Online Calibration of Phasor Measurement Unit Using Density-based Spatial Clustering

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GEIRI North America

Key Facts

- Founded in Dec. 2013 in Santa Clara, CA (www.geirina.net)
- Conducts cross-disciplinary R&D for power system modernization
- R&D subsidiary and overseas platform of State Grid Corporation of China
- 30+ Researchers and Engineers (recruiting)

Research Groups & Areas

- Graph computing & Grid Modernization
- Smart Chip & IoT
- PMU & System Analytics
- AI & Its Applications

Collaborations - Present

- Stanford, MIT, Berkeley, FSU(CAPS), Clemson and DOE Labs
- UTK (CURENT), ASU (PSERC)

Outline

- **Power System Parameter Calibration System (PSPCS) framework**

- System Implementation

Problems Description

- A lot of research has been conducted in the area of power system network/equipment parameter identification using PMU data.
  - Transmission line
  - Transformer
  - Generator
  - Load, etc.
- Generally speaking, parameter identification depends heavily upon the quality of measurements (sensitivity analysis).
- PMU data are expected to be highly accurate and reliable, BUT this potential accuracy and reliability are not always achieved in actual field installation due to various causes.
- Problems in practice
  - 1) how credible are the results obtained from our algorithms?
  - 2) what can be done when we see significant discrepancy?

PMU Data Quality

- Measurement chain
  - Instrumentation channel (PT/CT, control cables, burdens, filters, A/D converter)
  - PMU (GPS synchronized)
- Ideally, PMU device is supposed to have time tagging accuracy better than 1 microsecond (0.02 degrees @ 60Hz), and magnitude accuracy better than 0.1%.
- In practice, the instrumentation channel can introduced errors that are of magnitude higher than the PMU device itself [2].
- Impacts of the measurement chain can be summarized as:
  - Random error (random in either direction)
  - Bias error (consistent in the same direction)

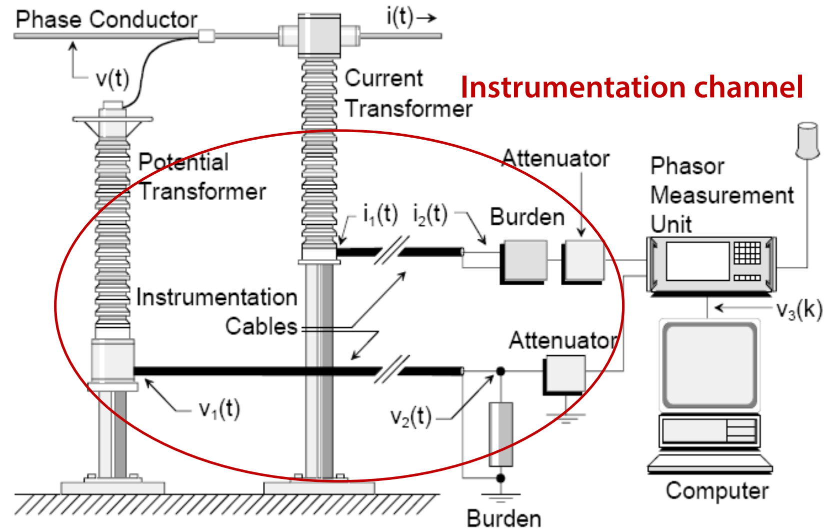


Fig 1. Typical PMU measurement chain[1]

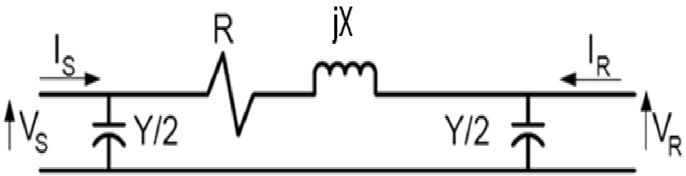
Table 1. Maximum Possible Error Introduced by the Instrumentation Channel in A Typical 230-kV System

Source of Error	Voltage Phasor				Current Phasor			
	Magnitude (%)		Phasor Angle (degree)		Magnitude (%)		Phasor Angle (degree)	
PT/CT	0.6		1.04		1.2		0.52	
Cabling	100 ft	400 ft	100 ft	400 ft	100 ft	400 ft	100 ft	400 ft
	0.009	0.009	0.115	0.411	0.066	0.066	0.03	0.09
PMU	0.1		0.02		0.1		0.02	
Total	0.709	0.709	1.175	1.471	1.366	1.366	0.57	0.63

[1]NASPI Performance & Standards Task Team, "Synchrophasor Measurement Accuracy Characterization," November 2007.
[2]D. Shi, D. Tylavsky, N. Logic, "An Adaptive Method for Detection and Correction of Errors in PMU Measurements," IEEE Trans. Smart Grid, 2012.

What has been achieved so far?

- Transmission line parameter identification (as an example)[1,2,3]
  - Line models: lumped vs. distributed
  - No. of measurements: single, two, multiple
  - Linear solution vs. nonlinear solutions
  - Direct vs. indirect approaches (two-port network)
  - Single-phase model vs. three-phase model
  - Positive-sequence only vs. three-sequence model
- Sensitivity analysis



Nodal analysis

$$I_S - V_S \cdot \frac{Y}{2} + I_R - V_R \cdot \frac{Y}{2} = 0$$

$$V_S - Z \cdot (I_S - V_S \cdot \frac{Y}{2}) - V_R = 0$$

$$Z = \frac{V_S^2 - V_R^2}{I_S \cdot V_R - I_R \cdot V_S} \qquad Y = 2 \cdot \frac{I_S + I_R}{V_S + V_R}$$

