

Enhancing power state estimation by integrating PMU measurement buffer length and correlation

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Delivering more than power.™



State estimation in the smart grid

- Increased renewable and distributed generation, storage and possible load management.
- More competitive and free electricity markets and loads responding to price (smart meters).
- Increased communication and integration of IT and ICT technologies, sensed data (PMUs) and need for control.

The grid should operate efficiently, reliably, securely.

Confidentiality should be insured as well.

Complexity of the future grid  Increased need for accurate SE

Static power state estimation

- Estimate the state $\mathbf{x} \in \mathbb{R}^{n-1}$ (voltage magnitude and phase angle) from the observation vector $\mathbf{z} \in \mathbb{R}^m$ (active, reactive powers and voltage magnitude): $\mathbf{z} = \mathbf{h}(\mathbf{x}) + \mathbf{e}$
- The WLS is the maximum likelihood estimate when: $\mathbf{z} = \mathbf{H} \cdot \mathbf{x} + \mathbf{e}$ and \mathbf{e} is Gaussian
- The vector of residuals is analyzed for outliers: $\mathbf{z} - \hat{\mathbf{z}} = \mathbf{S} \mathbf{z}$ where \mathbf{S} corresponds to a projector on $\text{Ker}(\mathbf{H}^T)$
- The financial and real life consequences of bad SE can be tremendous (Important research topic)

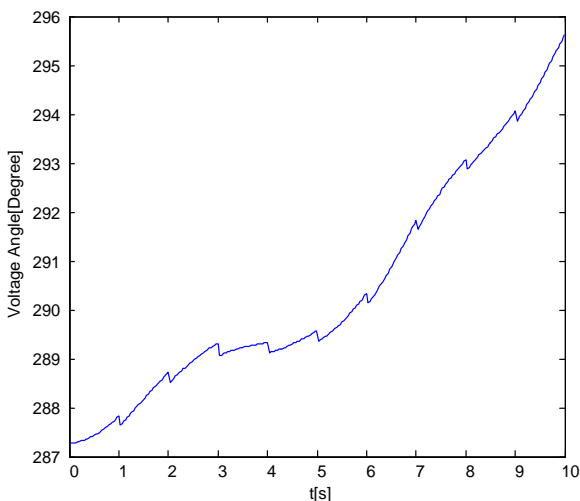
State estimation in the smart grid

Hybrid state estimation is becoming popular:

- The phasor measurement units (PMUs) measure the voltage magnitudes and phase angles directly.
- The measurements from PMUs are synchronized thanks to the use of GPS.
- Different reporting rates of conventional measurements (a new measurement every 2-5 s) and PMU measurements (30-120 measurements per second).
- PMUs are costly and still limited i.e. SE combines both regular measurements (SCADAs) and PMUs (Hybrid SE).

PMU measurements characteristics

- The PMUs' clocks are synchronized using the 1 ps signal from the GPS. Errors are present in the subintervals.
- Faulty synchronization of PMUs is called by **time skew**.



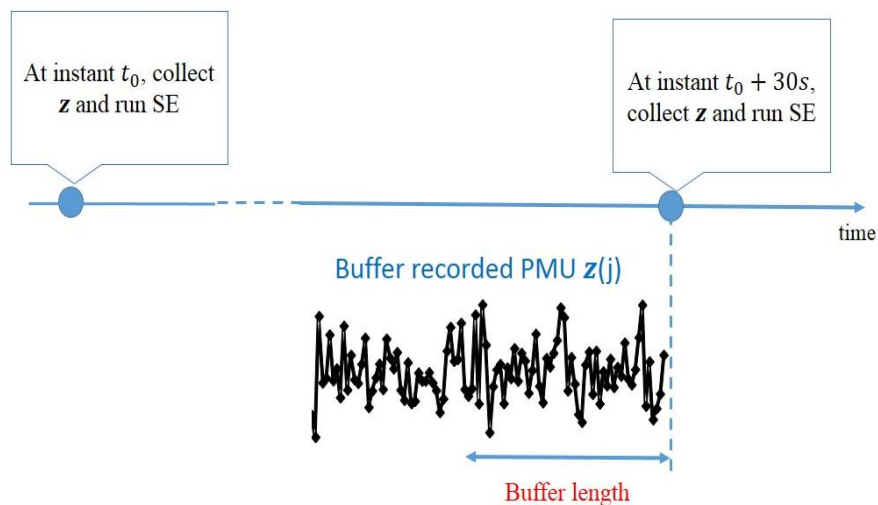
Jumps are present (every second) in the PMU phase angle measurements



