Panel 3： Experiences in Incorporating PMUs in Power System State Estimation, IEEE PES General Meeting, Denver, USA, July 26-30

Incorporating PMUs in Power System State Estimation for Smart Grid EMS

Boming Zhang， Prof., IEEE Fellow

Dept. of Electrical Engg., Tsinghua Univ.

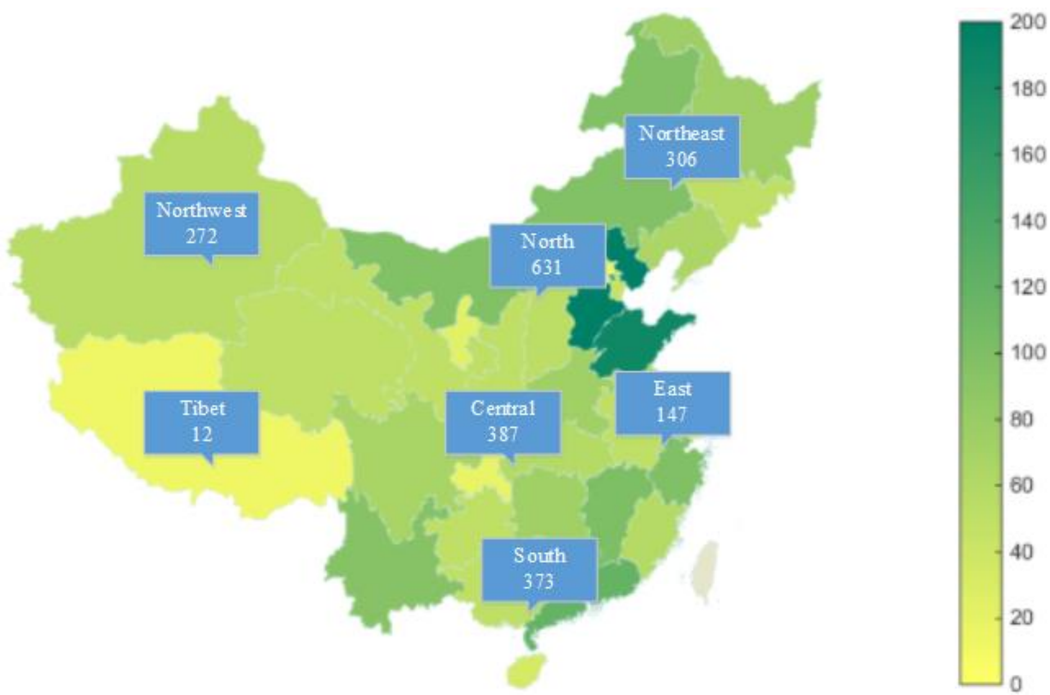
zhangbm@tsinghua.edu.cn

Content

- **PMU in China**
  - PMU Deployment
  - SE incorporating PMU measurements
  - Comparison between RTU and PMU measurements
  - Application & discussions
- **Multi-time interval dynamic state estimation** (MTIDSE)

PMU Deployment (1)

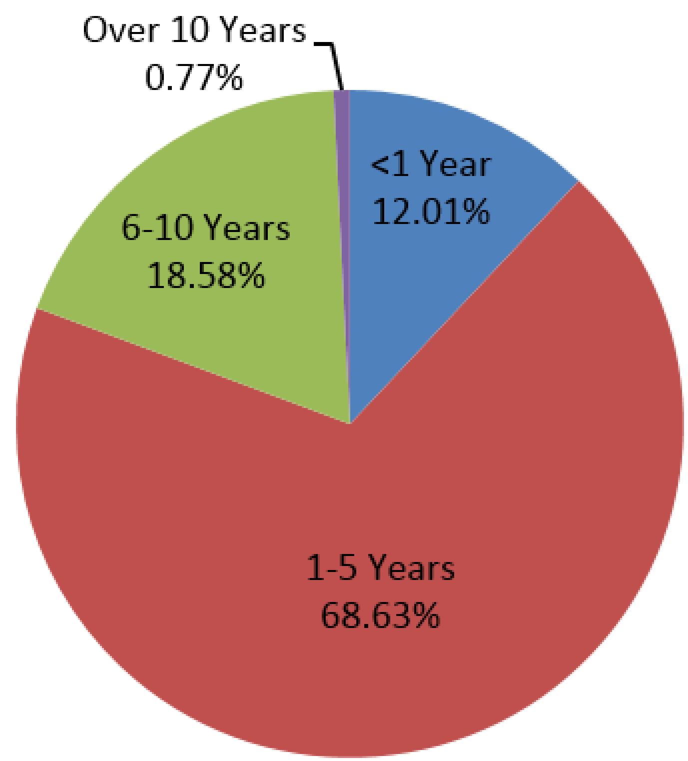
- Total number: around 2400
  - PMUs Cover all 500kV substations, all generators (>100MW), and some important 220/110kV substations
  - More than 30 WAMS center stations are in service



