Panel Session: Addressing Uncertainty, Data Quality and Accuracy in State Estimation

The Impact of Instrument Transformer Accuracy Class on the Accuracy of Hybrid State Estimation

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Presentation Outline

- Hybrid state estimator overview
- Measurement uncertainties
- Impact of Instrument Transformer (IT) accuracy class on the hybrid state estimator
- Consideration of IT accuracy class in measurement weighting

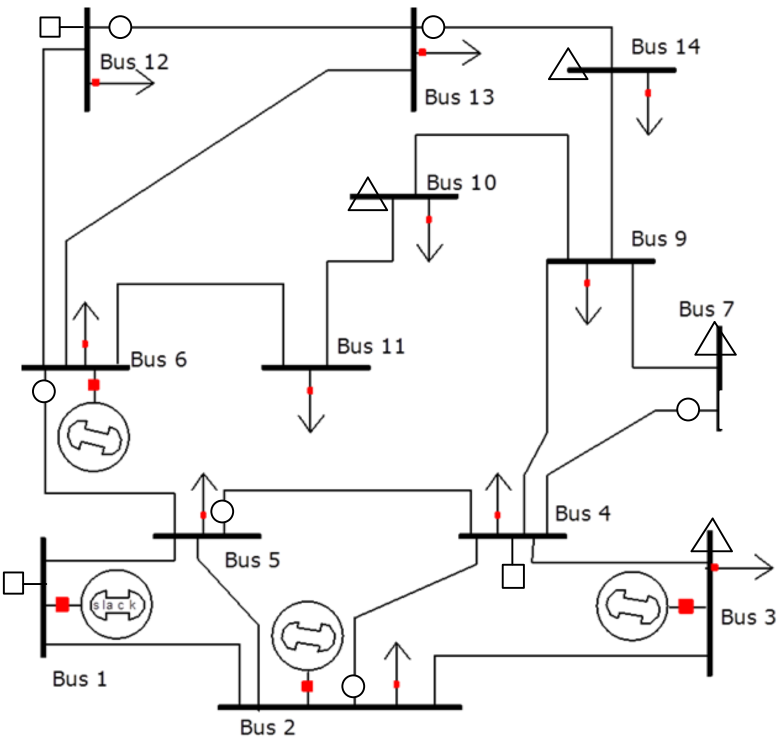
Synchronized Measurement Technology

- Present in the market since the early 1990s
- Synchronization of measurements
- The key element of SMT is the Phasor Measurement Unit (PMU)
- GPS synchronized equipment
- Synchronized voltage and current phasors
- High reporting rate
  - 100 or 120 phasors per second depending on the system operating frequency
  - Conventional measurements are updated every 2-10 seconds
- Angle measurements not possible with conventional measurement technology

Source: SEL

Source: Arbiter

State Estimation in 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

State Estimation in Power Systems

Model of the state estimator

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

$$\Downarrow$$

$$\begin{bmatrix} P_{flow} \\ Q_{flow} \\ P_{inj} \\ Qinj \\ V \end{bmatrix} = \begin{bmatrix} P_{ij} = V_i^2(g_{si} + g_{ij}) - V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}) \\ Q_{ij} = -V_i^2(b_{si} + b_{ij}) - V_i V_j (g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}), \\ P_i = V_i \sum_{j\in\aleph_i} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ Q_i = V_i \sum_{j\in\aleph_i} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \\ 1 \end{bmatrix} + \mathbf{e}$$

Measurement errors are independent following a normal distribution

The states of the system can be determined using a Weighted Least Squares (WLS) estimator

Hybrid State Estimator

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

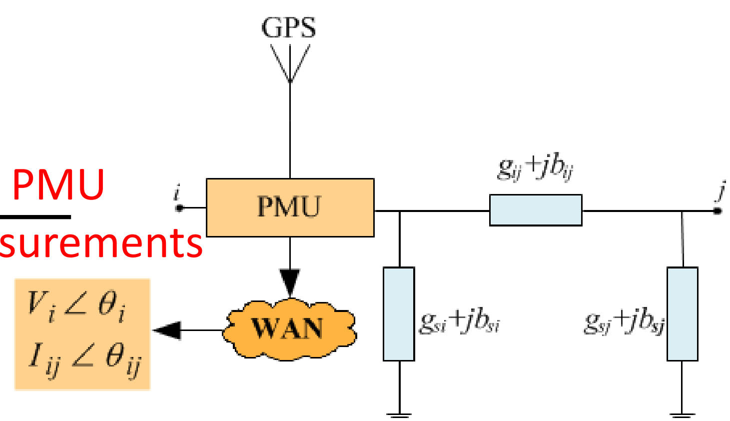
Incorporate these measurements into the existing state estimator

