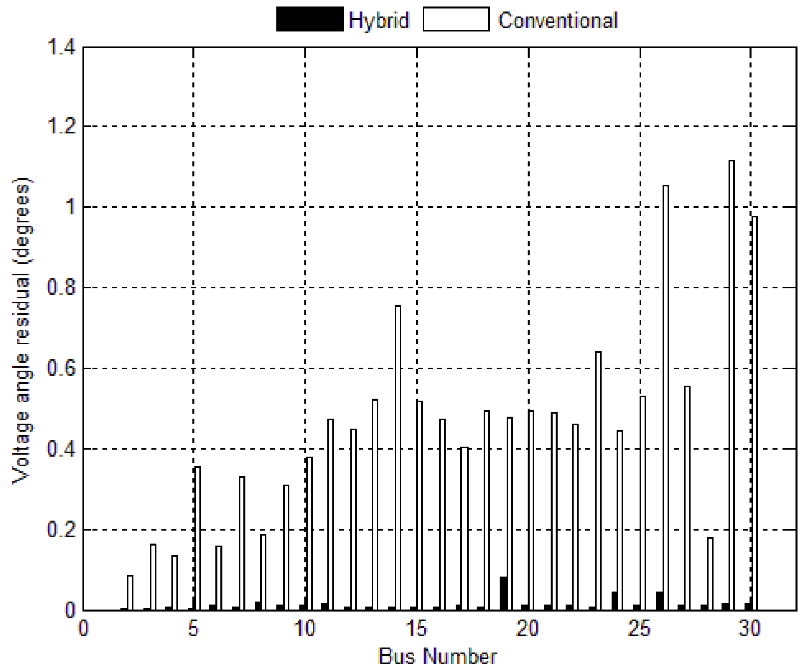
Related to state variables similar to the conventional flow measurements

$$P_{ij} = V_i^2 (g_{si} + g_{ij}) - V_i V_j (g_{ij} \cos(\theta_i - \theta_j) + b_{ij} \sin(\theta_i - \theta_j))$$

$$Q_{ij} = -V_i^2 (b_{si} + b_{ij}) - V_i V_j (g_{ij} \sin(\theta_i - \theta_j) - b_{ij} \cos(\theta_i - \theta_j))$$

Results - 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

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")

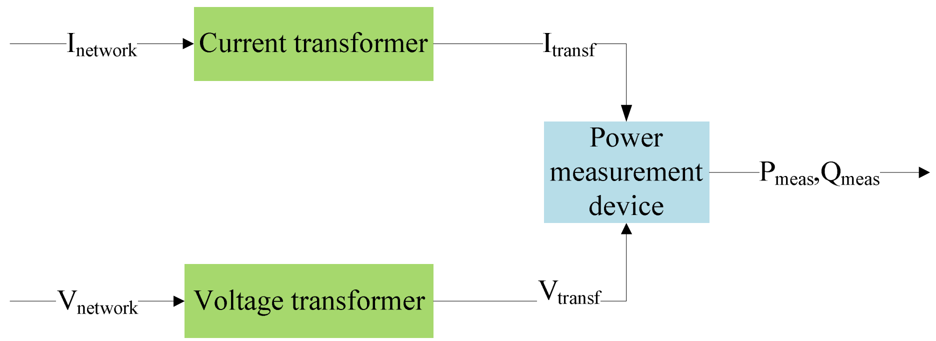
Approximation of network model (e.g., errors in line parameters)

Surveys have shown that the stored parameter values in control center databases could deviate from the real ones by as much as 30%

Measurement Chain Uncertainties

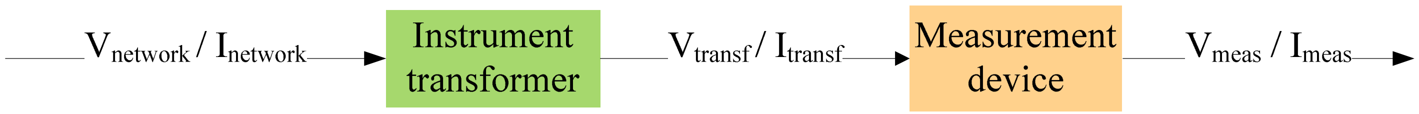
- **In practice, usually only the measurement device accuracy is used for measurement weighting**
- **Important to look at the whole measurement chain**

Conventional measurement chain



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

PMU measurement chain



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

Line Parameter Uncertainties

- **Many factors can affect the network parameters in the real field**
  - *The resistance of the transmission line can be affected by the ambient temperature, wind, and resistivity of the soil*
  - *Mutual coupling of parallel transmission lines can affect both the resistance and the reactance of the lines*
  - *Actual connection (e.g., joints and transmission lines that have overhead and underground parts) and the effects of maintenance work*

- **Surveys have shown that the line parameters stored in the electric utilities databases can vary up to 30% from their rated values**

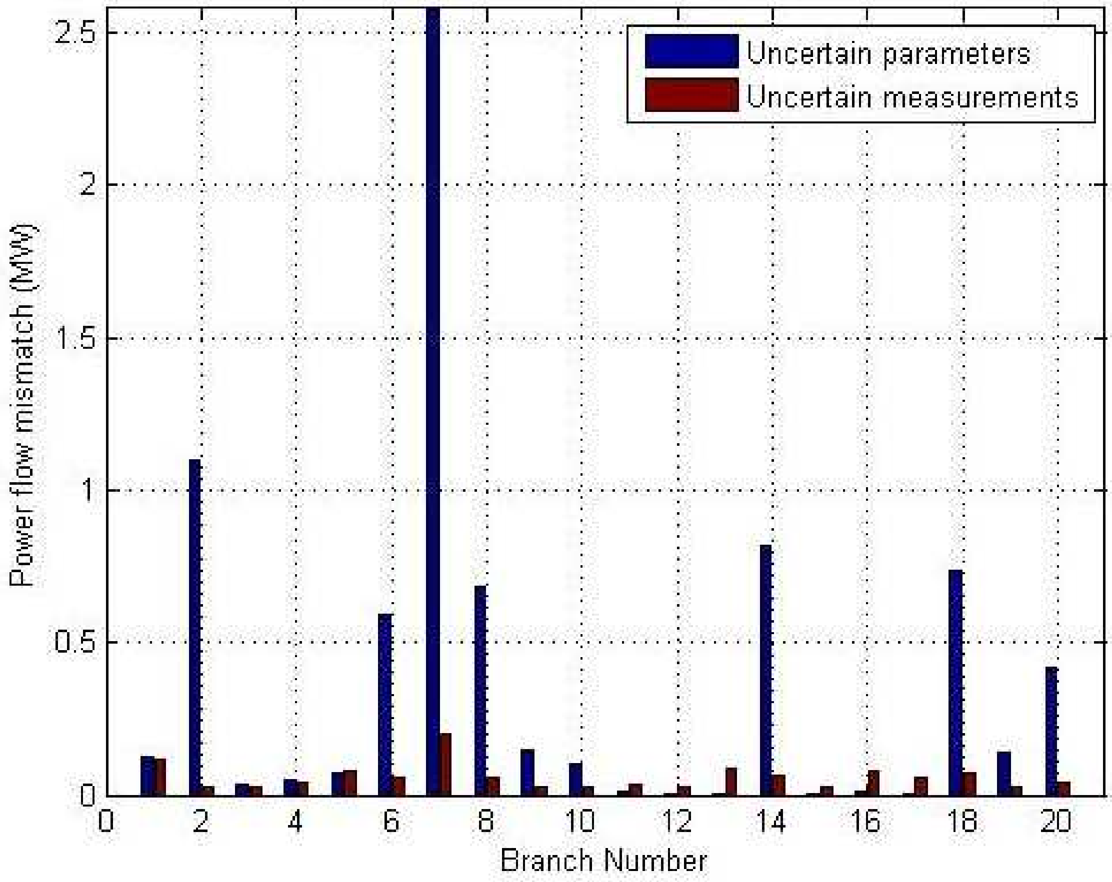
- **Important to investigate how the parameter uncertainties impact the state estimator accuracy**