1000kV	7
800kV	6
750kV	39
660kV	26
500kV	723
330kV	165
220kV	861
110kV	200

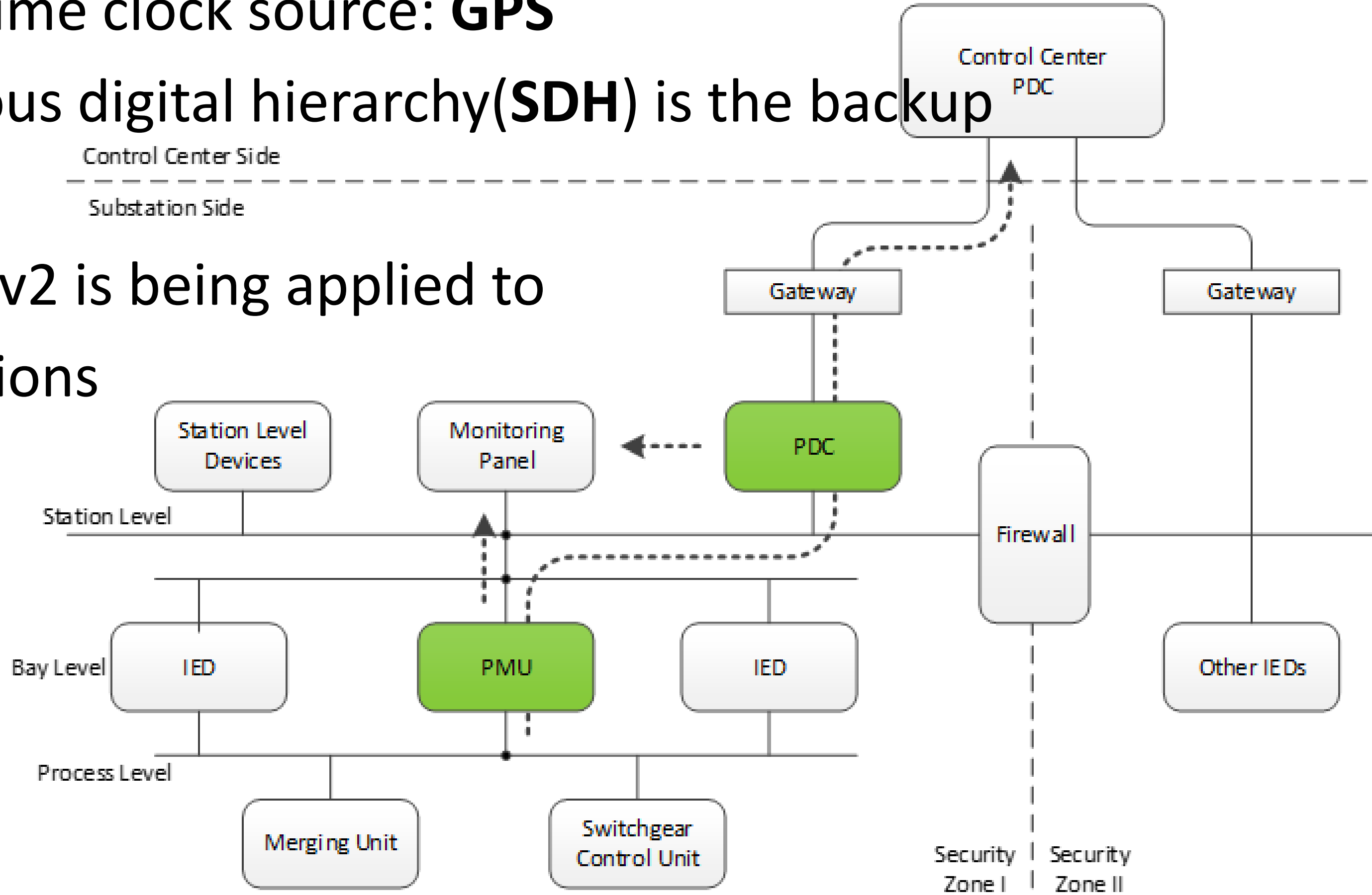
PMU Deployment (2)

- Most PMUs are installed after 2006
  - Predominate manufactures: Sifang Automation, NARI-Technology, China EPRI, NARI-Relays (98%)
  - Chinese standards on PMUs are being updated to conform to IEEE standards C37.118.1 and C37.118.1a
  - Tests for supporting IEC 61850 is being conducted



PMU Deployment (3)

- Architectures
  - Main clock source: **BeiDou** navigation satellite system
  - Auxiliary time clock source: **GPS**
  - Synchronous digital hierarchy(**SDH**) is the backup solution
  - IEEE 1588 v2 is being applied to communications between substations and control centers



IEEE PES Power & Energy Society®

SE incorporating PMU (1)

- <u>Method 1</u>:
- Directly use $\dot{V}$ measured by PMU in traditional SE

① Wang Yong, Ju Ping, Study on state estimation with PMU equipped at partial nodes of power systems, *J. of Hohai University*, 2004, 32(3)

② Liu Yi, The applying of GPS phasor measurement in electrical power system, *Master thesis, North China Electric Power University*

- Advantages: Simple and efficient;
- Drawbacks: impact of PMU measurement error on SE

SE incorporating PMU (2)

- Method 2:
- Convert PMU measurements to power measurements and use them as in traditional SE
  ① Wang Keying, Mu Gang, Chen Xueyun, Precision improvement and PMU placement studies on state estimation of a hybrid measurement system with PMUs, *Proc. of the CSEE*, 2001, 21(8): 29-33
- Advantages: compatible with existing SE program;
- Drawbacks:
  – Loss the linearity of PMU measurements

- Predominate approach in real dispatch centers

Comparison between PMU & RTU (1)

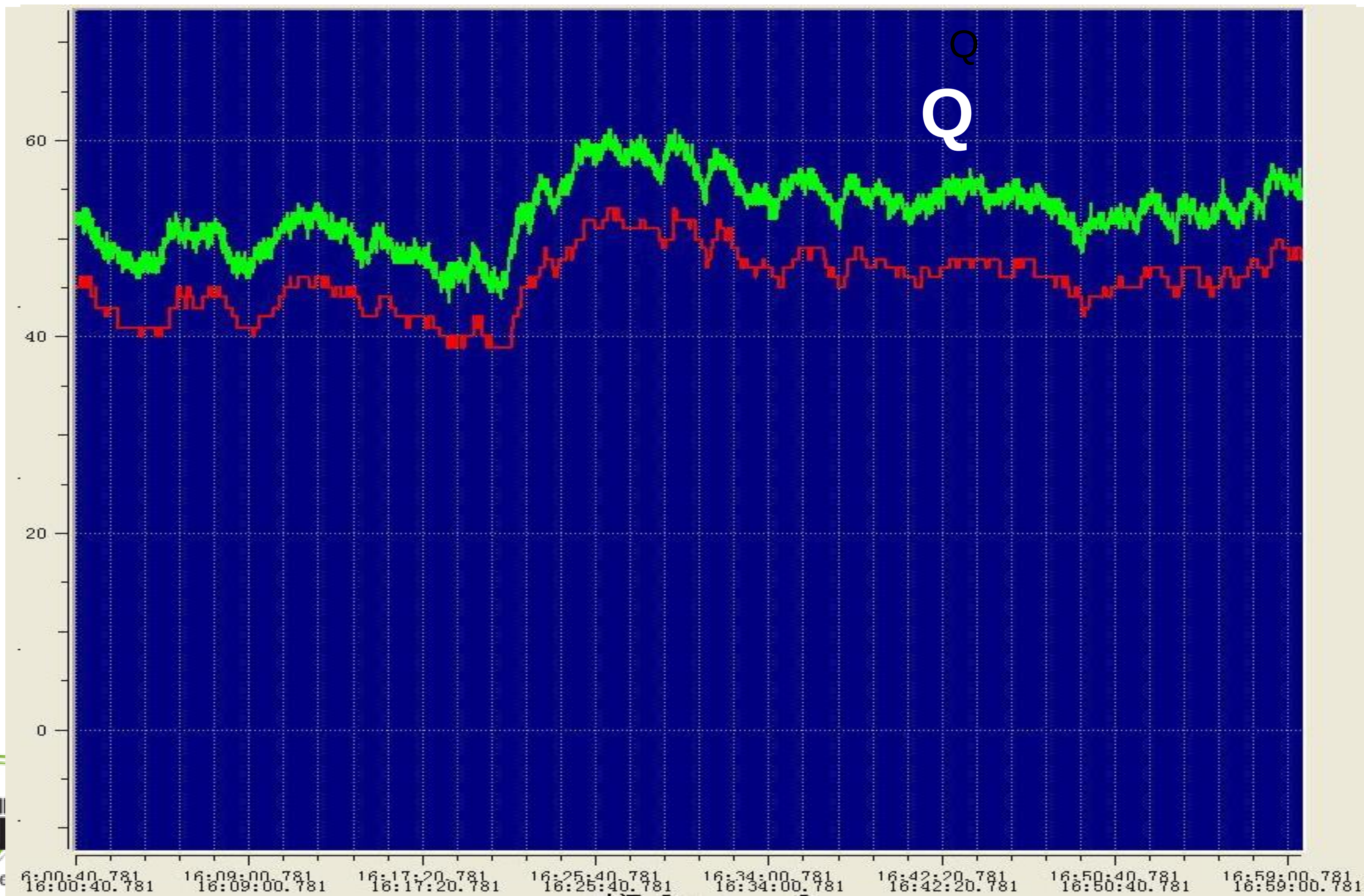
- Tests based on field data:
  - Measurements with extremely large or small values are excluded
  - Communication time: < 1s
  - differences between RTU and PMU