Emergence of a new state estimator: The Hybrid State Estimator

$$\mathbf{z}_{hyb} = \begin{bmatrix} \mathbf{P}_{flow} \\ \mathbf{P}_{inj} \\ \mathbf{Q}_{flow} \\ \mathbf{Q}_{inj} \\ \boldsymbol{\theta}^{V}_{PMU} \\ \mathbf{V}_{PMU} \\ \boldsymbol{\theta}^{V}_{PMU} \\ \mathbf{I}_{PMU} \end{bmatrix}$$

Conventional measurements

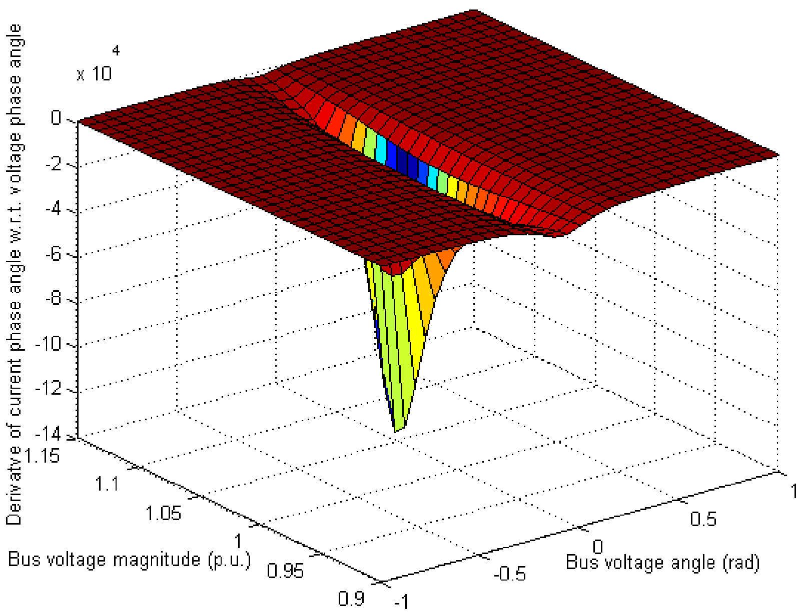
PMU measurements

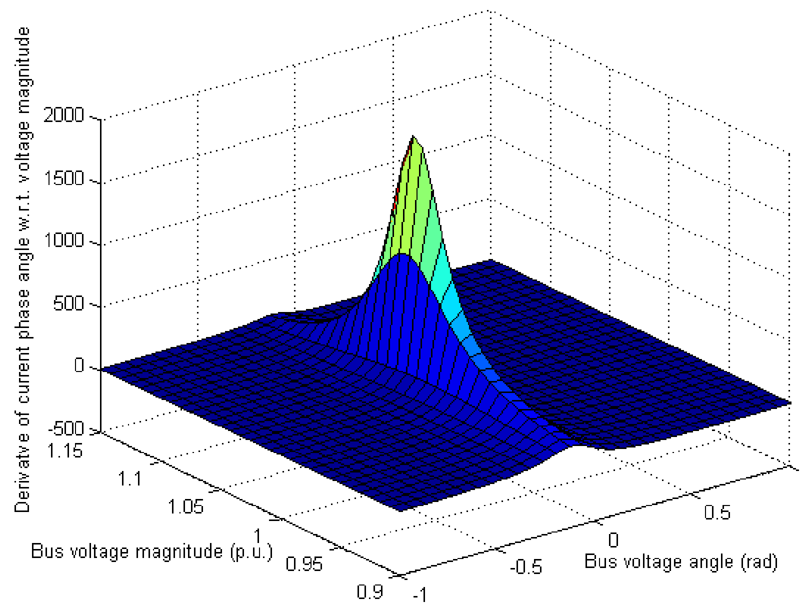


$$H_{hyb}(x) = \begin{bmatrix} \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial Q_{flow}}{\partial \theta} & \frac{\partial Q_{flow}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial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