Solutions are proposed, for example:
[Zhang et al. 2012]

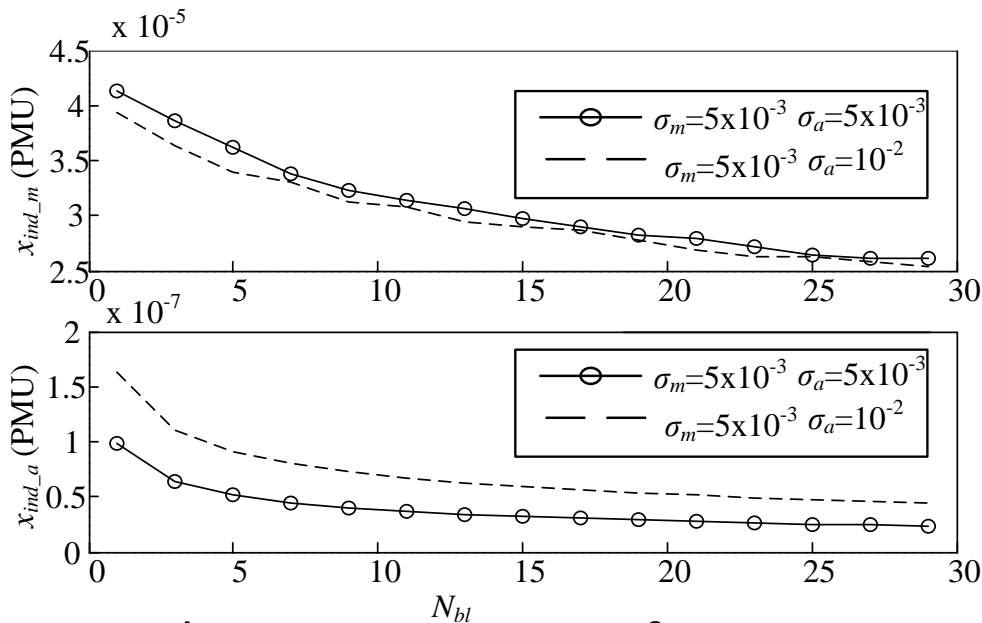
PMU measurements characteristics

- Presence of noise that could be reduced in static SE by exploiting the several available measurements.
- If the PMU noise is Gaussian, the averaging the PMU recorded measurements would reduce the noise.



Buffer length is the time length of PMU considered measurements starting from the last arriving measurement before SE.