measurement	Δ
P, *I*, and *V*	< 2%
Q	5% ~ 40%

- 24% of Q measurements whose Δ > 10%
- this difference keeps stable

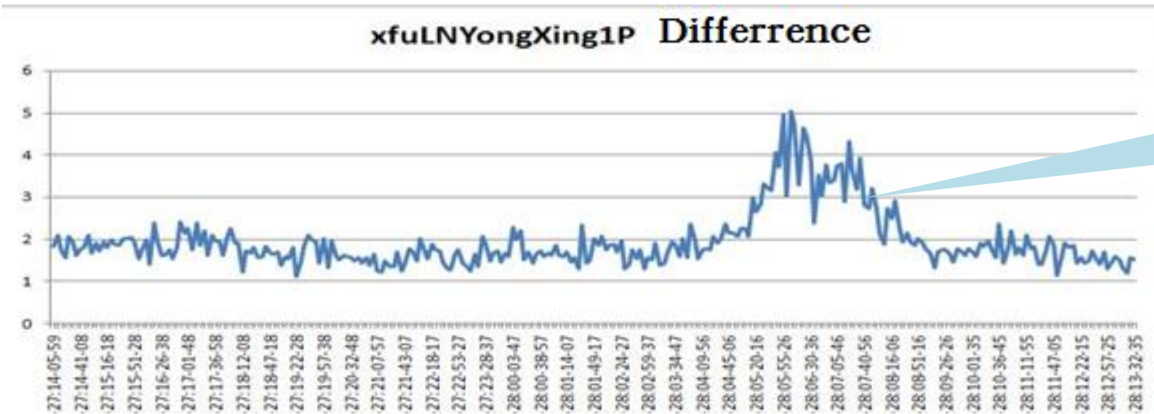
Comparison between PMU & RTU (2)

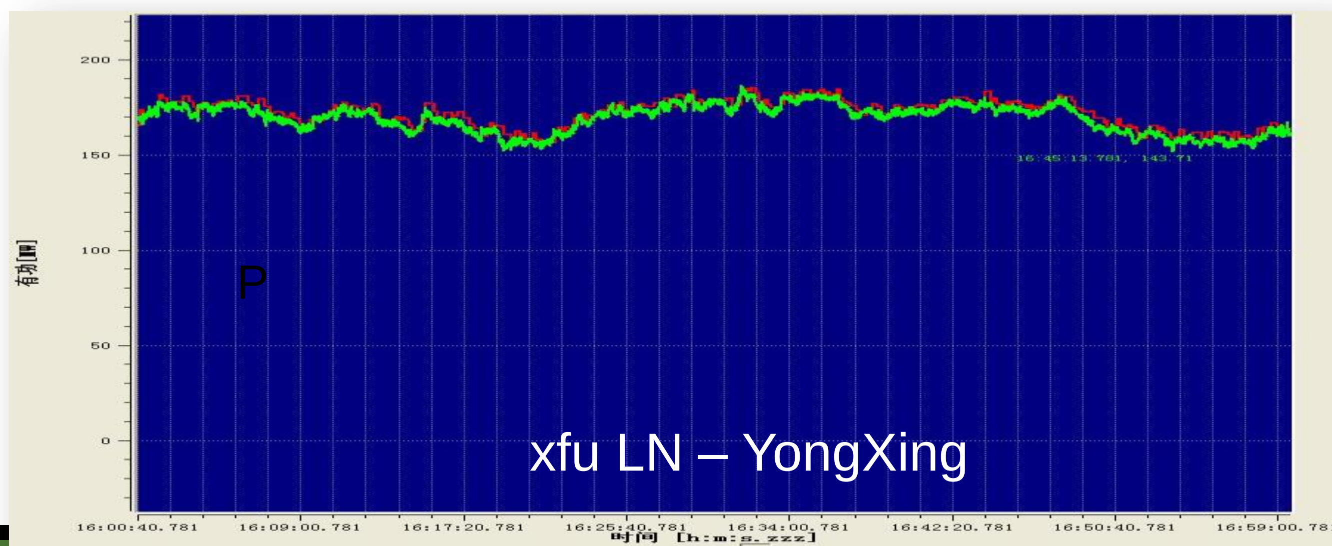
- Real power curves of RTU & PMU



Comparison between PMU & RTU (3)