Hybrid State Estimator

- The previous scheme may exhibit convergence problems during the iterative process
- The elements of the Jacobian matrix related to currents take relatively large values for specific values of the voltage



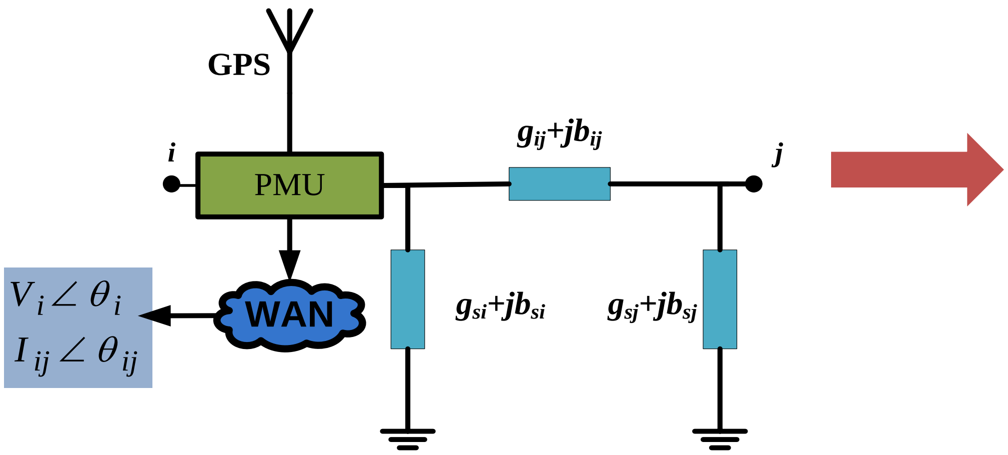


* S. Chakrabarti, E. Kyriakides, G. Ledwich, and A. Ghosh, “Inclusion of PMU current phasor measurements in a power system state estimator,” *IET Generation, Transmission, and Distribution*, vol. 4, no. 10, pp. 1104-1115, Sep. 2010.

Use of Pseudo Flow Measurements

Assuming that a PMU is connected to bus *i*, the voltage phasor at bus *i*, $\bar{V}_i$, 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.



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

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

* 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.

Use of Pseudo Flow Measurements

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

Extremely accurate measurements

Related to state variables similar to the conventional flow measurements

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

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

The use of pseudo flow measurements overcomes the convergence problem and improves the estimator accuracy

Measurement Chain Uncertainties

- The state estimator is based heavily on the measurements
- In practice, usually only the measurement device error is used for estimating the measurement uncertainty
- Important to look at the whole measurement chain (cables, ITs, measurement devices)

The Impact 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)**

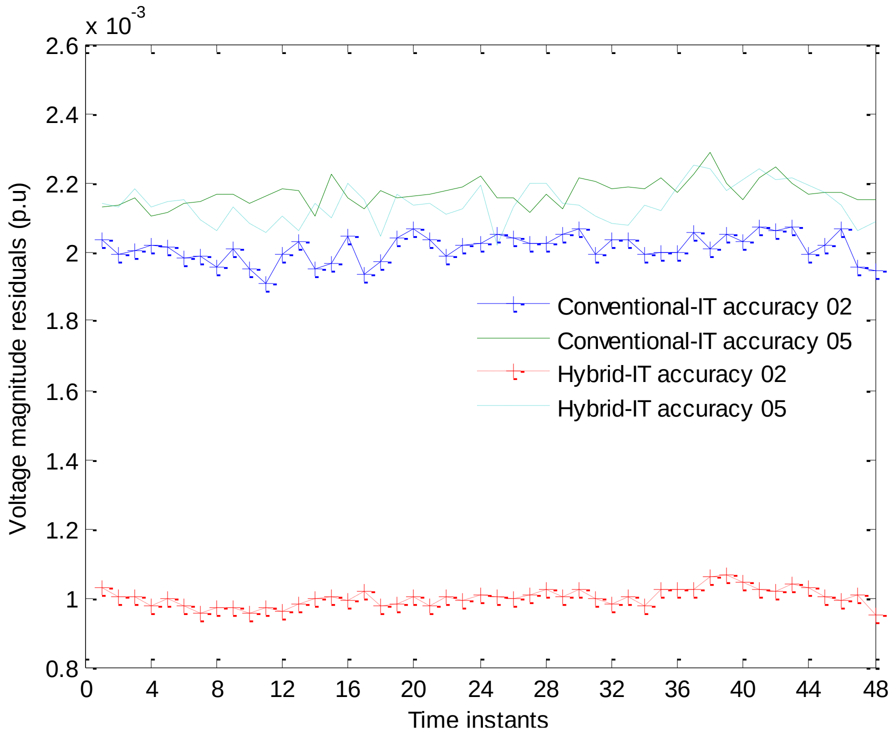
Hybrid and conventional state estimators are executed every half hour for a whole day for the IEEE 118 bus system, using a daily load profile