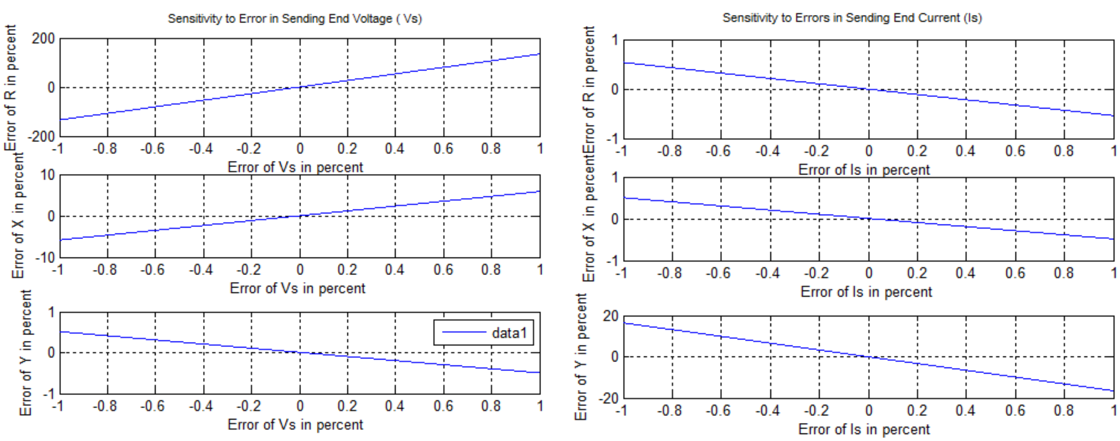


Fig. 1-2 Sensitivity analysis

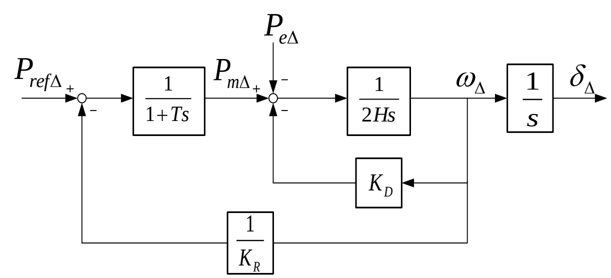
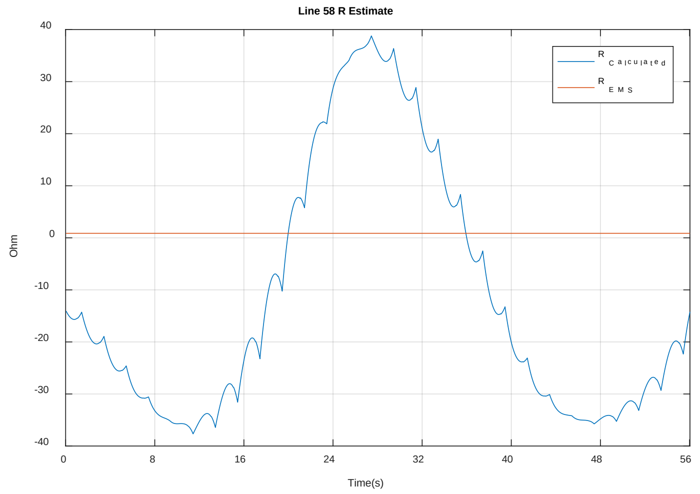
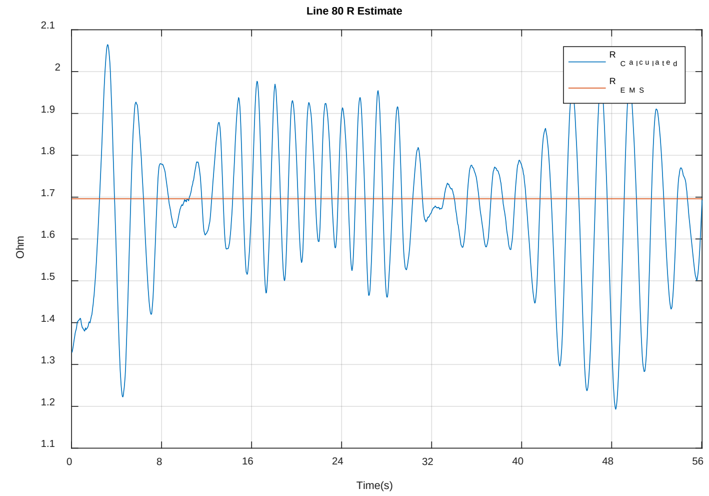


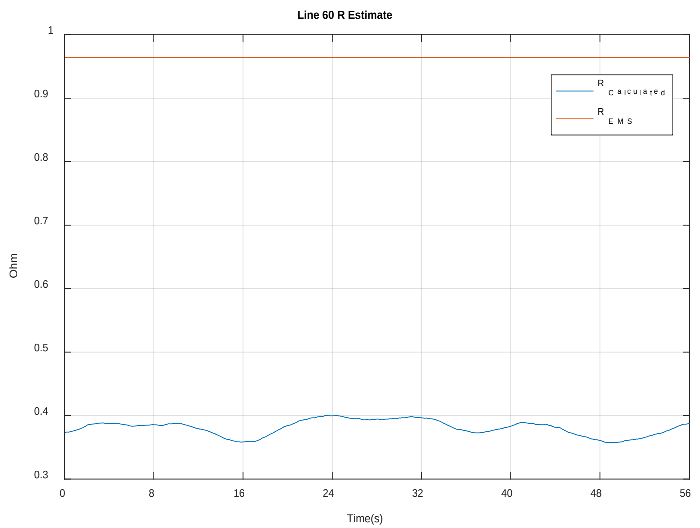
Fig. 3 Models & approaches

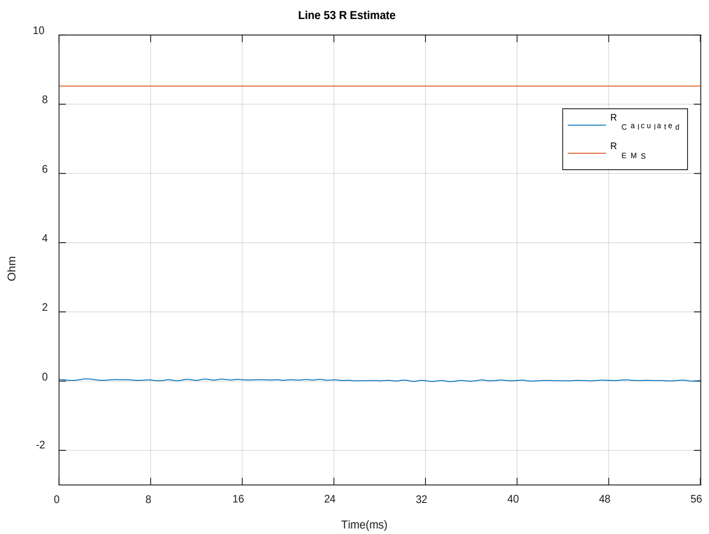
[1]D. Shi, D. Tylavsky, etc., "Identification of short-line parameters from synchrophasor measurements," NAPS, 2008.
[2]D. Shi, D. Tylavsky, etc., "Transmission line parameter identification using PMU measurements," Euro. Trans. Electrical Power, 2010.
[3]X. Zhao, H. Zhou, D. Shi, etc., "Online PMU-based transmission line parameter identification," CSEE Journal of Power and Energy Systems, 2015.

Results from Real Data (Line *R* Calculation)









Credibility Metric & PSPCS

- In general, it is very difficult to determine the credibility of the calculated parameters
  - true values are unknown
  - comparisons are difficult to make
- A credibility metric is of critical importance in practice for applications like such and so.
- A bootstrapping based technique is proposed.
  - random sampling with replacement
  - estimating properties of estimator
- Credibility metric: $\delta(x)/x_{ref} \leq \varepsilon$