PMU buffer length impact on SE



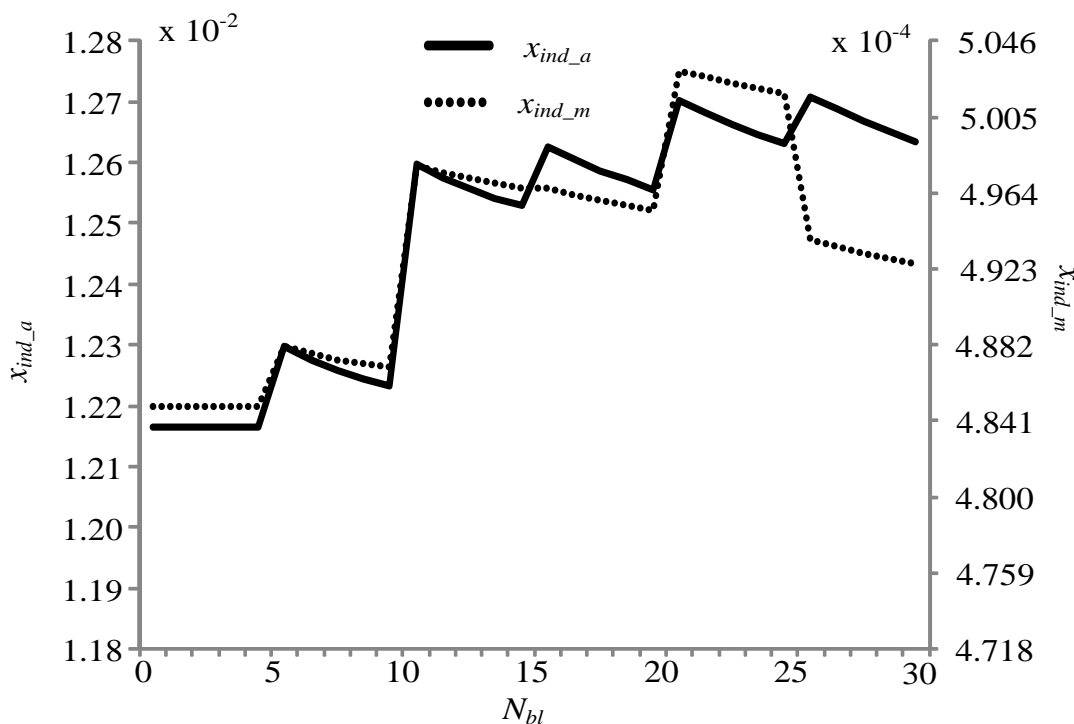
180 bus system with
20 PMUs installed

When the system is **really static**,
then increasing the buffer length
improves the estimation.

- The improvement of SE is more significant on the buses near electrically from the PMUS buses and depends on:
 - Number of installed PMUs.
 - Noise ratio PMUs versus SCADAs.
 - PMUs placement.

PMU buffer length impact on SE

- The real system could be **dynamic** (changing loads, impedances, generators,...)

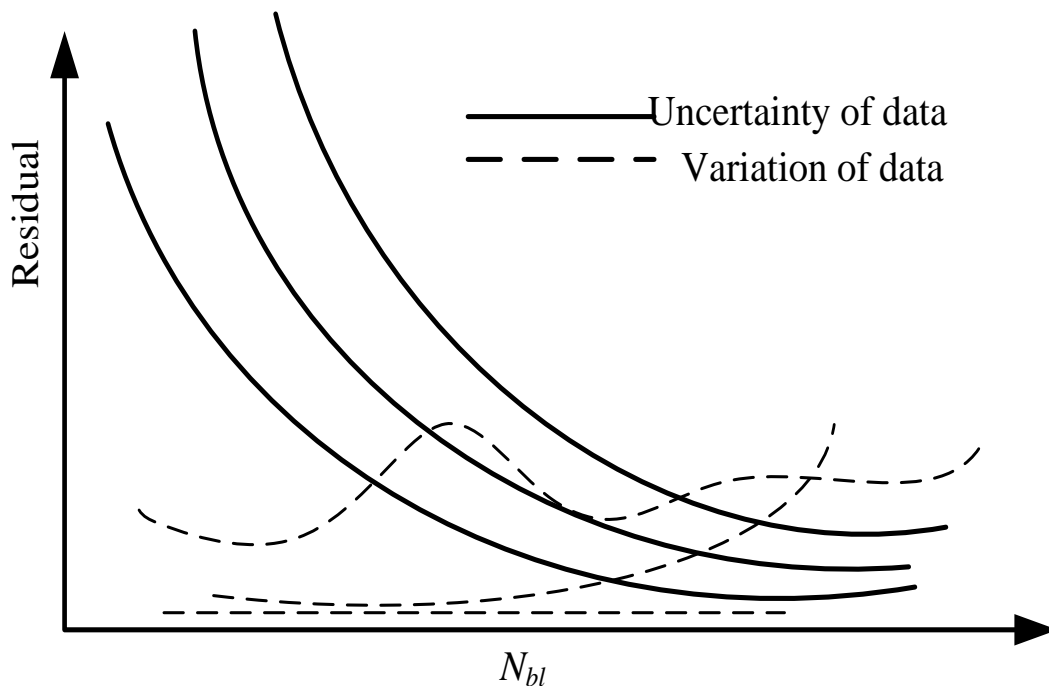


Simulations with loads that jump after 5 observations

When BL increases, the committed estimation error accumulates (random curve)

PMU buffer length impact on SE

- In real life, both static noise and a dynamic system are added together.

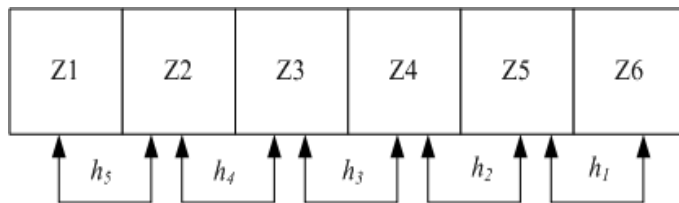


Objective: insure the best possible tradeoff between reducing noise uncertainty impact on estimation and improving system change tracking accuracy.