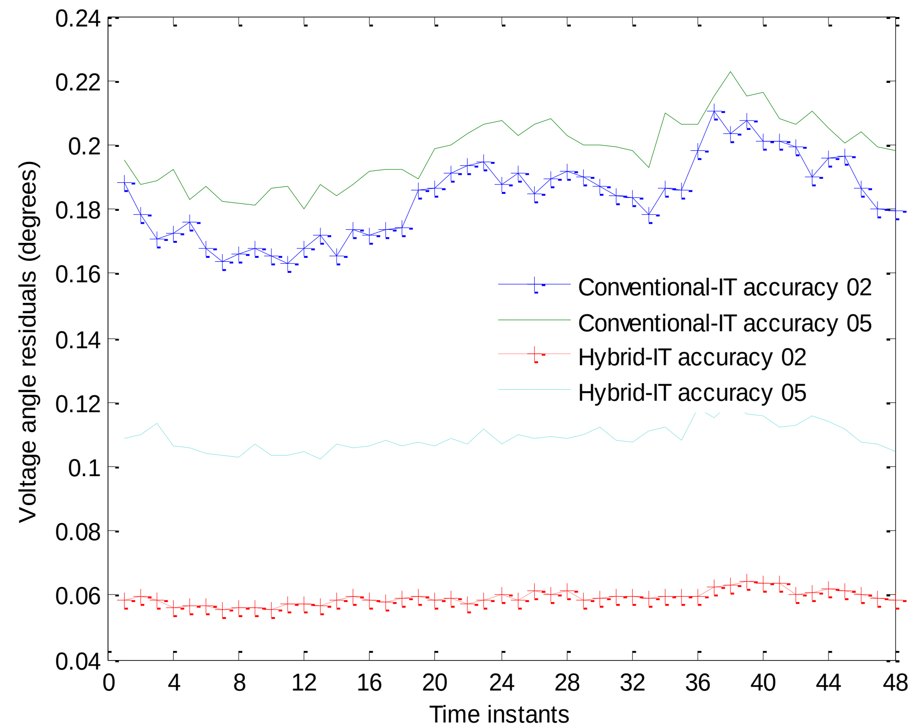
Metric of accuracy: Average sum of voltage magnitude and angle residuals

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

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

Instrument Transformers 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.

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

*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.

Weights for PMU Measurements

The hybrid state estimator uses voltage phasor measurements and pseudo flow measurements

Uncertainty of PMU measurements

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

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

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

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

Derived from the sum of two Gaussian distributions

Magnitude uncertainty

$$u_{MU}^{I} = \frac{\bar{e}_{MU}^{I}}{1.96}|I_{meas}| \qquad u_{MU}^{V} = \frac{\bar{e}_{MU}^{V}}{1.96}|V_{meas}|$$

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

Angle uncertainty

$$u_{MU}^{\theta_I} = \frac{\bar{e}_{MU}^{\theta_I}}{1.96} \qquad u_{MU}^{\theta_V} = \frac{\bar{e}_{MU}^{\theta_V}}{1.96}$$

$$u_{CT}^{\theta_I} = \frac{\bar{e}_{CT}^{\theta_I}}{1.96} \qquad u_{VT}^{\theta_V} = \frac{\bar{e}_{VT}^{\theta_V}}{1.96}$$