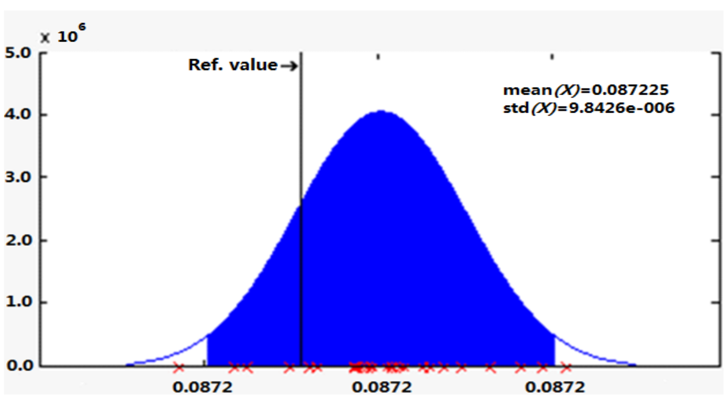


Fig. 2 Credibility metric

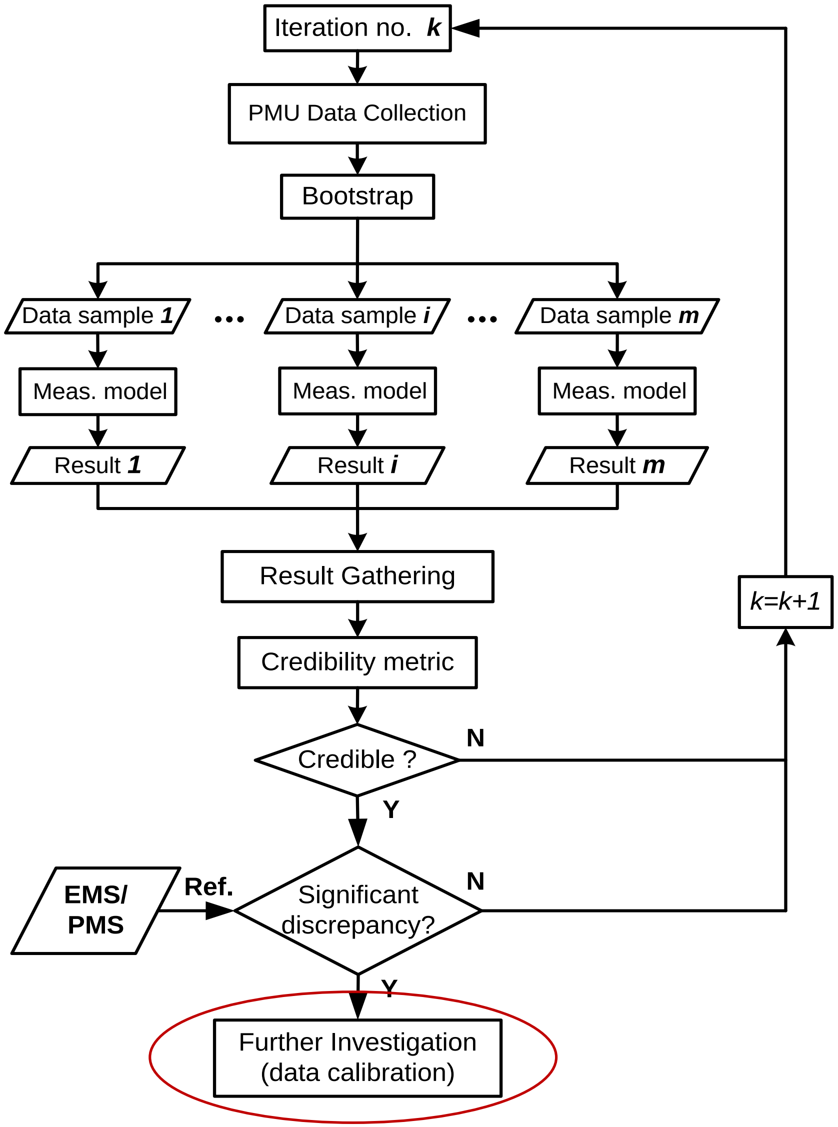


Fig.1 PSPCS Algorithm flowchart

PMU Data Calibration

- Parameter identification was developed as a database/data screening tool.
- Existing approaches for PMU data calibration
  - Offline testing/calibration
  - Model-based approaches
- Limitations of existing approaches
  - Offline: unable to compensate error from instrumentation channel
  - Model-based: parameters need to be known *a prior* (not practical)
- Our approach: online calibration of the overall bias error in PMU data without knowing the exact model

Fig. PMU calibration equip.[1]

$$Z = \frac{\overline{V}_s^{\,2} - \overline{V}_r^{\,2}}{\overline{I}_s \cdot \overline{V}_r - \overline{I}_r \cdot \overline{V}_s} \qquad Y = 2 \cdot \frac{\overline{I}_s + \overline{I}_r}{\overline{V}_s + \overline{V}_r}$$

derivatives

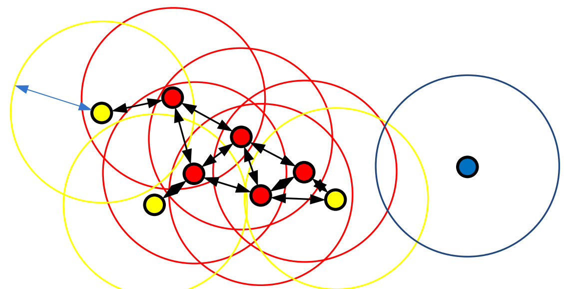
errors

$$\begin{aligned}
\partial R &= A_R \cdot \partial V_s + B_R \cdot \partial V_r + C_R \cdot \partial I_s + D_R \cdot \partial I_r + E_R \cdot \partial \theta'_{V_s} + F_R \cdot \partial \theta'_{V_r} + G_R \cdot \partial \theta'_{I_s} \\
\partial X &= A_X \cdot \partial V_s + B_X \cdot \partial V_r + C_X \cdot \partial I_s + D_X \cdot \partial I_r + E_X \cdot \partial \theta'_{V_s} + F_X \cdot \partial \theta'_{V_r} + G_X \cdot \partial \theta'_{I_s} \\
\partial B_c &= A_B \cdot \partial V_s + B_B \cdot \partial V_r + C_B \cdot \partial I_s + D_B \cdot \partial I_r + E_B \cdot \partial \theta'_{V_s} + F_X \cdot \partial \theta'_{V_r} + G_X \cdot \partial \theta'_{I_s}
\end{aligned}$$

[1] 6135A/PMUCAL Phasor Measurement Unit Calibration System, Fluke Calibration.

A Data Mining Approach[1,2]

- Density-based spatial clustering of applications with noise (DBSCAN) is an unsupervised data mining technique, which is able to classify data points of any dimension into *core points*, *reachable points* and *outliers*.



red: core points
yellow: reachable points
blue: outlier

Fig. 1 Schematic diagram of DBSCAN with *minPts*=4

- Constraints: error bands for EMS references

$$\begin{cases}(1-\alpha)R_{EMS} \le R \le (1+\alpha)R_{EMS}\\(1-\alpha)X_{EMS} \le X \le (1+\alpha)X_{EMS}\\(1-\alpha)B_{EMS} \le B_c \le (1+\alpha)B_{EMS}\end{cases}$$