Line Parameter vs Measurement Uncertainties

- **Two case studies 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**
- **Comparison of the two cases to determine which of the two sources of uncertainty affects more the hybrid state estimator**

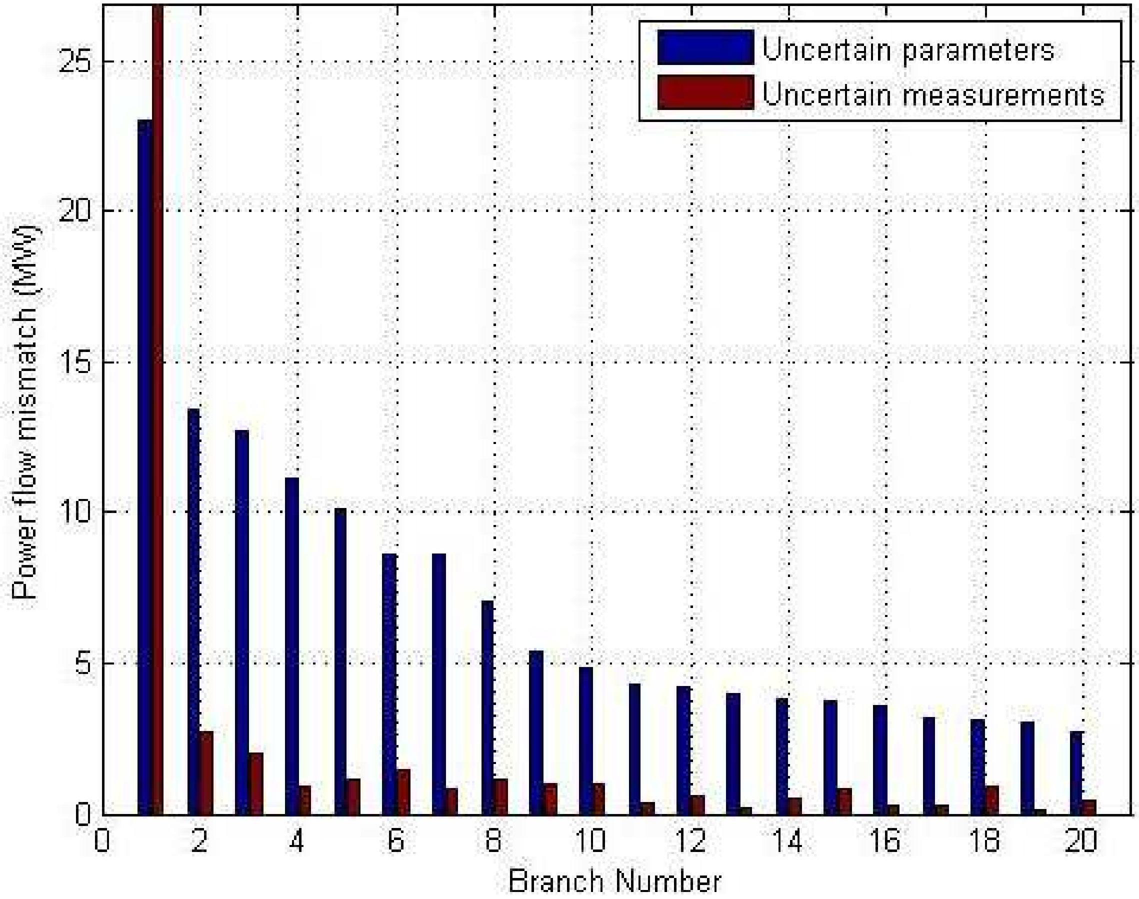
Line Parameter vs Measurement Uncertainties

IEEE 14 bus system



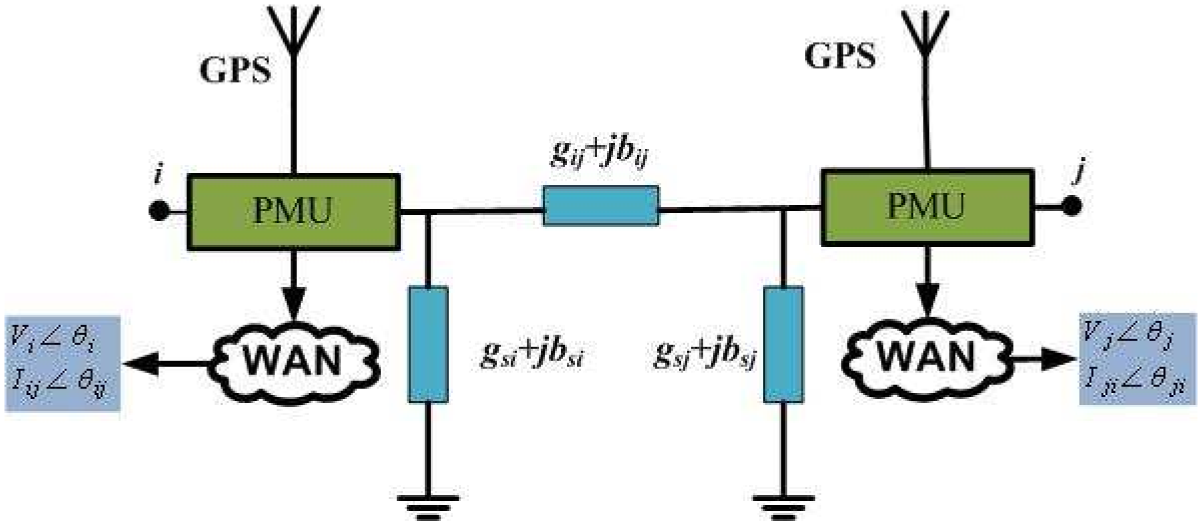
Line Parameter vs Measurement Uncertainties

IEEE 118 bus system



Line Parameter 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 calculated.