- Real P difference between RTU & PMU

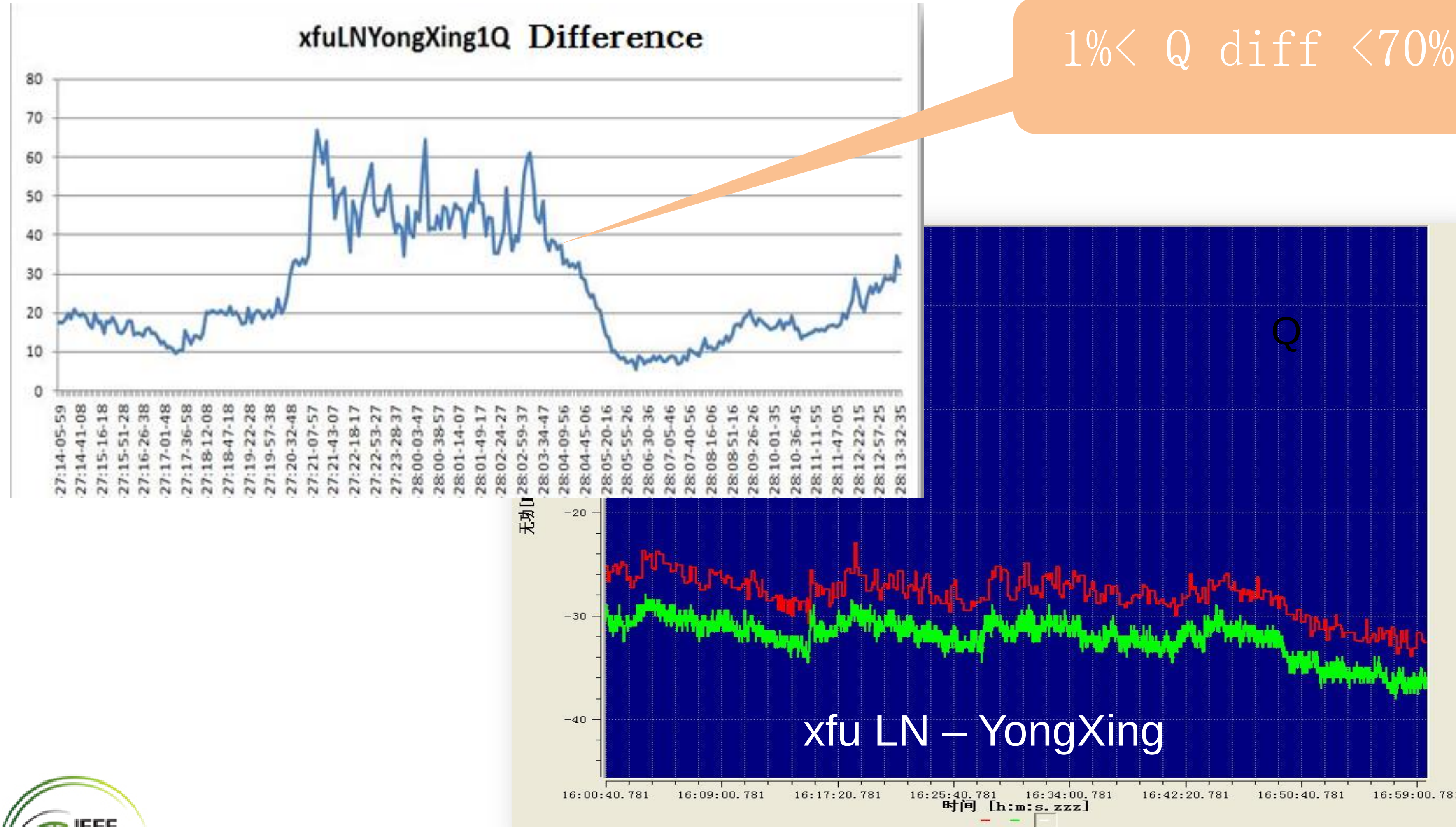




Comparison between PMU & RTU (4)