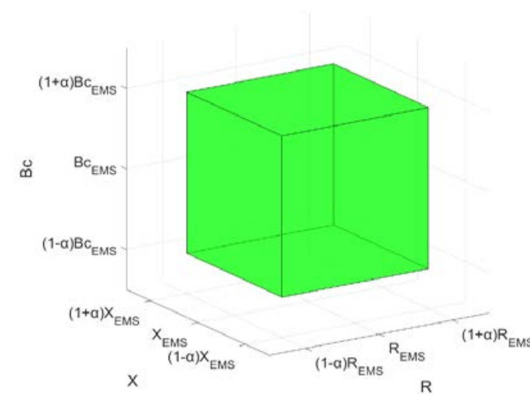


Fig. 2 Feasible region for transmission line impedances

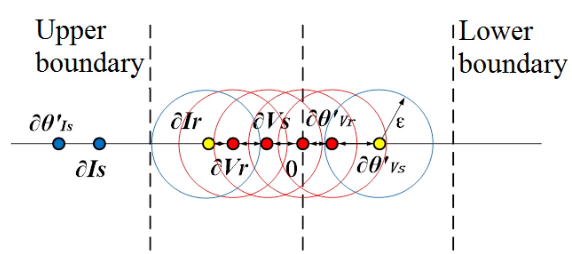


Fig. 3 An example

[1] X. Wang, D. Shi, Z. Wang, etc., "Online calibration of Phasor Measurement Unit using density-based spatial clustering," IEEE Trans. Power Delivery, 2nd round review.
[2] X. Lu, D. Shi, B. Zhu, etc., "PMU assisted power system parameter calibration at Jiangsu Electric Power Company," IEEE PES General Meeting, 2017.

Algorithm Flowchart

- Form the H matrix
- Conduct LSE iteratively with the points selected inside the feasible region
- DBSCAN clustering
- Compare the clusters and find out the biggest cluster with minimum searching distance
- Decode the cluster information into PMU data bias error information
- Calibrate PMU data according to the clustering result

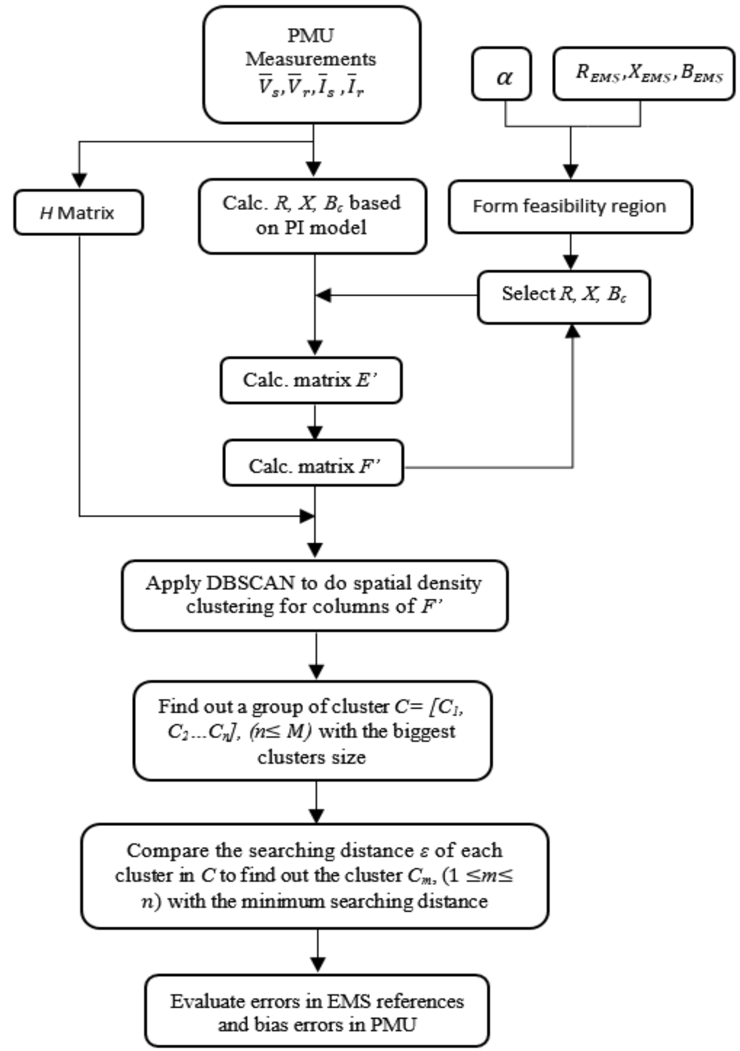


Fig. Algorithm flowchart[1]

[1] X. Wang, D. Shi, Z. Wang, etc., "Online calibration of Phasor Measurement Unit using density-based spatial clustering," IEEE Trans. Power Delivery, 2nd round review.

Numerical Results (Simulated Data I)

- Case I: One referenced impedance has error (-2% in R in EMS database; 0.01pu error in magnitude is added to sending-end current phasor)

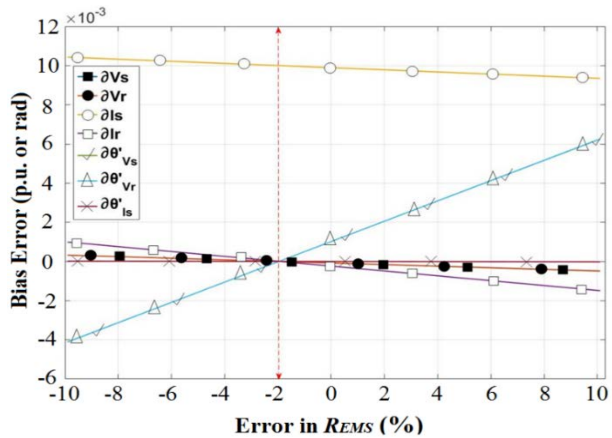


Fig. 1 Relationships between identified bias errors and error in R_{EMS}

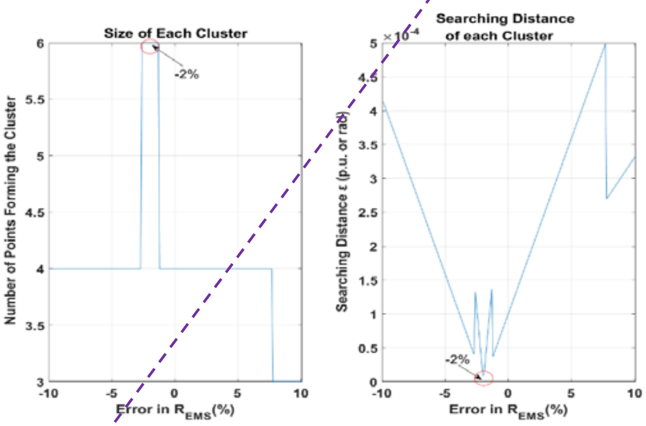


Fig. 2 Results of DBSCAN

Table I Result Summary

	True	Calculated	Calculated Error in		
	p.u. or rad (×10^{-3})		R (%)	X (%)	B_C (%)
∂V_s	0	0.0230	-2.02	0.01	-0.01
∂V_r	0	0.0345			
∂I_s	10	10.0328			
∂I_r	0	-0.0175			
$\partial \theta'_{Vs}$	0	0.0224			
$\partial \theta'_{Vr}$	0	0.0130			
$\partial \theta'_{Is}$	0	-0.0149			

NASPI North American SynchroPhasor Initiative

Numerical Results (Simulated Data II)

- Case II: -4% error and -6% error are considered for R_{EMS} and X_{EMS}, respectively; bias errors of 0.01 p.u. and 0.00175 rad are added to V_s and θ_{Vr}, respectively.