* 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

Identification of Erroneous Branches and Estimation of Branch Parameters

Ongoing work – promising results for one type of erroneous parameter (susceptance).

Main idea: Use available PMU measurements (no requirement for full observability by PMUs) to identify erroneous branches. Once erroneous branches are identified, proceed with estimating their parameters.

Case Study-IEEE 14 Bus System

Conventional State Estimator

- **Number of measurements**

  82

- **Number of times that the methodology identifies the erroneous branch**

  14 out of 20

- **Estimation error range**

  0.035%-18.4%

Hybrid State Estimator

- **Number of measurements**

  63

- **Number of times that the methodology identifies the erroneous branch**

  16 out of 20

- **Estimation error range**

  0.01%-0.56%

Erroneous branch (Bus #-Bus#)	Susceptance true value (p.u.)	Conventional		Hybrid	
		Susceptance Estimated Value (p.u.)	Error (%)	Susceptance Estimated Value (p.u.)	Error (%)
1 (1-2)	-15.2631	-18.0680	18.4	-15.2372	0.17
2 (1-5)	-4.2350	-4.3070	1.7	-4.2318	0.08
3 (2-3)	-7.6151	-7.6373	0.29	-7.6480	0.43
4 (2-4)	-5.1158	-5.0885	0.53	-5.1168	0.02
5 (2-5)	-5.1939	-5.2135	0.38	-5.1977	0.07
6 (3-4)	-5.0688	-5.0362	0.64	-5.0537	0.3
7 (4-5)	-21.5786	-	-	-	-
8 (4-7)	-4.7819	-4.7449	0.77	-4.7969	0.31
9 (4-9)	-1.7980	-1.7906	0.41	-1.8014	0.13
10 (5-6)	-3.9679	-	-	-3.9732	0.15
11 (6-11)	-4.0941	-	-	-4.0711	0.56
12 (6-12)	-3.1760	-3.1541	0.69	-3.1757	0.01
13 (6-13)	-6.1028	-6.0989	0.06	-6.1121	0.15
14 (7-8)	-5.6770	-	-	-	-
15 (7-9)	-9.0901	-9.2611	1.88	-	-
16 (9-10)	-10.3654	-	-	-10.4144	0.47
17 (9-14)	- 3.0291	-	-	-	-
18 (10-11)	-4.4029	-4.4296	0.61	-4.3825	0.46
19 (12-13)	-2.2520	-2.2262	1.15	-2.2563	0.19
20 (13-14)	-2.3150	-2.3158	0.03	-2.3204	0.23

The Effect of Instrument Transformers

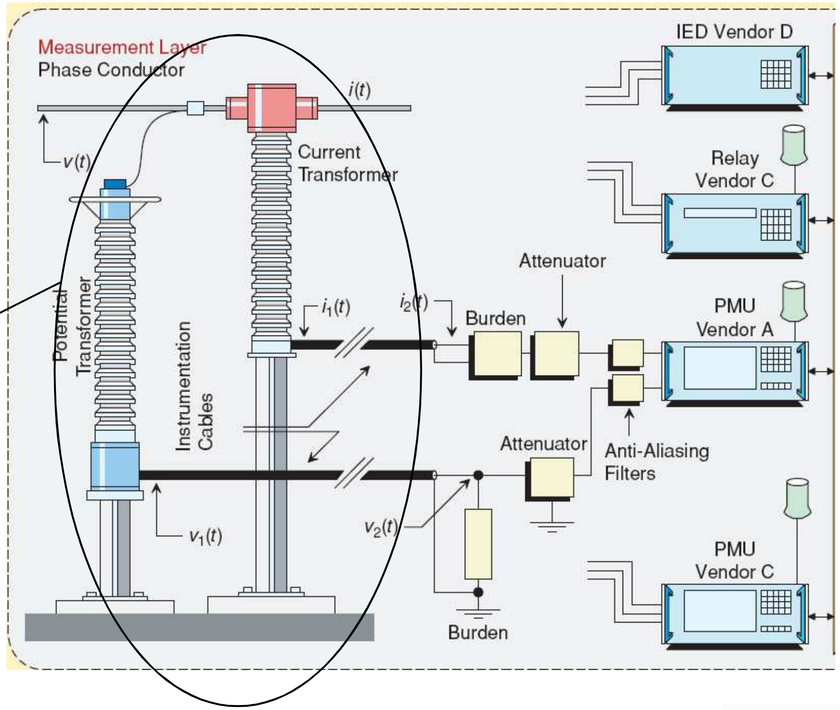
Current transformer maximum errors

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?



The Effect of 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

Case studies

- **Measurement chain includes instrument transformers with good accuracy class (0.2S)**
- **Measurement chain includes instrument transformers with lower accuracy class (0.5)**

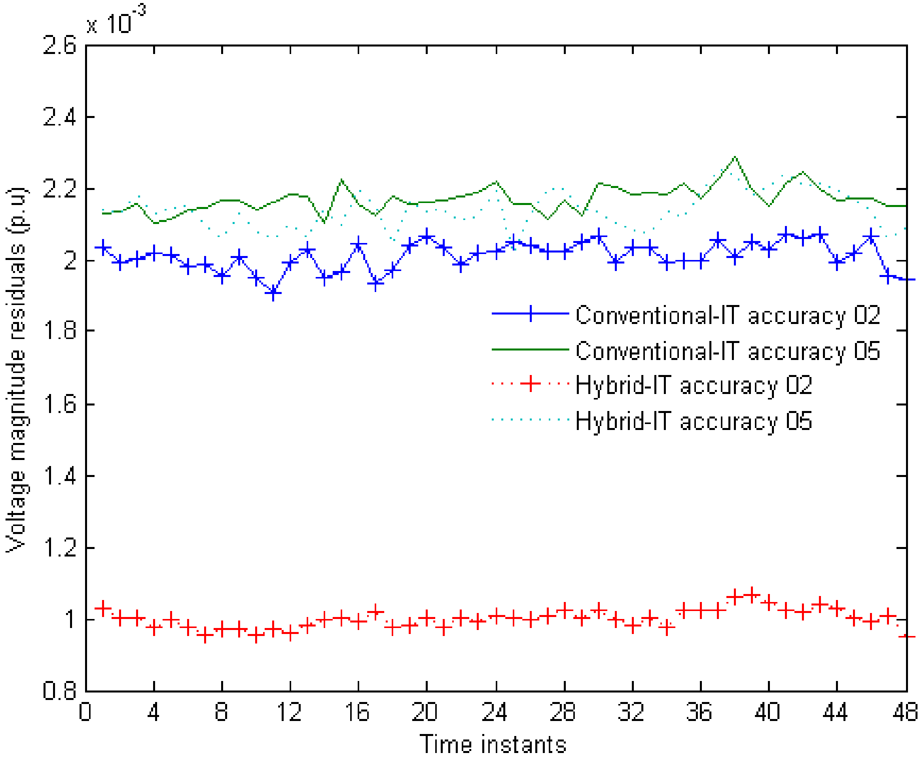
Hybrid and conventional state estimators are executed every half hour for a whole day for the IEEE 118 bus system (tests performed for other systems as well)