Solution: A simple hypothesis testing based method is proposed in [Zhang et al. 2013]

PMU buffer length impact on SE

Principle: Test for the null hypothesis (H_0 : The two means are equal) versus alternate hypothesis (H_1 = The two means are not equal) between subsets.



					1
				1	0
		1	0	0	0
	1	0	0	0	0
1	0	0	0	0	0
0	0	0	0	0	0

Optimal buffer

$$N_{op_bl} = n_{bfl}$$

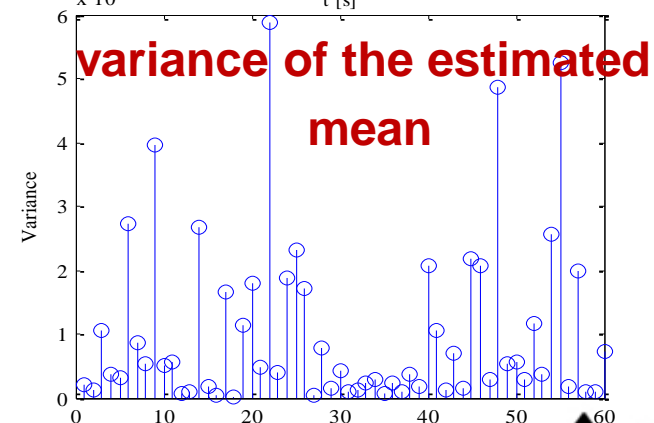
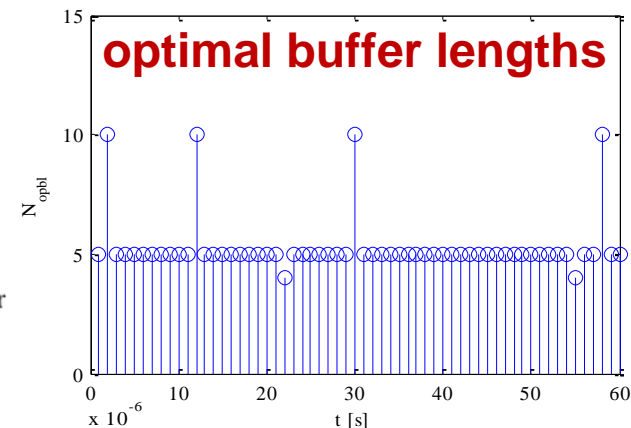
$$N_{op_bl} = 10$$