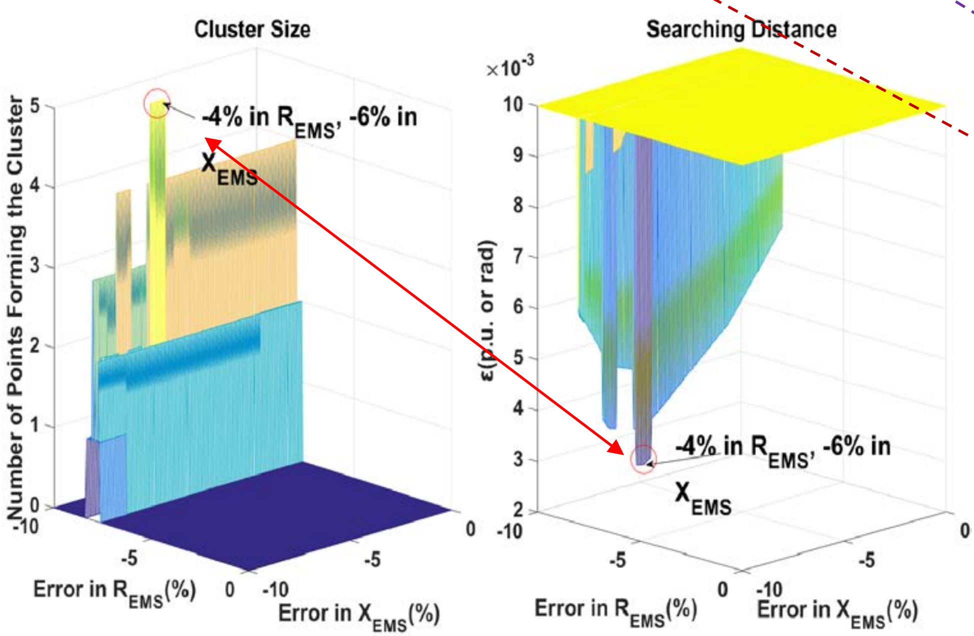


Fig. DBSCAN clustering results

Table Result Summary

	True	Calculated	Calculated Error in		
	p.u. or rad ($\times 10^{-3}$)		R (%)	X (%)	B_C (%)
∂V_s	10	10.0612			
∂V_r	0	0.0334			
∂I_s	0	0.0316			
∂I_r	0	0.1591	−4.2	−5.8	0.02
$\partial \theta'_{Vs}$	0	0.0036			
$\partial \theta'_{Vr}$	1.75	1.7617			
$\partial \theta'_{Is}$	0	0.0047			

Results with Real Data

- Cluster result is plotted in 3-D. X, Y, Z axis's correspond to errors in R_{EMS}, X_{EMS} and B_{EMS}.
- Colors of points represent the cluster size. As color become warmer, cluster size increases.

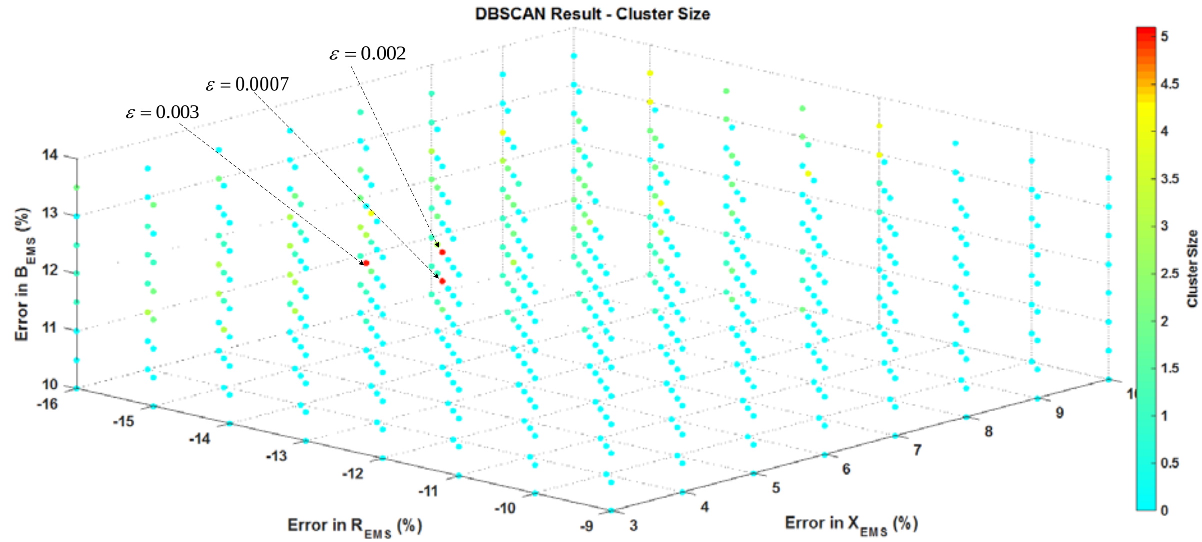


Fig. Results for *“Huadong-Tianhui Line #5621”*

Table Result Summary

	Calculated	Calculated Error in		
	p.u. or rad ($\times 10^{-3}$)	R (%)	X (%)	B_C (%)
∂V_s	-0.0032			
∂V_r	-0.0033			
∂I_s	0.0171			
∂I_r	0.0164	-14.0	6.4	12.6
$\partial \theta'_{Vs}$	0.0003			
$\partial \theta'_{Vr}$	0.0027			
$\partial \theta'_{Is}$	-5.6238e-5			

- PMU data collected from *“Huadong-Tianhui Line #5621”* in Jiangsu Electricity Power Grid has been used.
- Test result shows a -14% error in R_{EMS}, 6.4% error in X_{EMS}, 12.60% error in B_{EMS}.