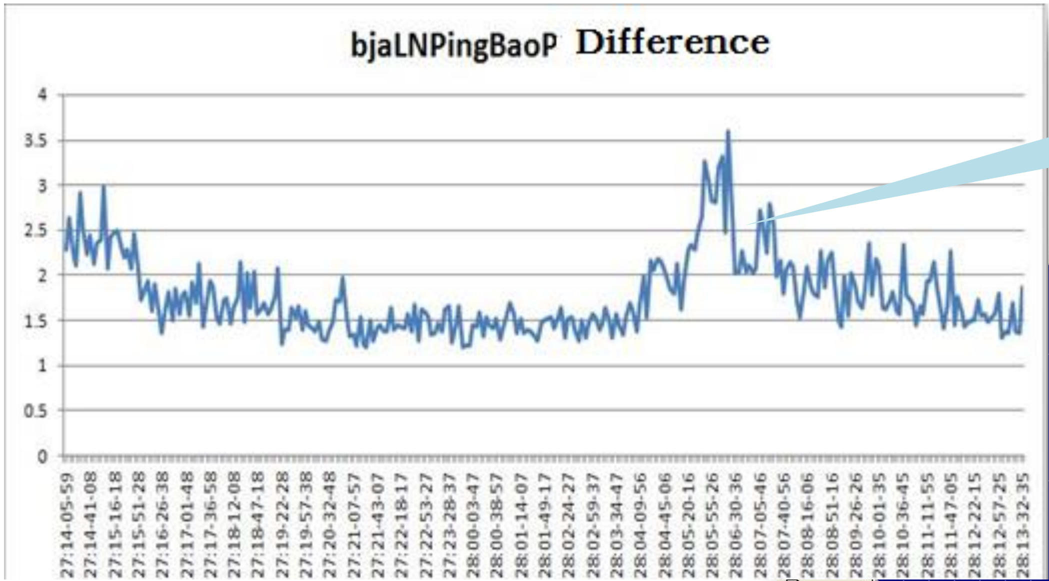
- Real Q difference between RTU & PMU

1%< Q diff <70%

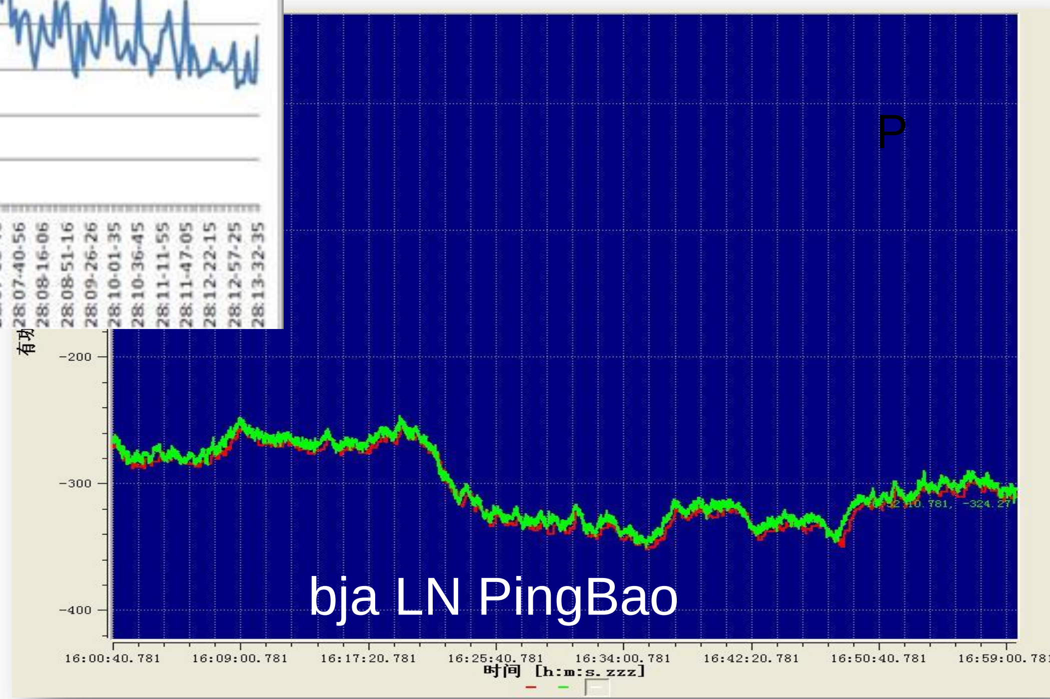


Comparison between PMU & RTU (5)

- Real P difference between RTU & PMU

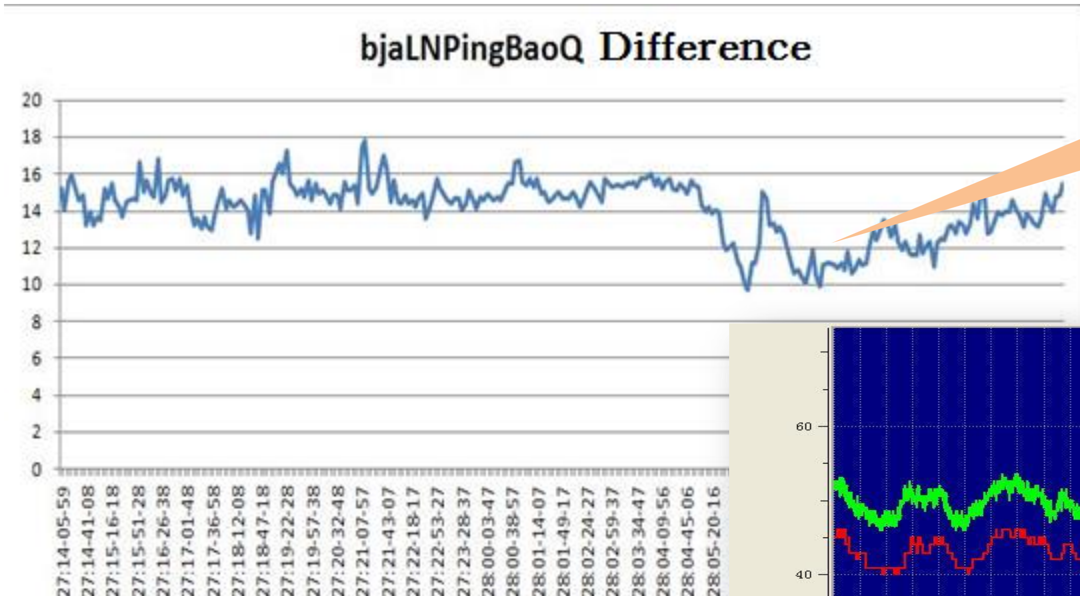


1%< P diff <3%

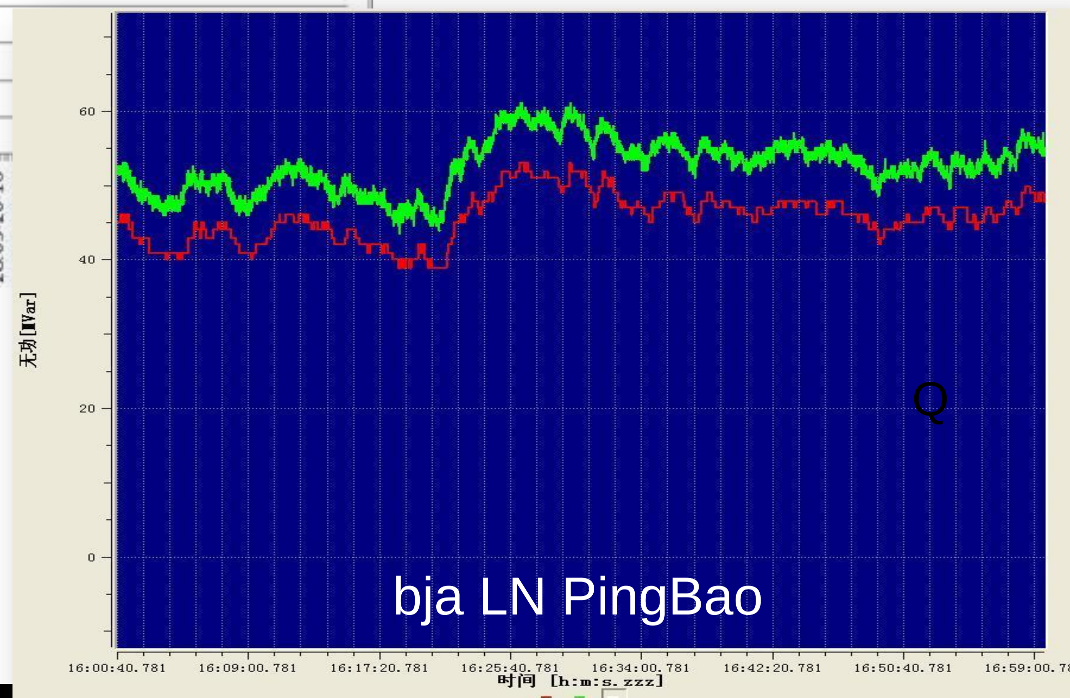


Comparison between PMU & RTU (6)

- Real Q difference between RTU & PMU



10%< Q diff <18%



Comparison between PMU & RTU (7)

- Large Error on Q caused by PMU measurement
  - The ways in computing Q
    - RTU: $Q=\frac{1}{N}\sum_{k=1}^{N} U_k I_{k+N/4}$
    - PMU: P = IUcosϕ, Q = IUsinϕ
  - Error in P measurement is OK
  - If the measured ϕ has an error of 0.1°, the Q measurement will have 10% error (ϕ=1°)