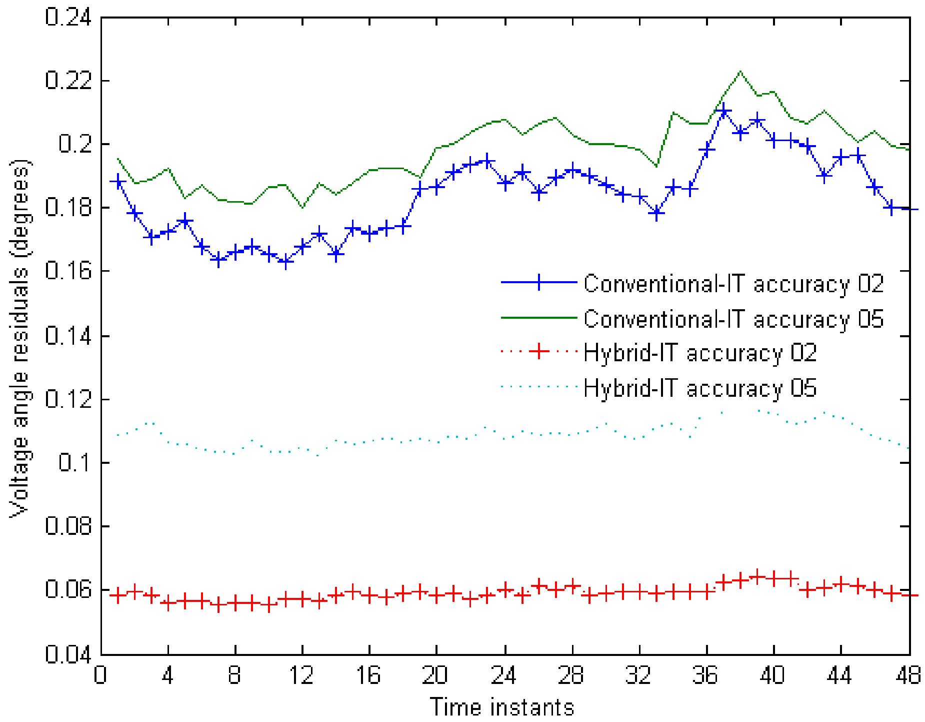
Metric of accuracy: Average sum of voltage magnitude and angle residuals

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

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

Case Studies: The Effect of IT Accuracy Class





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).**

Lessons Learned

- **The accuracy of ITs so far did not play a major role in state estimation since we have been using the state estimation with conventional measurements.**
- **The connection of an extremely accurate device (e.g., a PMU) to an instrument transformer of low accuracy will deteriorate the accuracy of the measurements, overshadowing the true capabilities of the advanced measuring device.**
- **Consideration of the accuracy class of the instrument transformers before the installation of PMUs is important for exploiting the true capabilities of PMUs**
- **With the addition of the more accurate PMU measurements we should use ITs of higher accuracy class if we want to see improvement in our state estimator results**