Errors follow a normal distribution with coverage factor 95%

Weights for PMU Measurements

Uncertainty of pseudo flow measurements

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

Pseudo flow measurements are correlated

Use of uncertainty propagation theory

$$u(P_{ij_{pseudo}}) = \sqrt{\sum_{k=1}^{4} [\partial P_{ij_{pseudo}} / \partial \mathbf{p}(k)]^2 . [u(\mathbf{p}(k))]^2}$$

$$u(Q_{ij_{pseudo}}) = \sqrt{\sum_{k=1}^{4} [\partial Q_{ij_{pseudo}} / \partial \mathbf{p}(k)]^2 . [u(\mathbf{p}(k))]^2}$$

Diagonal elements of the weighting matrix

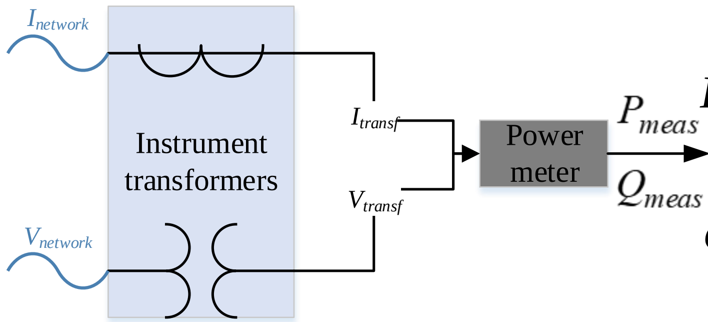
$$u(P_{ij_{pseudo}}, Q_{ij_{pseudo}}) = \sqrt{\sum_{k=1}^{4} \left[\frac{\partial P_{ij_{pseudo}}}{\partial \mathbf{p}(k)} \frac{\partial Q_{ij_{pseudo}}}{\partial \mathbf{p}(k)} \right] [u(\mathbf{p}(k))]^2}$$

Non-diagonal elements of the weighting matrix

$$\mathbf{p}(k) = \begin{bmatrix} V_{meas} & \theta^{V}_{meas} & I_{meas} & \theta^{I}_{meas} \end{bmatrix}$$

$$u(\mathbf{p}) = \begin{bmatrix} u^{V}_{meas} & u^{\theta_V}_{meas} & u^{I}_{meas} & u^{\theta_I}_{meas} \end{bmatrix}$$

Weights for Conventional Measurements



$$P_{meas} = V_{transf} I_{transf} \cos(\theta^V_{transf} - \theta^I_{transf}) + N(0, u^P_{MU})$$

$$Q_{meas} = V_{transf} I_{transf} \sin(\theta^V_{transf} - \theta^I_{transf}) + N(0, u^Q_{MU})$$

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

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

$$\frac{u^{Q_{meas}}_{IT}}{Q_{meas}} = \sqrt{\left(\frac{u^V_{VT}}{V}\right)^2 + \left(\frac{u^I_{CT}}{I}\right)^2 + \left(\frac{u^{\theta_V}_{VT}}{\tan\Delta\theta}\right)^2 + \left(\frac{u^{\theta_I}_{CT}}{\tan\Delta\theta}\right)^2}$$

Diagonal elements

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

Non-diagonal elements

$$\mathbf{p}_{tr}(k) = [V_{transf}, I_{transf}, \theta^V_{transf}, \theta^I_{transf}] \quad u(\mathbf{p}_{tr}) = \left[u^V_{VT} \quad u^I_{CT} \quad u^{\theta_V}_{VT} \quad u^{\theta_I}_{CT}\right] \quad \tan\Delta\theta = Q_{meas} / P_{meas}$$