→ better

Δϕ	ϕ= 1	ϕ= 3	ϕ= 5	ϕ= 10	ϕ= 15	ϕ=20
0.1	**9.9**	3.3	1.9	0.98	0.6	0.4
0.3	29.9	9.9	5.9	2.96	1.9	1.4
0.5	49.9	16.6	9.9	4.94	3.2	2.3
0.8	79.9	26.6	15.9	7.91	5.2	3.8
1	99.9	33.3	19.9	9.89	6.5	4.7

Applications & Discussions (1)

- Summary: For PMU, |V | is quite accurate, but the θ is some inaccurate, resulting in a significant Q error
- Suggestions by manufacturers
  - Calibrate the accuracy of PMU measurements periodically.
  - Introduce an artificial compensation factor to revise error of phase angle measurements. Update these compensation factors periodically.
  - Improve the computational method for Q

Applications & Discussions (2)

- Overall affect tests
  - SE with RTU measurements only vs. SE with hybrid RTU/PMU measurements
  - 4 scenarios, SE creditability assessed by acceptance percentage (percentage of the measurements whose residuals < certain thresholds)
  - Accuracy improvement is not significant, or even worse

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	RTU	RTU/ PMU	RTU	RTU/ PMU	RTU	RTU/ PMU	RTU	RTU/ PMU
Meas. number	2728	4451	2728	4451	2734	4673	2734	4673
Acceptable meas.	2589	4227	2586	4205	2589	4453	2577	4423
Acceptance percent (%)	96.138	96.221	95.991	95.742	96.138	96.469	95.693	95.819

Applications & Discussions (3)

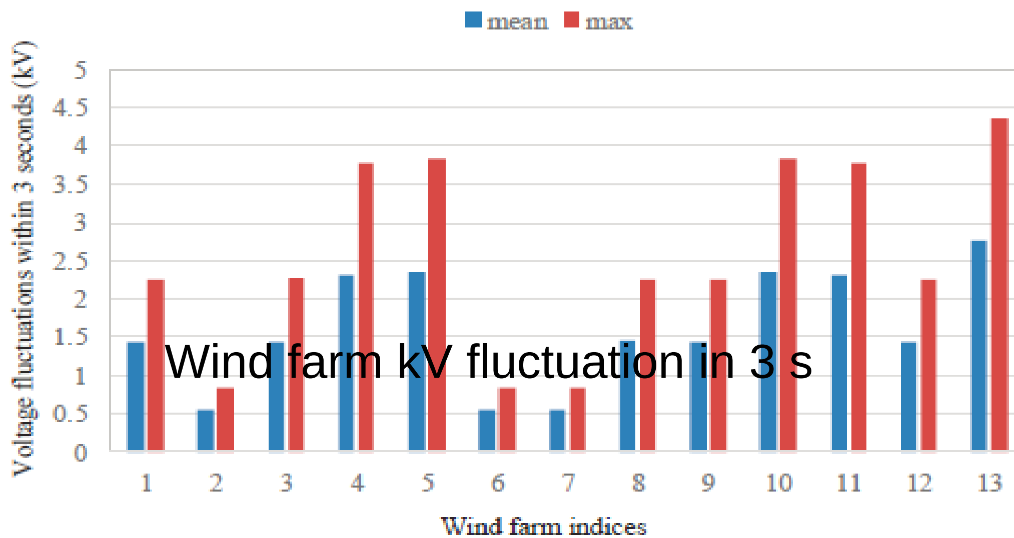
- Why PMU did not improve SE result ?
  - Phase angle measured is not so accurate.
  - More important: PMUs are used just as a supplementary measurement to conventional RTU measurements in current SE approaches
- The point of view :
  - RTU is just for steady state application, whiles PMU should be used for dynamic state application
  - suitable application scene should be identified

Applications & Discussions (4)

- PMU:
  - high sampling frequency
  - accurate time stamps
- These superiorities of the PMU should be utilized
  – Fluctuant and intermittent renewables generations should be monitored by using PMUs
  – For most part of the power grid, SE based on RTU is enough for power flow application.
- Multi-time interval state estimation will be a better choice

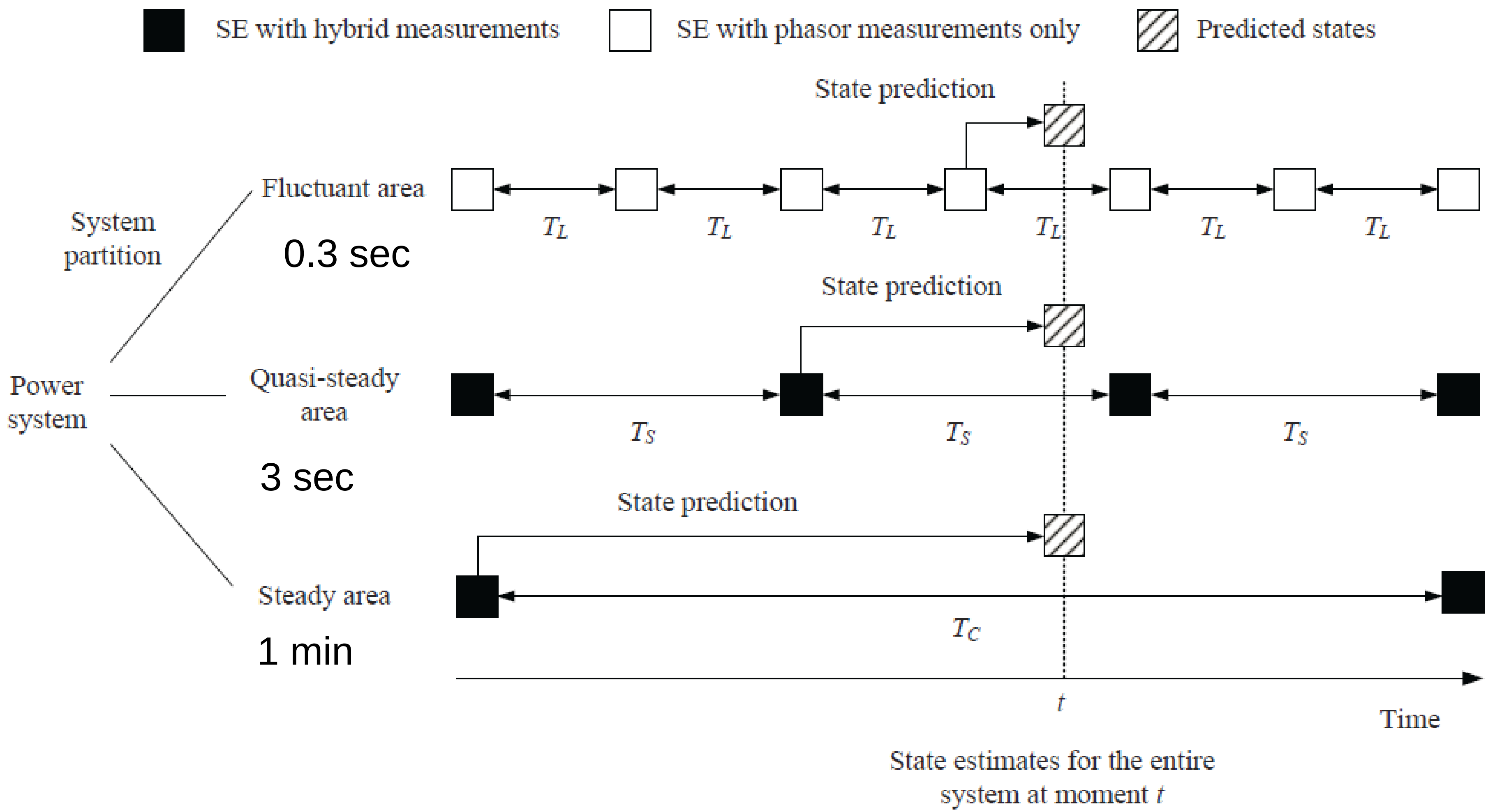
Multi-time interval dynamic state estimation (**MTIDSE**)