$$N_{op_bl} = 15$$

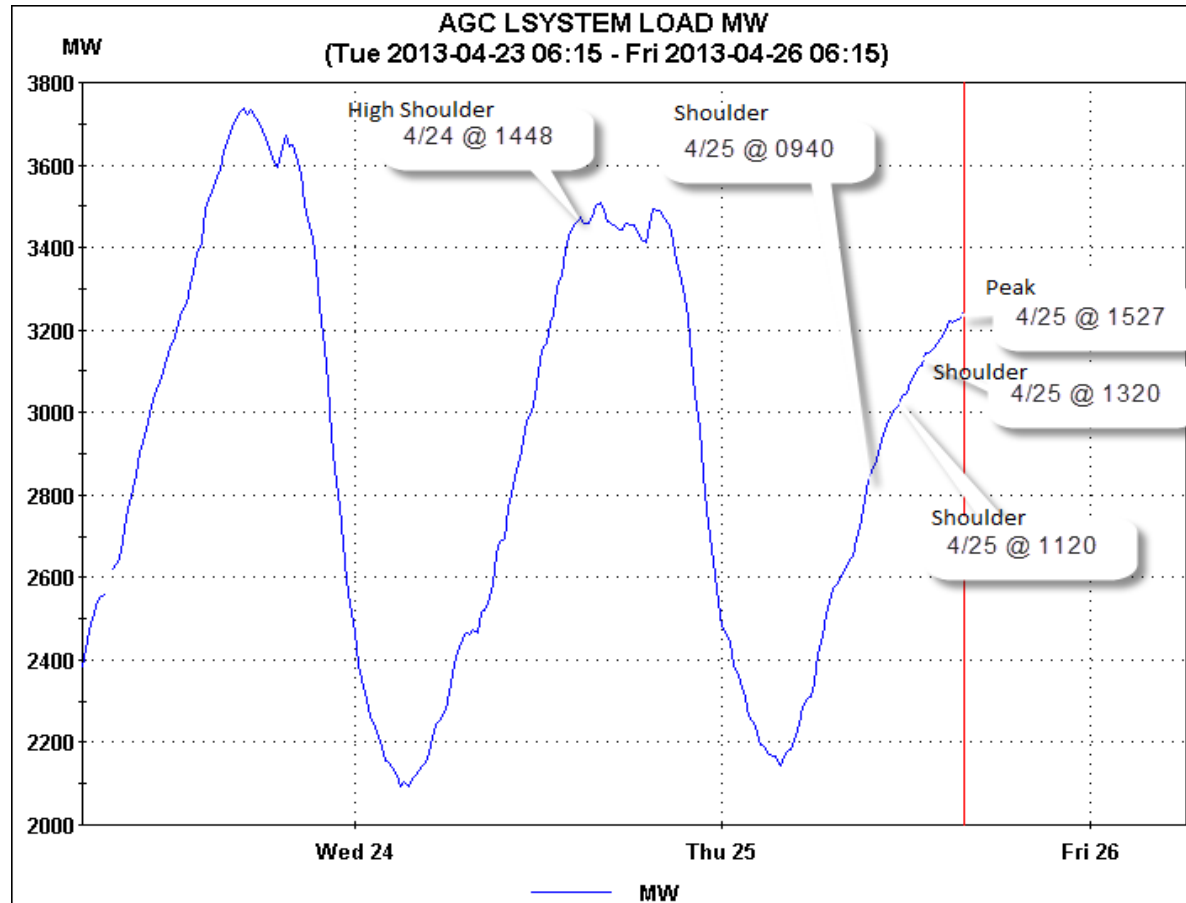
$$N_{op_bl} = 20$$

$$N_{op_bl} = 25$$

$$N_{op_bl} = 30$$

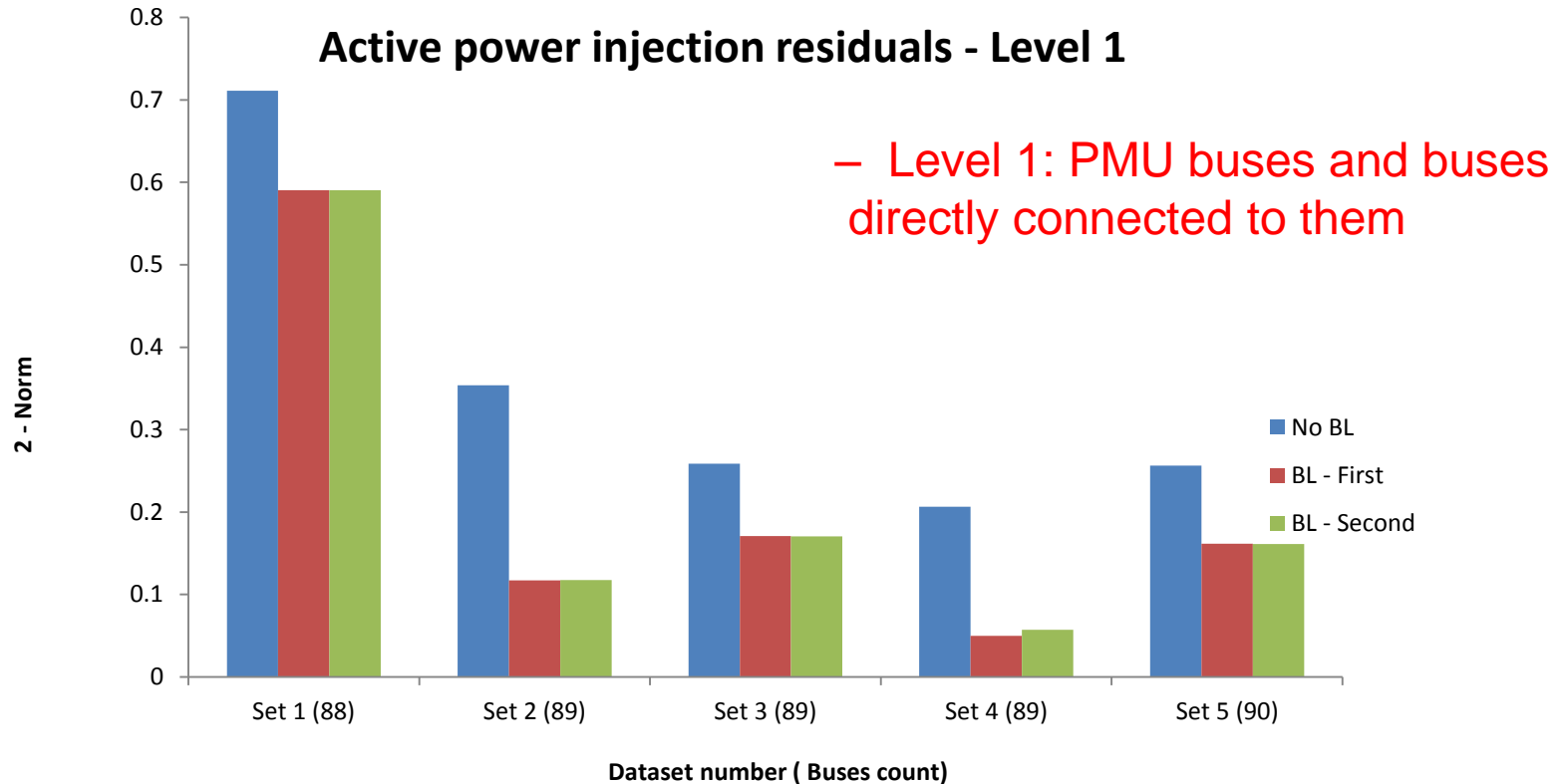