Resulted Weighting Matrix

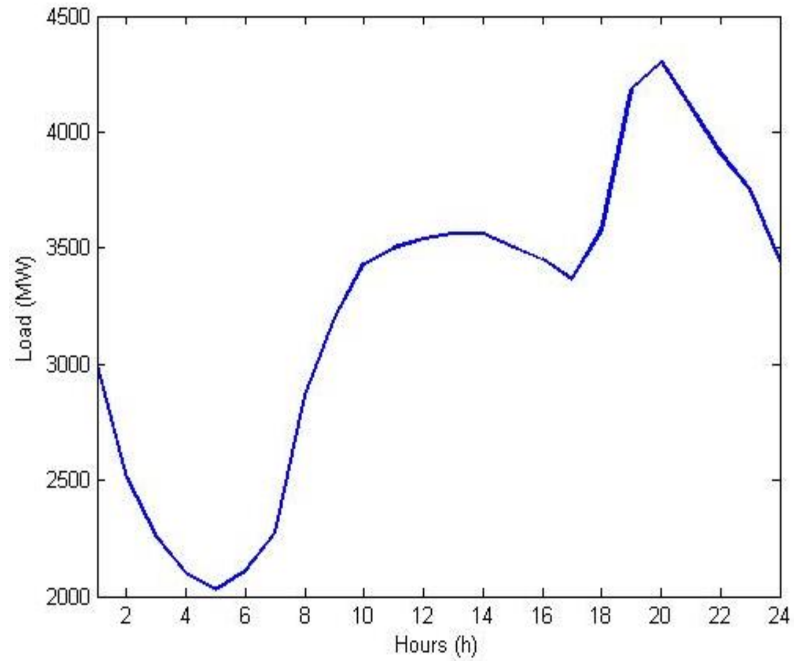
The measurement error covariance matrix **R** based on the instrument transformer and measurement device uncertainties is formed as:

$$\mathbf{R}=\begin{bmatrix} \mathbf{u}^2(P_{flow}) & 0 & 0 & \mathbf{u}(P_{flow},Q_{flow}) & 0 & 0 & 0 & 0 \\ 0 & \mathbf{u}^2(P_{flow}^{pse}) & 0 & 0 & \mathbf{u}(P_{flow}^{pse},Q_{flow}^{pse}) & 0 & 0 & 0 \\ 0 & 0 & \mathbf{u}^2(P_{inj}) & 0 & 0 & \mathbf{u}(P_{inj},Q_{inj}) & 0 & 0 \\ \mathbf{u}(Q_{flow},P_{flow}) & 0 & 0 & \mathbf{u}^2(Q_{flow}) & 0 & 0 & 0 & 0 \\ 0 & \mathbf{u}(Q_{flow}^{pse},P_{flow}^{pse}) & 0 & 0 & \mathbf{u}^2(Q_{flow}^{pse}) & 0 & 0 & 0 \\ 0 & 0 & \mathbf{u}(Q_{inj},P_{inj}) & 0 & 0 & \mathbf{u}^2(Q_{inj}) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{u}^2(V_{meas}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{u}^2(\theta_{meas}^{V}) \end{bmatrix}$$

Case Study 1 – No Systematic Errors

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

Assume a daily load profile.
Run hybrid state estimation every 30 minutes
Results shown for 118 bus system