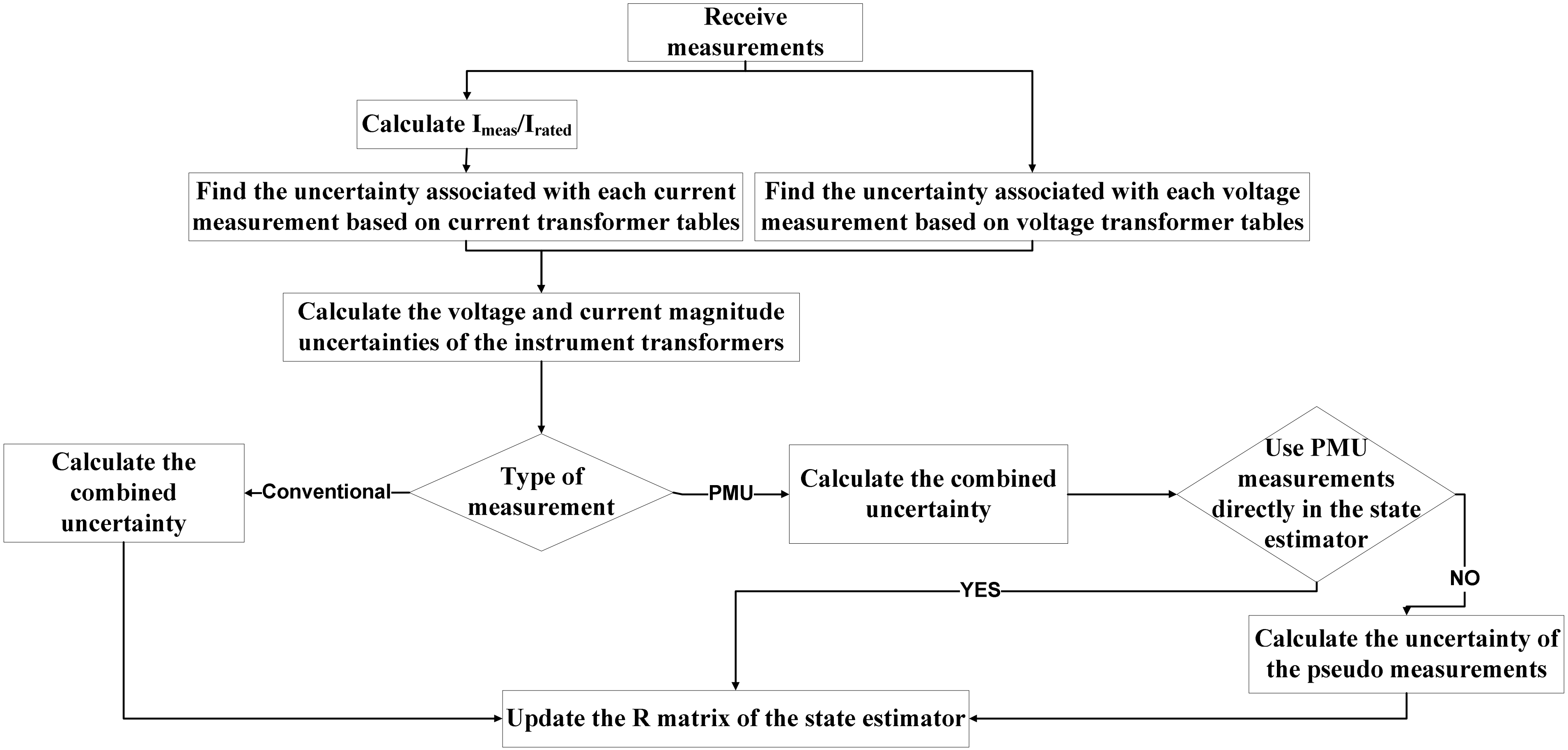
Variable Weights in State Estimation

- In WLS state estimation, the measurements are weighted according to the inverse of the square of their uncertainty. The instrument transformer uncertainty is ignored (as highlighted previously).
- In the case of current transformers, the measurement error depends on the loading level – concept of variable weights

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

A Variable Weight State Estimator

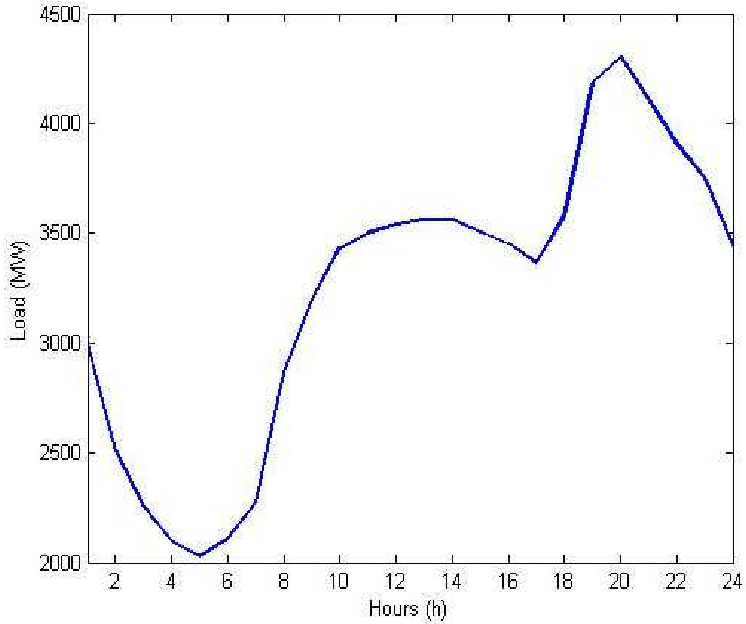


*M. Asprou, E. Kyriakides, and M. Albu, "The effect of variable weights in a WLS state estimator considering instrument transformer uncertainties," IEEE Transactions on Instrumentation and Measurement, vol. 63, no. 6, pp. 1484-1495, June 2014.

Case Studies

Case study 1: Weighting scheme 1 (current practice: only measurement device uncertainties, constant weights)
Case study 2: Weighting scheme 2 (only measurement device uncertainties, variable weights)
Case study 3: Proposed weighting scheme (consider instrument transformers, variable weights)

Assume a daily load profile.
State estimation runs every 30 minutes
Results shown for 118 bus system



Measurement configuration (118 bus system)

Conventional measurements
65 flow measurements and 52 injection measurements

PMU measurements
20 PMUs

- Optimal locations (*)
- Arbitrary locations

* M. Asprou and E. Kyriakides, “Optimal PMU placement for improving hybrid state estimation accuracy,” IEEE PowerTech 2011, Trondheim, Norway, pp. 1-7, June 2011.

Results-SPFMs for the Hybrid State Estimator

SPFM for optimal PMU locations (MW)			SPFM for arbitrary PMU locations (MW)		
Weighting scheme 1	Weighting scheme 2	Proposed weighting scheme	Weighting scheme 1	Weighting scheme 2	Proposed weighting scheme
294.57	291.25	260.6	433.17	430.19	344.17

Metric of performance:
Sum of Power Flow Mismatches (SPFM)

$$SPFM = \frac{1}{T}\sum_{k=1}^{T}\left(\frac{1}{M}\sum_{i=1}^{M}\sum_{j=1}^{B}\left|P_{f_j}^{real} - \hat{P}_{f_j}^{i}\right|\right),$$

where,

$P_{f_j}^{real}$ **is the real power flow for the branch *j* as it is provided by the power flow solution**

$\hat{P}_{f_j}^{i}$ **is the estimated power flow for the branch *j* in the Monte Carlo trial *i* as it is estimated by the state estimator**

***B* is the number of branches of the power system**

***M* is the number of the Monte Carlo trials**

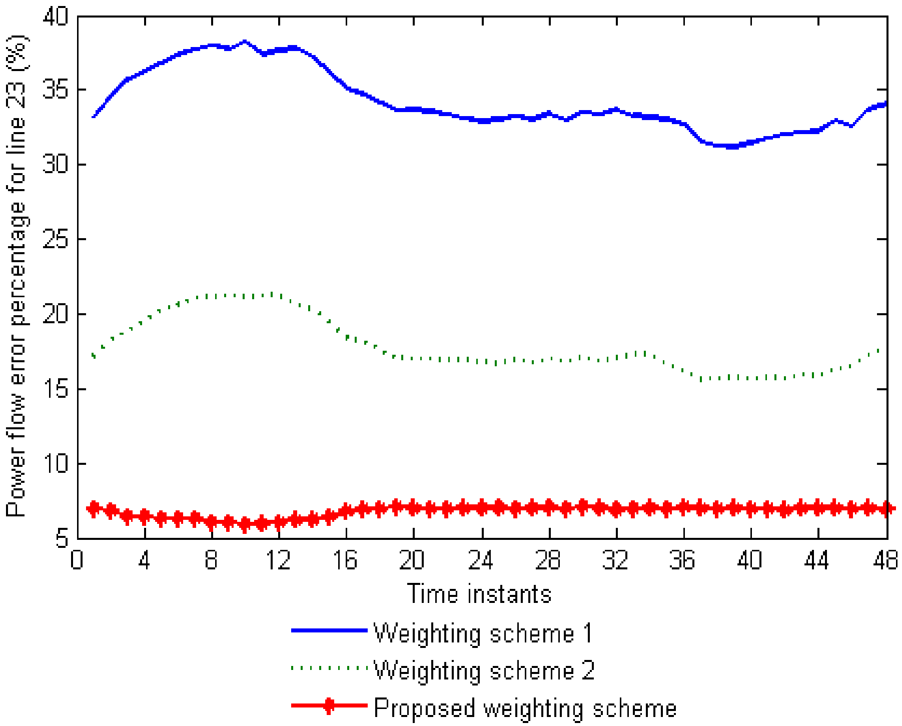
***T* is the number of state estimation executions for a whole day.**