Outline

- Power System Parameter Calibration System (PSPCS) framework

- **System Implementation**

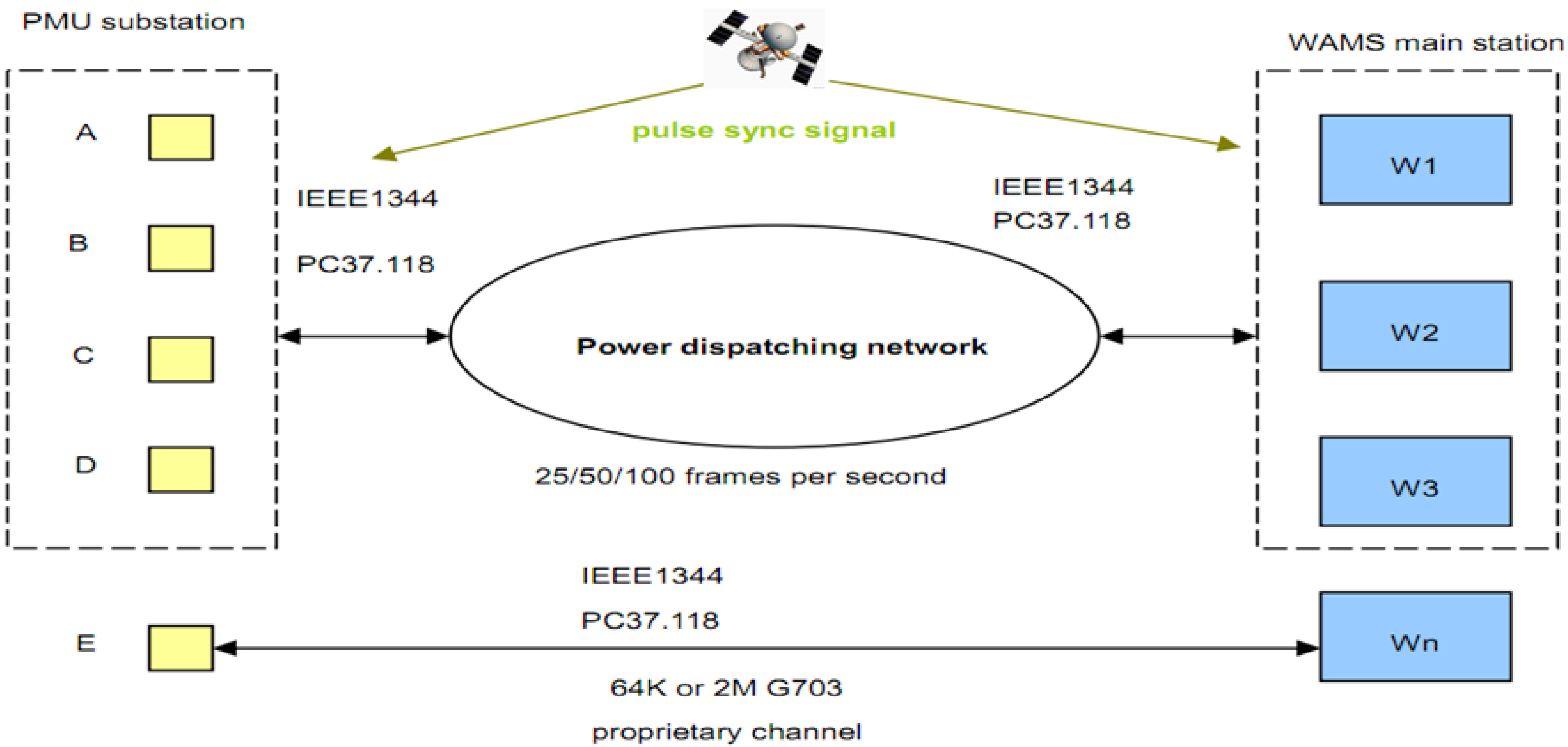
PSPCS Implementation

- GEIRI North America partnered with NARI group to implement PSPCS at the grid dispatch center of Jiangsu Electric Power Company.
- NARI is a key manufacture subsidiary of State Grid Corporation of China.
  - largest whole set supplier of electric power equipment
  - provide technologies, products, services and total solutions for utilities, railway transportation, industrial control

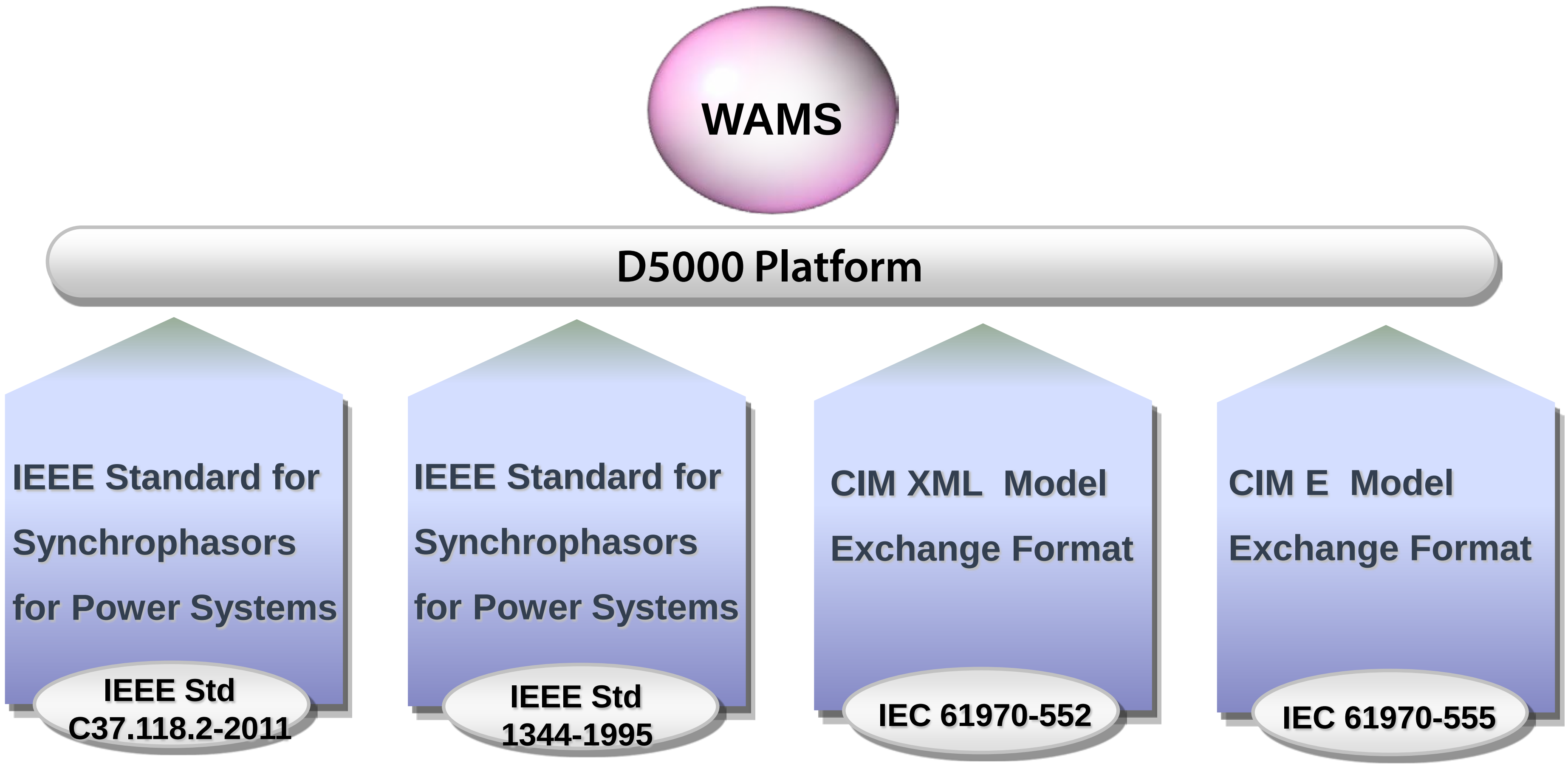
Table Features of NARI WAMS master station