Application on a real life system



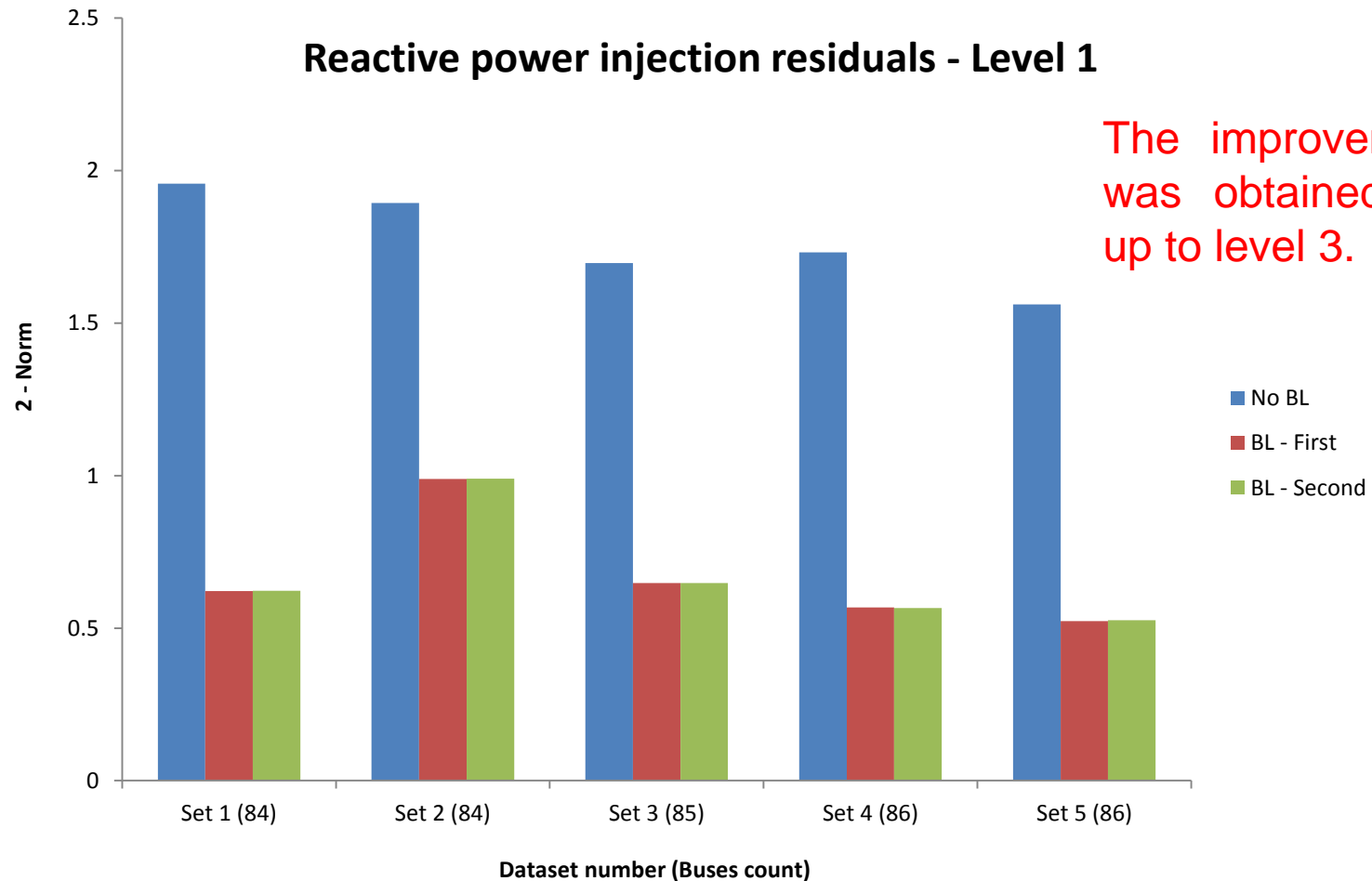
Evaluation at five different load conditions