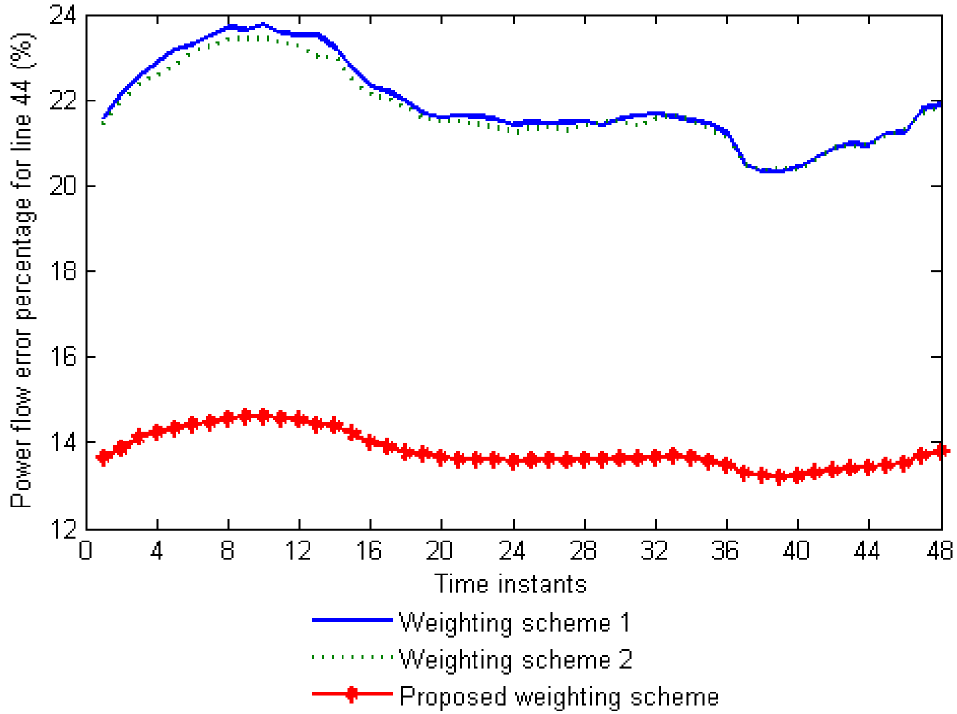
Effect of Erroneous PMU Measurements?

Assume one PMU (out of the 20) provides measurements that are biased by a 10% systematic error from their actual values.

SPFMs for the Hybrid State Estimator for arbitrary PMU locations (MW)		
Weighting scheme 1	Weighting scheme 2	Proposed weighting scheme
1537.2	1516.2	851.8

Percentage error in power flows





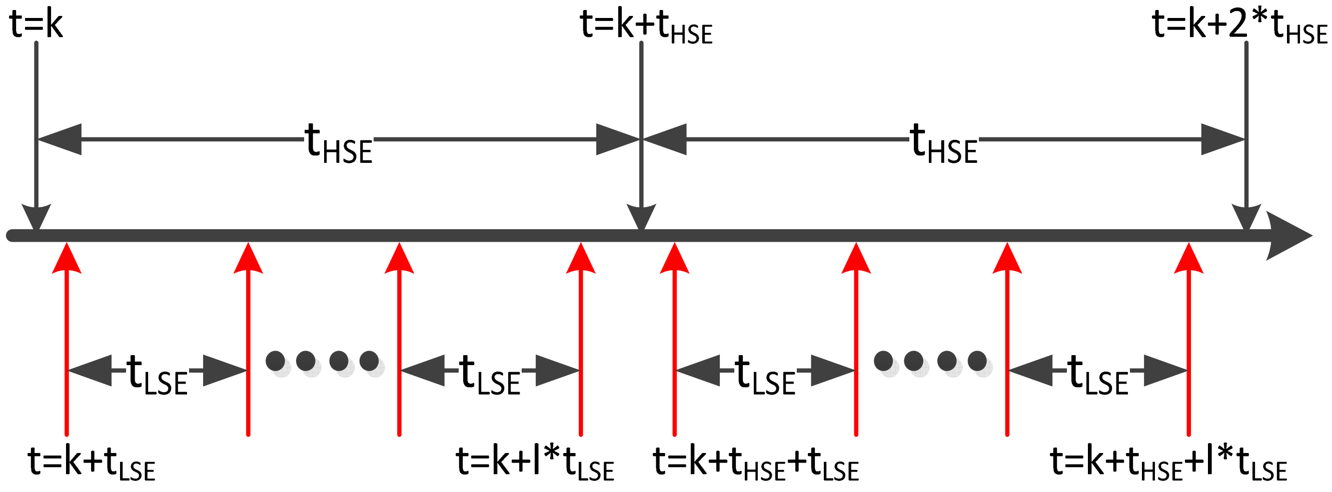
Main results

- **Weighting the measurements based on the combined uncertainty of the instrument transformer and the measurement device improves considerably the accuracy of the state estimator.**
- **The proposed methodology outperforms the measurement weighting schemes that consider only the measurement device uncertainty.**
- **In case of erroneous measurements, the proposed methodology's impact is even more significant.**

Towards Real Time Monitoring…

- **Tracking the transients is of paramount importance for the power system operators, both for real time actions, as well as for post-mortem analysis.**
- **Electric utilities use fault recorders (mainly at the generator terminals) to track the transients. However, they cannot provide a wide area picture of the power system operating condition.**

A Two-Stage State Estimator



Stage 1:

Execute a hybrid state estimation (both conventional and synchronized measurements).