- Extensive integration of intermittent renewable generation is introducing a fluctuation, MTIDSE needed



- Conventional SE (calc. period: 1min) --- steady state
- SCADA (sampling period: 3s) --- asynchronism problem
- PMU SE ----- 0.3s

MTIDSE: Framework



MTIDSE: method (1)

- **System partition**
  - Steady area: $\mathcal{S} = \{j \in \mathcal{N} | \Delta S_j \leq \epsilon_S\}$
  - Fluctuant area: in which states may change significantly within 3s, PMU observable $\mathcal{F} = \{j \in \mathcal{N} | \Delta S_j > \epsilon_F \& j \in \mathcal{P}\}$
  - Quasi-steady area: the rest area $\mathcal{Q} = \{j \in \mathcal{N} | j \notin \mathcal{S} \& j \notin \mathcal{F}\}$
- **How to partition? Based on load flow sensitivity!**
  - Assess the fluctuation level of intermittent generators
  - Calculate the fluctuation level of branches:

$$\Delta P_l = \sum_{i=1}^{n} |S_P(k_i, l)\Delta P_i|, \Delta Q_l = \sum_{i=1}^{n} |S_Q(k_i, l)\Delta Q_i|$$

  - Estimate the fluctuation level of nodes, and then divide the system into different areas.

$$\Delta S_j = \sqrt{\Delta P_j^2 + \Delta Q_j^2},$$
$$\Delta P_j = \max_{l \in \mathcal{A}_j} P_l, \Delta Q_j = \max_{l \in \mathcal{A}_j} Q_l$$

IEEE PES Power & Energy Society® IEEE

MTIDSE: method (2)

- State estimation in steady area & Quasi-steady area
  - Use RTU/PMU measurements
  - SE interval: Steady area: ~ 1 min; Quasi-steady area: ~ 3s

$$\min_{x_S} \quad (z_S - h_S(x_S, x_{BS}))^{\dagger} W_S (z_S - h_S(x_S, x_{BS}))$$

  - Perform and update SE for the entire system at 1 min
  - perform and update SE for quasi-steady area at 3 sec
  - perform and update SE for fluctuant area at 0.3 sec
- Linear SE model by PMU
  - State estimation in fluctuant area done directly by PMU at 0.3 sec.

$$\min_{\boldsymbol{x}_F} \quad \left(z_F - H_{F-F} x_F - H_{F-FS} x_{FS}\right)^{\dagger} W_F \left(z_F - H_{F-F} x_F - H_{F-FS} x_{FS}\right)$$

IEEE PES Power & Energy Society® IEEE

MTIDSE: method (3)

- Use dynamic estimator to predict the states between two consequent SEs
- Fusion of state estimates in all areas:

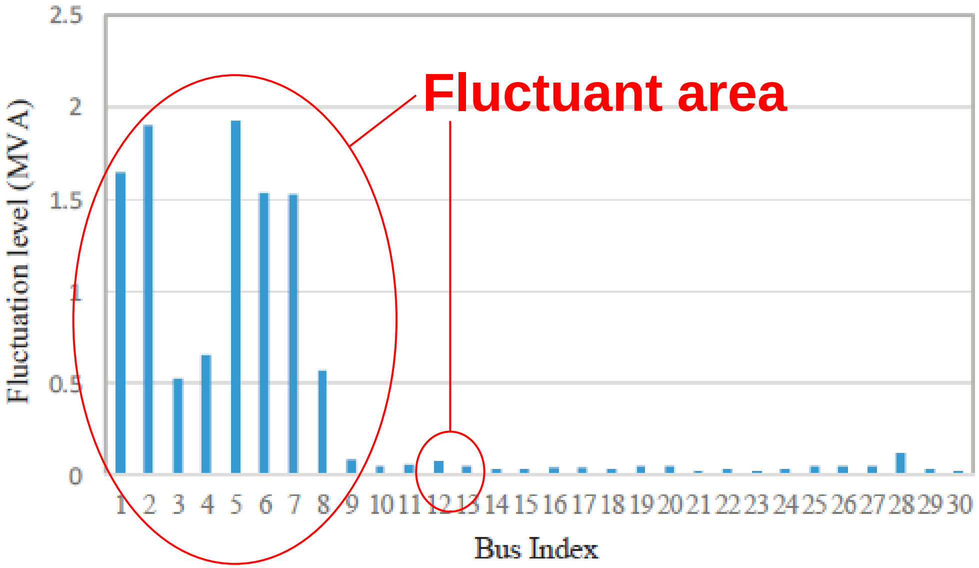
$$\tilde{x}(k+1) = F(k)\hat{x}(k) + g(k) \qquad \tilde{x}(t) = \frac{t - t_S}{T_C}\tilde{x}(t_S + T_C) + \frac{t_S + T_C - t}{T_C}\hat{x}(t_S)$$