Application on a real life system



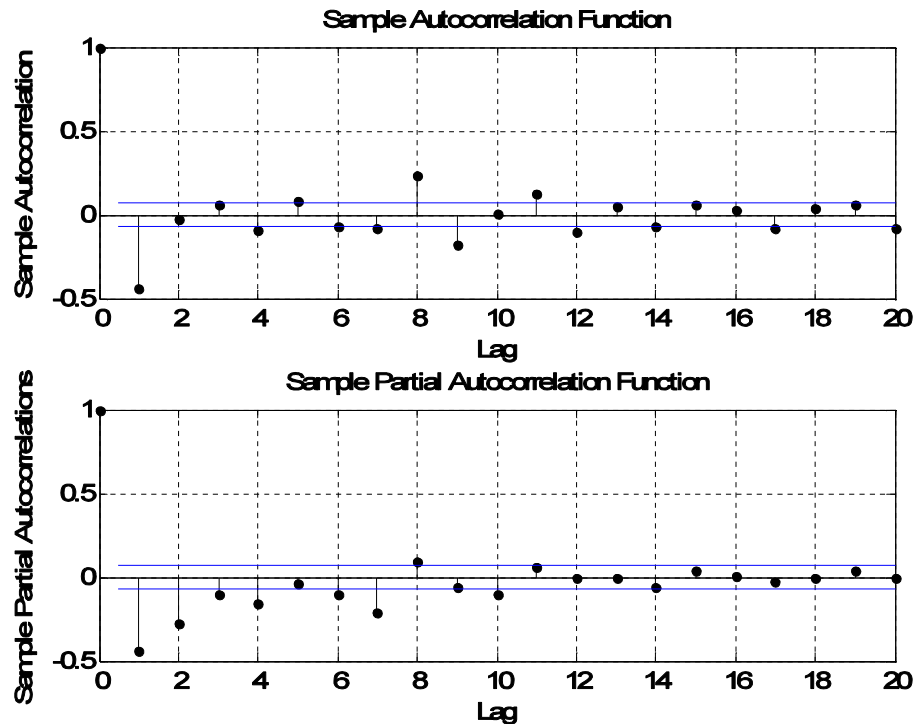
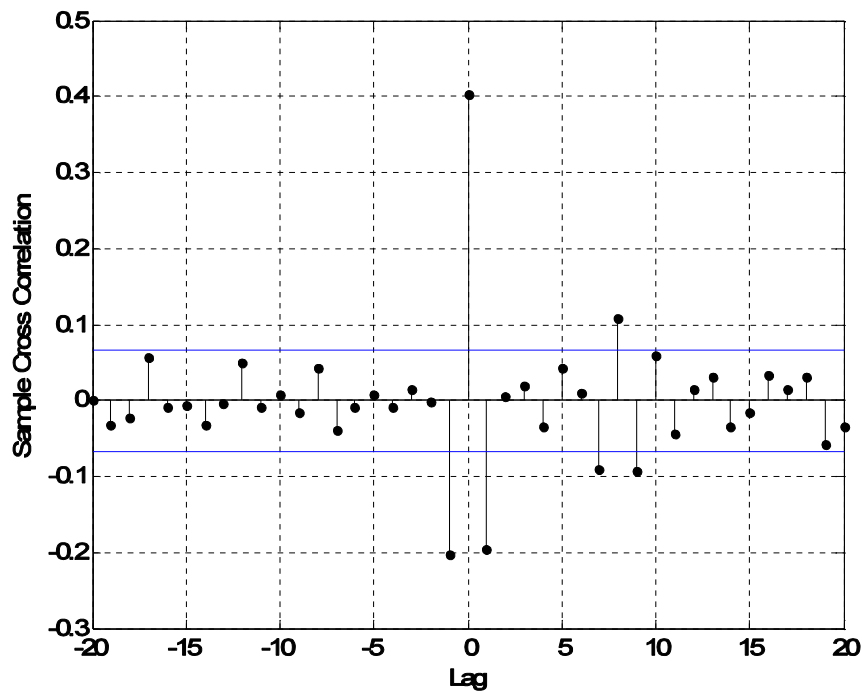
- No BL – Case without any PMU measurements
- BL First – Case with algorithm from previous project
- BL Second – Case with algorithm from present project