NARI WAMS master station	
Connected PMU stations (If measurements number of each station <100)	>800
Data frame	25~120/s
Measured point scale	>100k
Performance of database	3M events/s
Compression of His data	lossless / loss
Time for query 1hr his data of 1 point	<1s

NARI WAMS Architecture

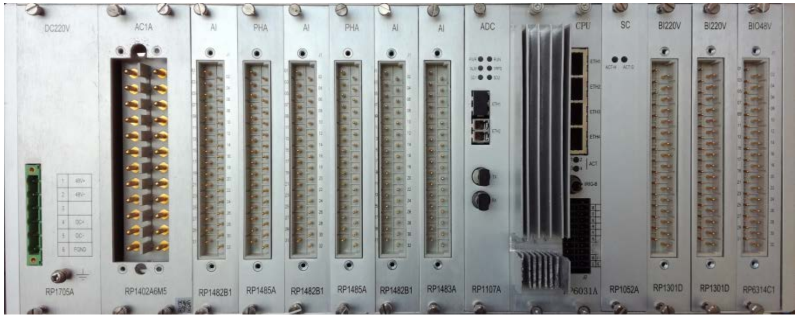


NARI WAMS

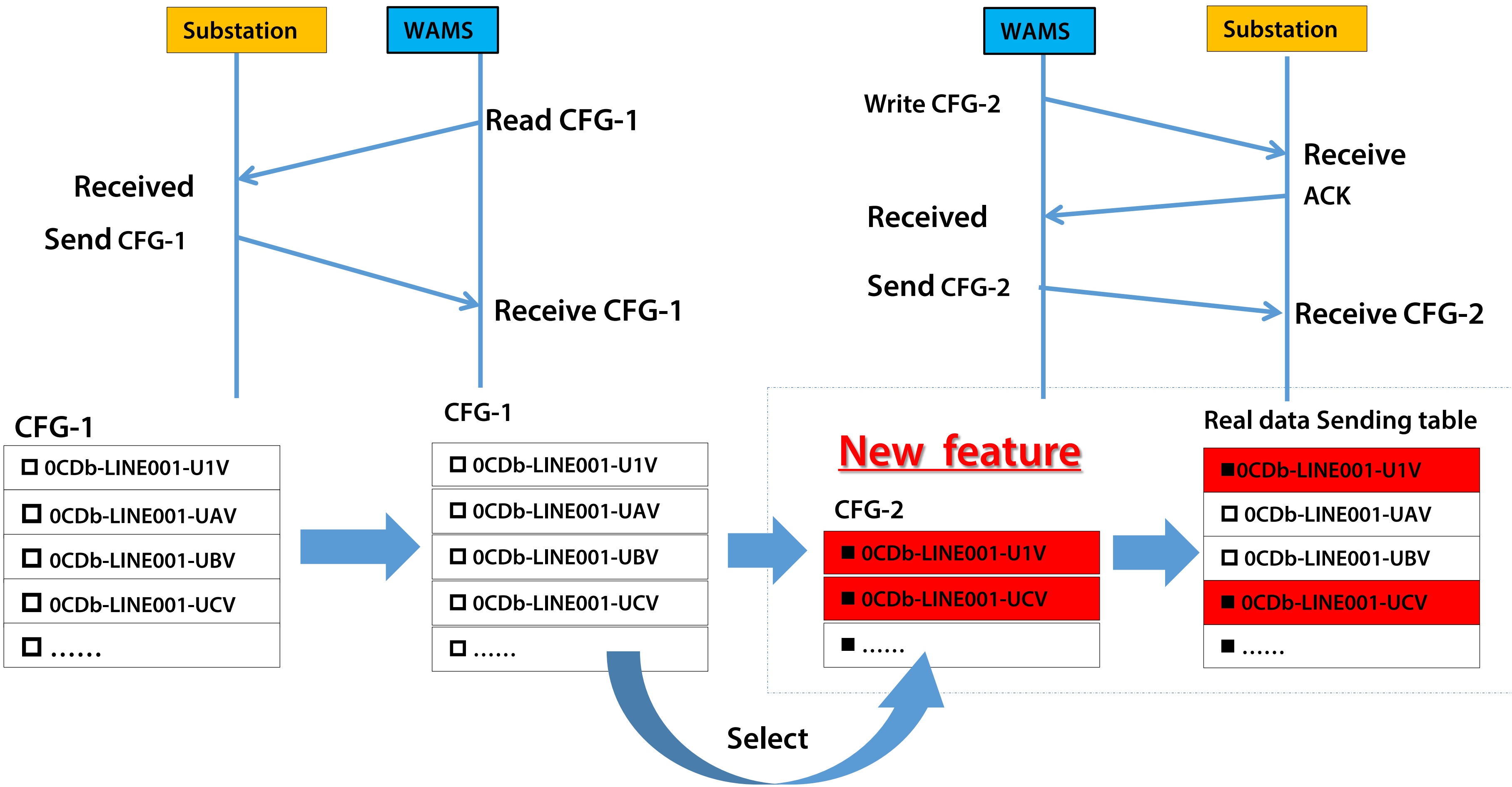

WAMS
D5000 Platform
IEEE Standard for Synchrophasors for Power Systems
IEEE Std C37.118.2-2011
IEEE Standard for Synchrophasors for Power Systems
IEEE Std 1344-1995
CIM XML Model Exchange Format
IEC 61970-552
CIM E Model Exchange Format
IEC 61970-555

NARI PMU Performance

NARI PMU Substation	
AD Sample Or IEC61850-9-2 SV	48
Binary Input Or GOOSE	46
DC Output(4-20mA)	2
Storage	256GB
Time Synchronization Accuracy	<1μs
Time Keeping Accuracy	<10μs/h



Real-time Data Service



History Data Service

Data Type	Format	Feature
Fault Record	*.cfg *.dat	Fs = 4000Hz; Sample Values; Each record for 15 seconds；
Continuo-us Record	*.cfg *.dat	Fs = 1000Hz; Sample Values; Each record for 60 seconds;
Dynamic Record	*.dyn	Fs = 100Hz; Each record for 60 seconds;

Substation Data Storage

Level 1

PMU

Type	Capacity
Fault Record	1000 items
Continuous Record	72 hours
Dynamic Record	21 days

Level 2

PDC

Type	Capacity
Fault Record	1000 items per PMU
Continuous Record	72 hours per PMU
Dynamic Record	21 days

Dispatch Center Data Storage

Level 3

WAMS

Type	Capacity
Dynamic Record	>1 months per PDC

PMU Coverage at Jiangsu

- Jiangsu Electric Power Company, the biggest provincial utility in China, owned by State Grid Corporation of China.
- Peak load reached 92GW in 2016, installed generation capacity 100GW, power imported from west and northwest China 15GW.
- 100% PMU coverage at 500kV and above substations.
- Majority of 220 kV substations.
- Major power plants.
- A total of ~160 PMUs (still increasing).
- All renewable power plants.
- Thousands of data channels.