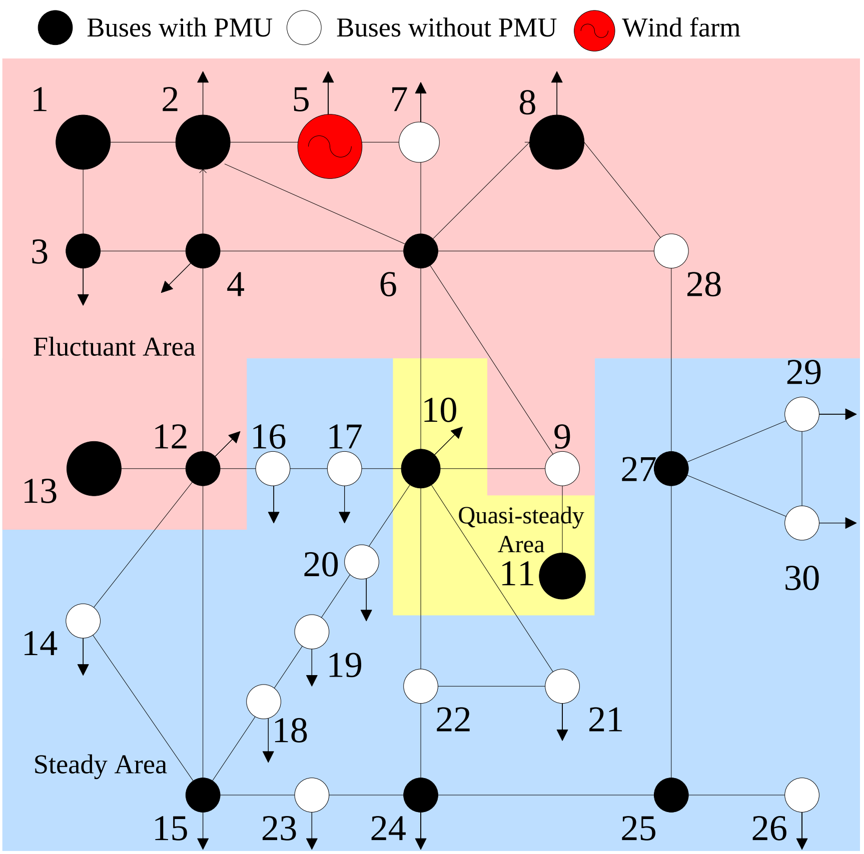
$$\hat{x}(t) \approx [\tilde{x}_S(t), \tilde{x}_Q(t), \tilde{x}_F(t)]$$

MTIDSE: Numerical tests (1)

- IEEE 30-bus system
  - System partition
  - Coincide with the true fluctuant levels

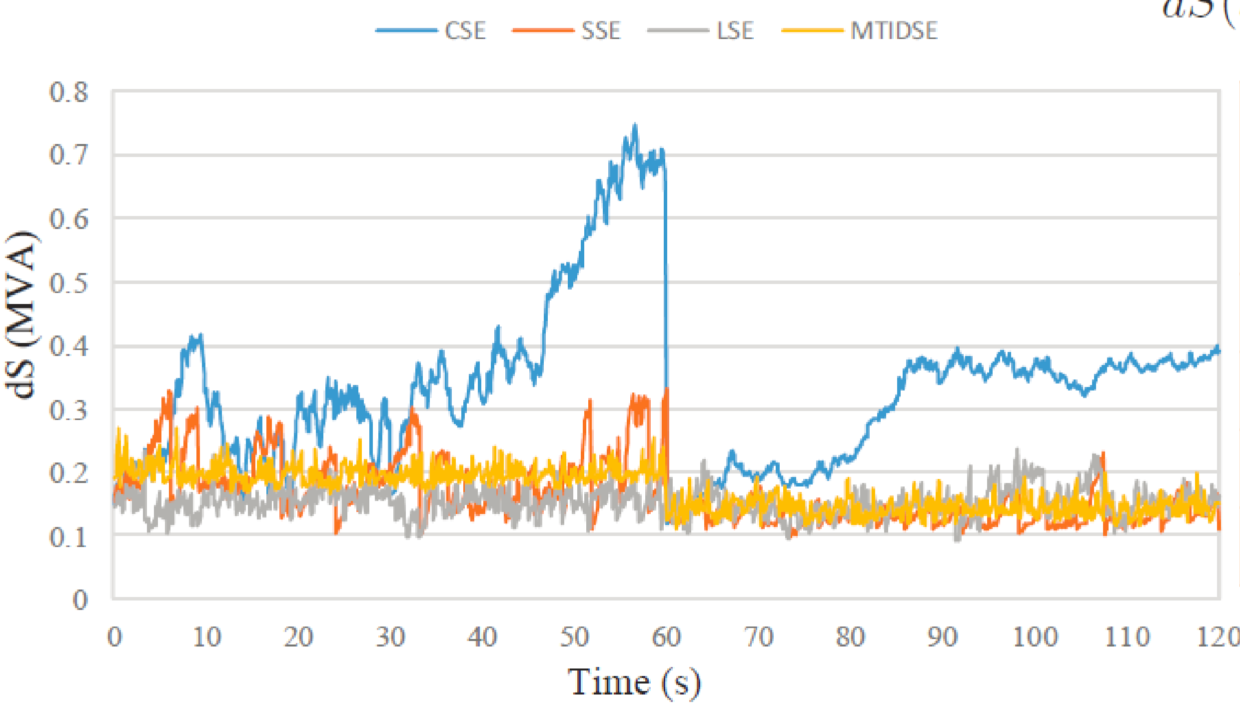
$$\Delta S_j = \max_{l \in \mathcal{A}_j}\{mean(|S_{True,lj}(t) - mean(S_{True,lj}(t))|)\}$$





MTIDSE: Numerical tests (2)

- Comparison of four approaches
  - CSE: Estimate all states with 1 min, by RTU/PMU
  - SSE: Estimate all states with 3s, by RTU/PMU
  - LSE: Estimate all states with 0.3s, by RTU/PMU
  - MTIDSE: Multi-time interval dynamic SE



$$dS(t) = mean(|S_{SE}(t) - S_{True}(t)|)$$

	Est. Error (MVA)	Time cost (s)
CSE (1min)	0.3288	0.257
SSE (3sec)	0.1773	5.104
LSE (0.3s)	0.1528	48.691
MTIDSE	0.1714	3.916

Conclusions

- PMUs are widely deployed in China
  - The-state-of-art: perform SE with PMU/RTU by using P and Q calculated by PMU
  - Q calculated by PMU is inaccurate
  - Benefit from SE with PMU/RTU is insignificant
- A multi-time interval dynamic state estimator is proposed
  - In real systems, only a portion states, rather than all, are fluctuant and need do SE by PMU directly
  - Benefit: Balancing between accuracy and efficiency
  - The high sampling rate of PMUs is fully utilized

Thanks for your attention！