Application on a real life system



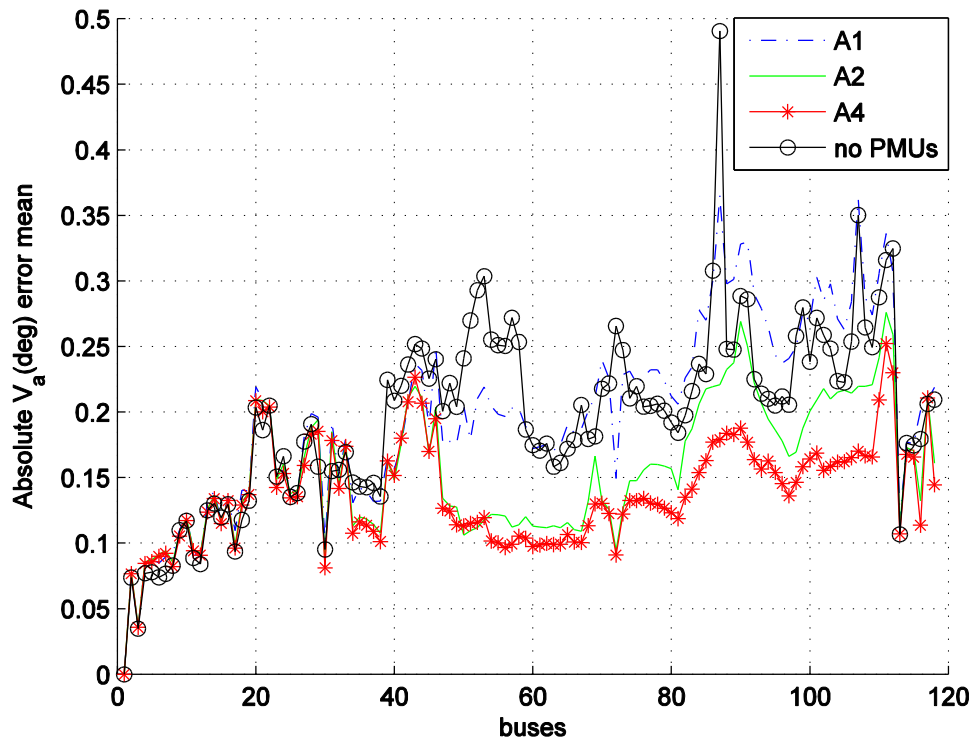
Modeling PMUs correlation in SE

- Measured PMUs show both time correlation and space correlation



Modeling PMUs correlation in SE

- Considering multiple short-order, small dimensional VARs improves the performance while begin tractable.



Monte Carlo average absolute error in voltage phase angle

- A1 last arriving PMU.
- A2 averaging the data.
- A4 space-time correlation.

PMUs and cyber-security

Cyber attacks?

$\mathbf{z}_c = \mathbf{z} + H \cdot \mathbf{c}$; the attack is in the space $\text{Im}(H)$;
 $\mathbf{r}_c = \mathbf{r}$ (stealthy attack) and $\hat{\mathbf{x}}_c = \hat{\mathbf{x}} + \mathbf{c}$.

- PMUs are used by some practitioners as **secure sensors** to improve cyber-security.
- PMUs could be subject to cyber-attacks as well.
- When considering robust SE estimators such as LTS, PMUs should be treated separately if clean.

Conclusions

- Including PMUs in SE is promising for the future smart grid.
- Exploiting the information provided in PMUs needs further investigation in signal processing and statistics.
- Cyber-security for power systems is becoming crucial and further investigation is needed.

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