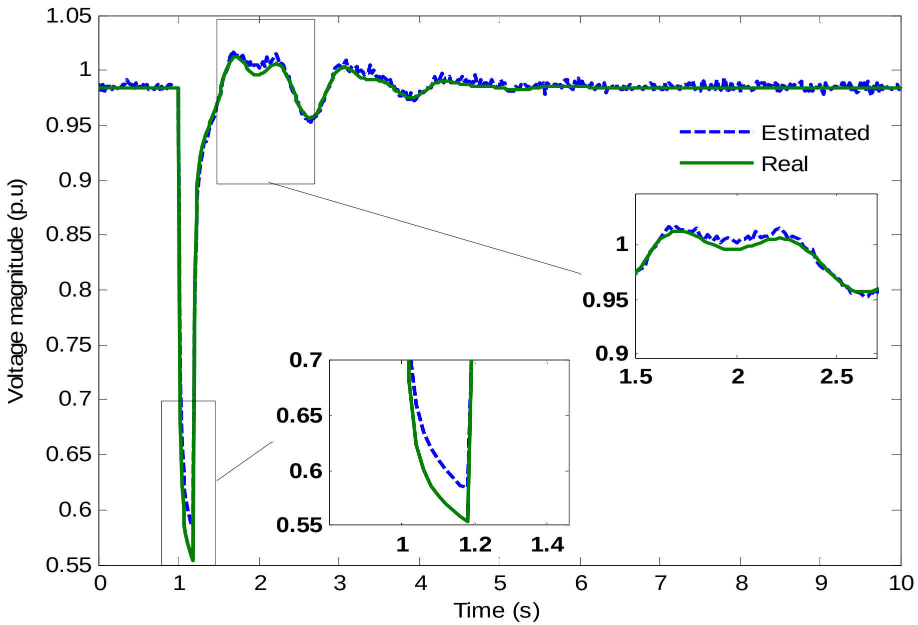
Stage 2:

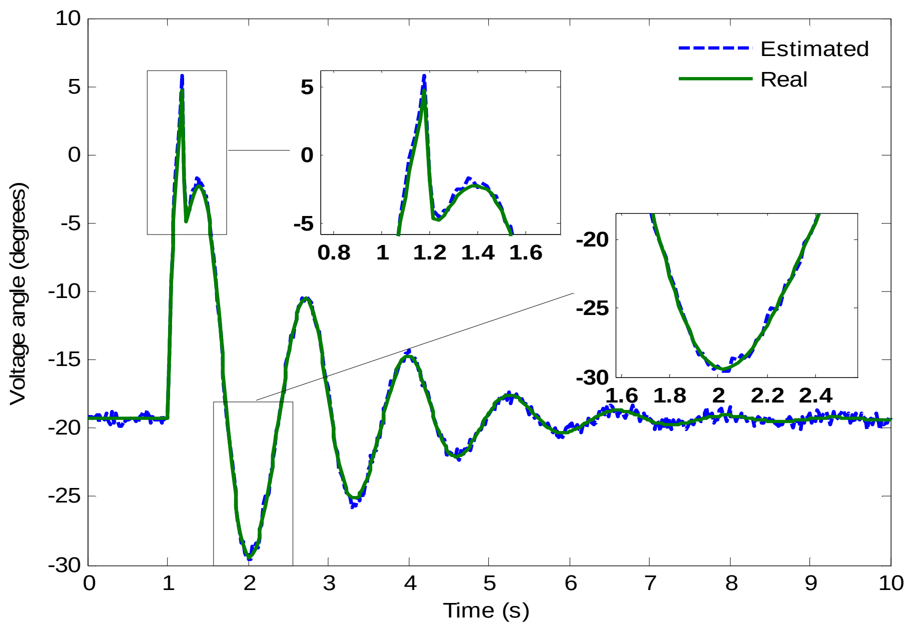
Execute a number of consecutive linear state estimations (use synchronized measurements and pseudomeasurements created using the previously estimated states)

Dynamic Monitoring - Results

IEEE 118 bus system
22 PMUs installed – 32 required for full observability

Bus 14 has the largest average estimation error



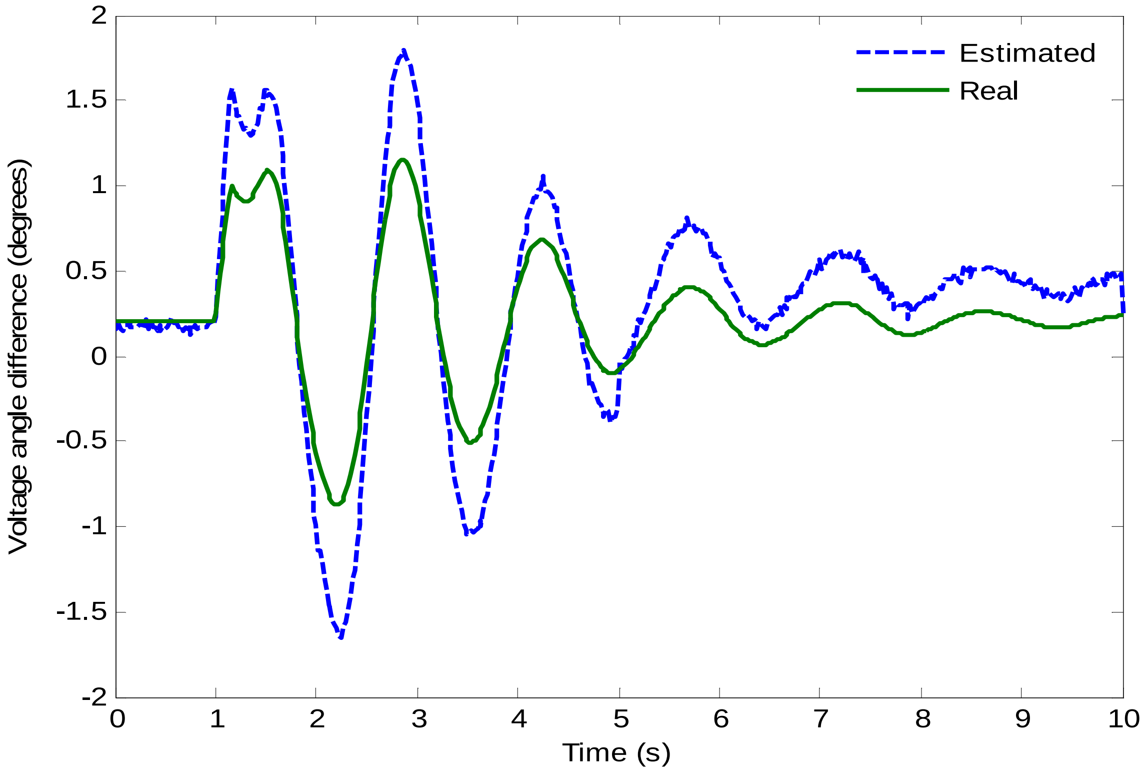


* M. Asprou, S. Chakrabarti, and E. Kyriakides, "A two-stage state estimator for dynamic monitoring of power systems," IEEE Systems Journal, pp. 1-8 (accepted Nov. 2014).

Dynamic Monitoring - Results

The tracking of the angle difference between two buses is extremely important for stability monitoring.