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

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

Case Study 1 – Results

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

Average of 30.6 MW better estimation for each time instant - 10% improvement

Average of 86 MW better estimation for each time instant - 20% improvement

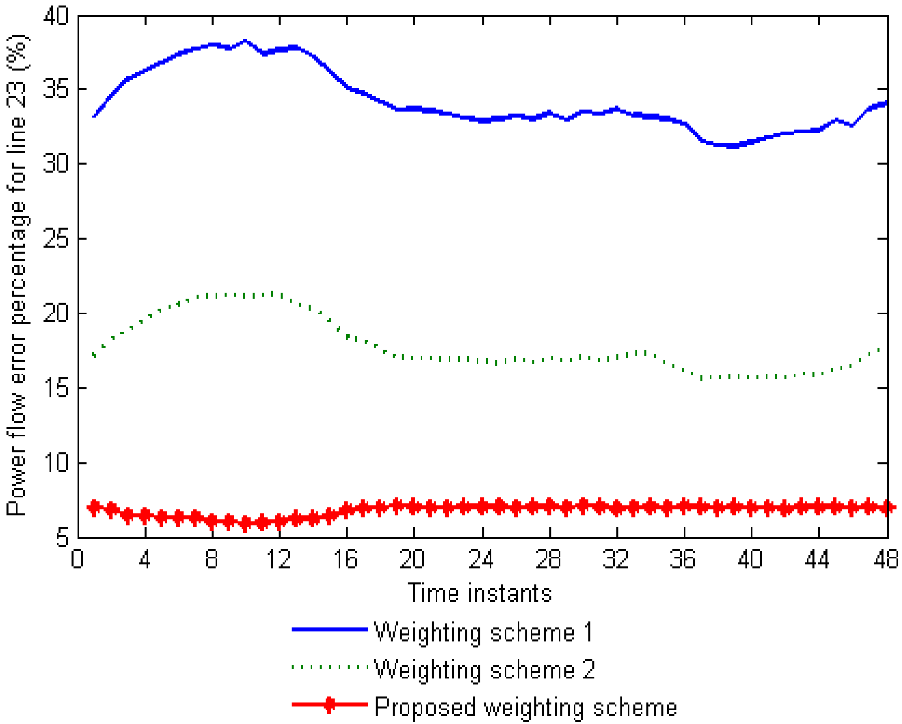
Case Study 2 – Erroneous PMU

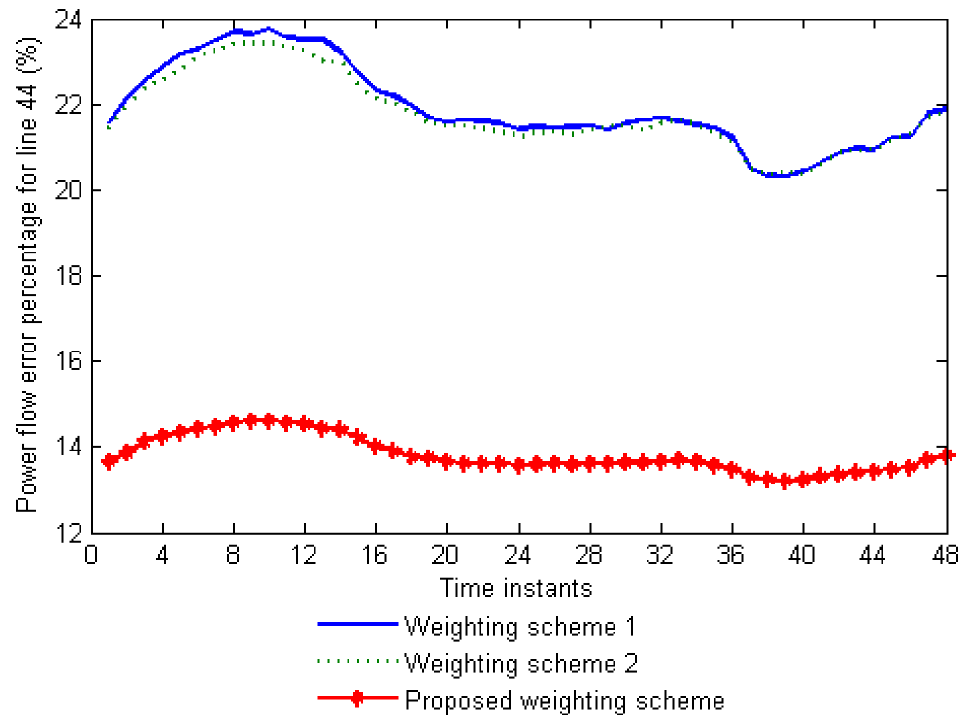
Assume one PMU (out of the 20) provides measurements that are biased by a 10% systematic error from their actual values.

Type of weighting scheme	SPFM (MW)
Weighting scheme 1	1537.2
Weighting scheme 2	1516.2
Proposed weighting scheme	**851.8**

Average of 664.4 MW better estimation for each time instant-42% improvement

Percentage error in power flows





Conclusions – Lessons Learned

- The accuracy of ITs did not play a major role in state estimation so far, 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.
- Weighting the measurements based on the combined uncertainty of the instrument transformer and the measurement device improves considerably the accuracy of the state estimator (even more important in the case of erroneous measurements).
- 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.

Acknowledgements

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