Voltage angle difference between buses 96 and 87



Getting Closer to Real Time Monitoring

- **Now possible to track the power system states under transient conditions using the two-stage state estimator.**
- **High degree of accuracy, even with a limited number of PMUs (up to now only possible for systems completely observable by PMUs).**
- **Tested in several systems and under several faults (bolted short circuit, open line, sudden load changes).**
- **No additional computational complexity.**

Further Reading

1. M. Asprou, S. Chakrabarti, and E. Kyriakides, "A two-stage state estimator for dynamic monitoring of power systems," *IEEE Systems Journal*, pp. 1-8 (accepted Nov. 2014).
2. M. Asprou, E. Kyriakides, and M. Albu, "The effect of variable weights in a WLS state estimator considering instrument transformer uncertainties," *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 6, pp. 1484-1495, June 2014.
3. G. Valverde, S. Chakrabarti, E. Kyriakides, and V. Terzija, "A constrained formulation for hybrid state estimation," *IEEE Trans. on Power Systems*, vol. 26, no. 3, pp. 1102-1109, Aug. 2011.
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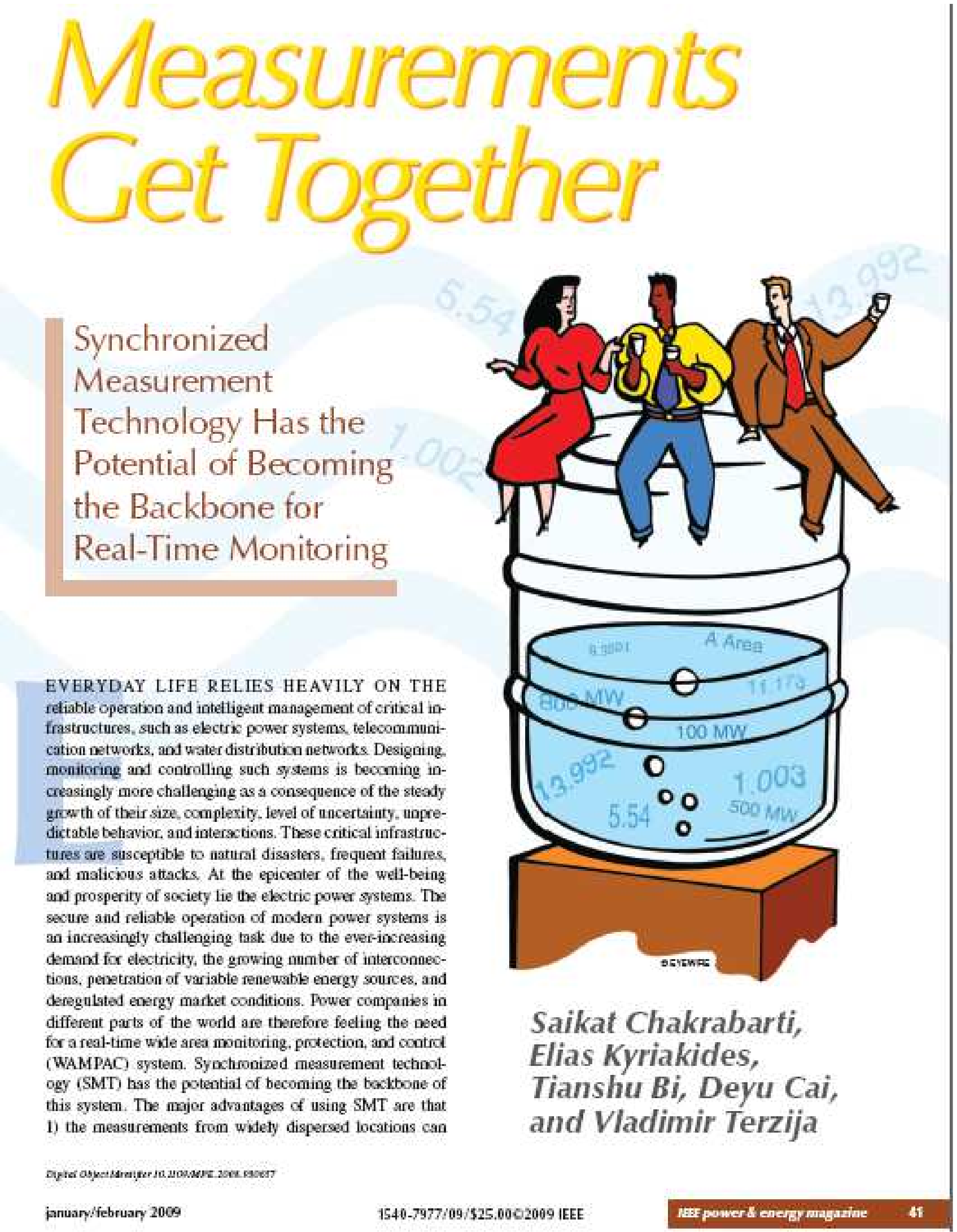
5. S. Chakrabarti, E. Kyriakides, and M. Albu, "Uncertainty in power system state variables obtained through synchronized measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 8, pp. 2452-2458, Aug. 2009.
6. S. Chakrabarti and E. Kyriakides, "PMU measurement uncertainty considerations in WLS state estimation," *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 1062-1071, May 2009.
7. S. Chakrabarti, E. Kyriakides, T. Bi, D. Cai, and V. Terzija, "Measurements get together," *IEEE Power and Energy Magazine*, vol. 7, no. 1, pp. 41-49, Jan. 2009.
8. S. Chakrabarti, E. Kyriakides, and D. G. Eliades, "Placement of synchronized measurements for power system observability," *IEEE Trans. on Power Delivery*, vol. 24, no. 1, pp. 12-19, Jan. 2009.
9. S. Chakrabarti and E. Kyriakides, "Optimal placement of phasor measurement units for power system observability," *IEEE Trans. on Power Systems*, vol. 23, no. 3, pp. 1433-1440, Aug. 2008.

Thank you!



Measurements Get Together

Synchronized Measurement Technology Has the Potential of Becoming the Backbone for Real-Time Monitoring

EVERYDAY LIFE RELIES HEAVILY ON THE reliable operation and intelligent management of critical infrastructures, such as electric power systems, telecommunication networks, and water distribution networks. Designing, monitoring and controlling such systems is becoming increasingly more challenging as a consequence of the steady growth of their size, complexity, level of uncertainty, unpredictable behavior, and interactions. These critical infrastructures are susceptible to natural disasters, frequent failures, and malicious attacks. At the epicenter of the well-being and prosperity of society lie the electric power systems. The secure and reliable operation of modern power systems is an increasingly challenging task due to the ever-increasing demand for electricity, the growing number of interconnections, penetration of variable renewable energy sources, and deregulated energy market conditions. Power companies in different parts of the world are therefore feeling the need for a real-time wide area monitoring, protection, and control (WAMPAC) system. Synchronized measurement technology (SMT) has the potential of becoming the backbone of this system. The major advantages of using SMT are that 1) the measurements from widely dispersed locations can

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