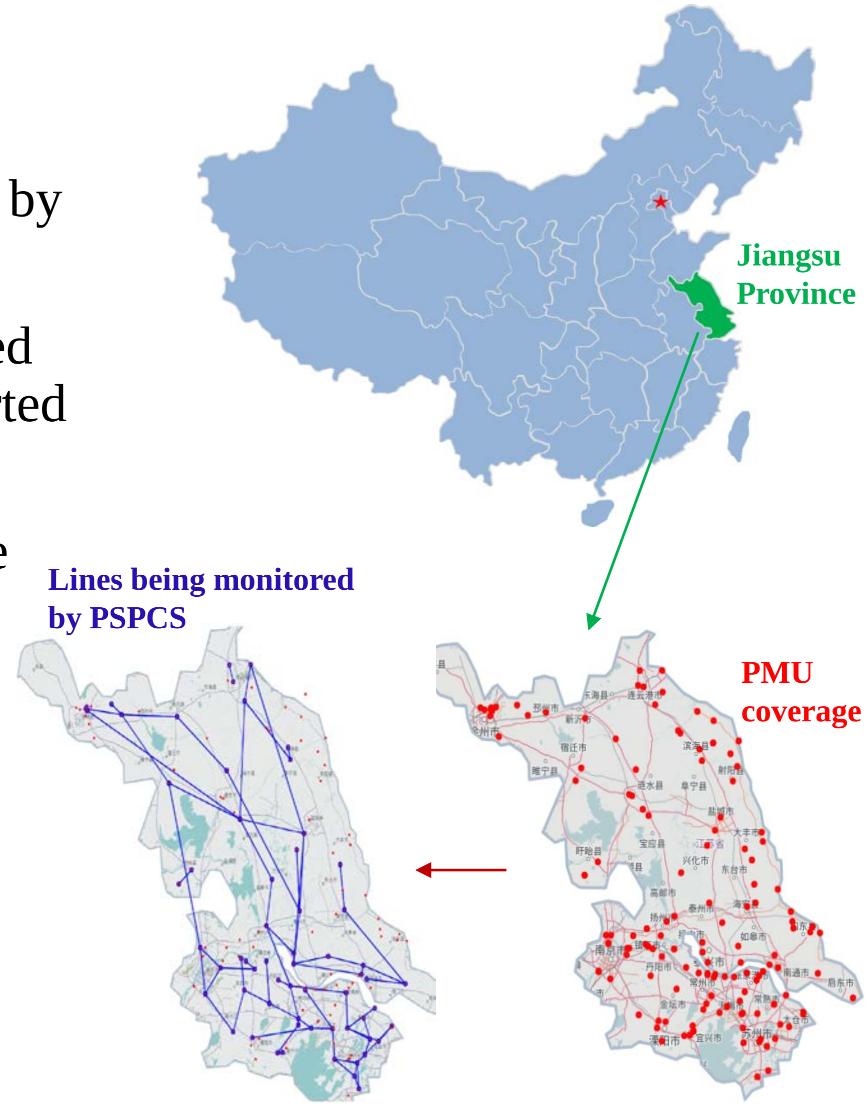
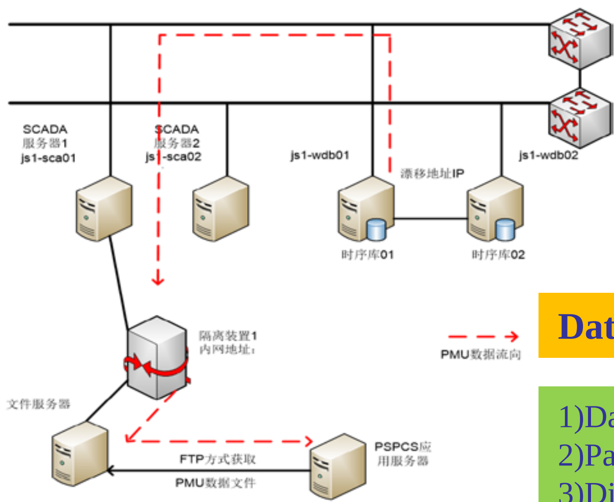


Fig. PMU coverage in Jiangsu

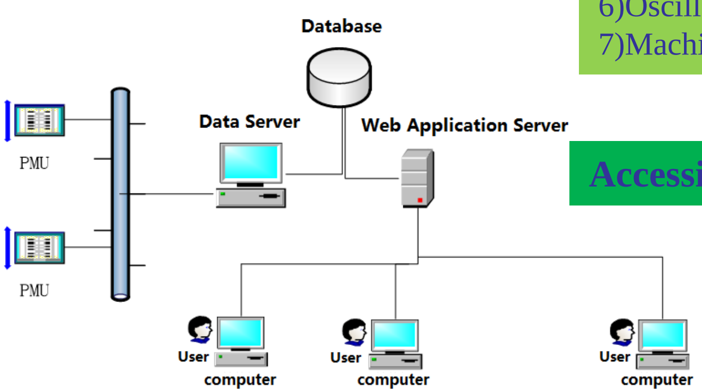
System Implementation at Jiangsu Electric Power Company



Data flow

Interface

1)Data Quality Improvement
2)Parameter Calibration
3)Distributed data storage & processing
4)Online stability assessment
5)Voltage instability
6)Oscillation detection (distributed)
7)Machine learning & big data analytics



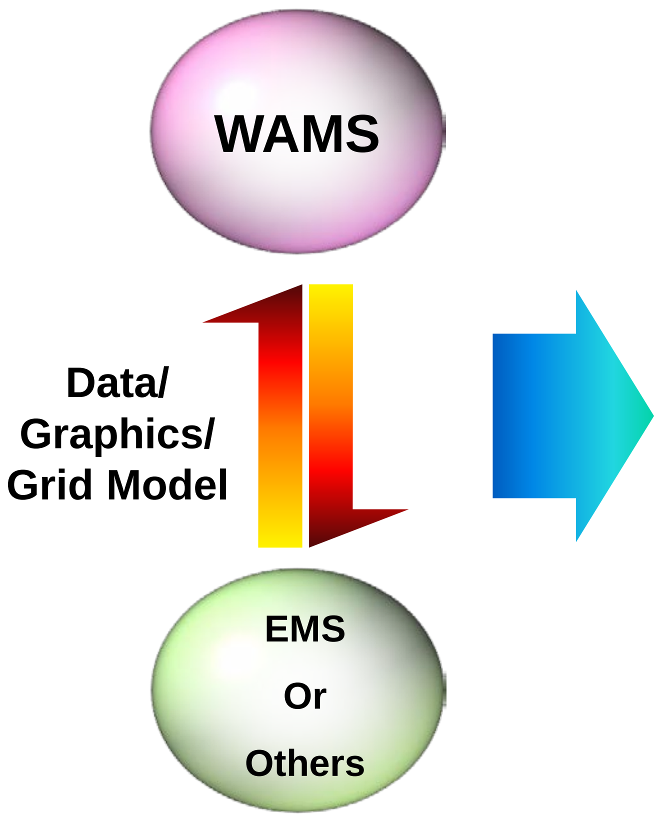
Accessibility

Onsite deployment

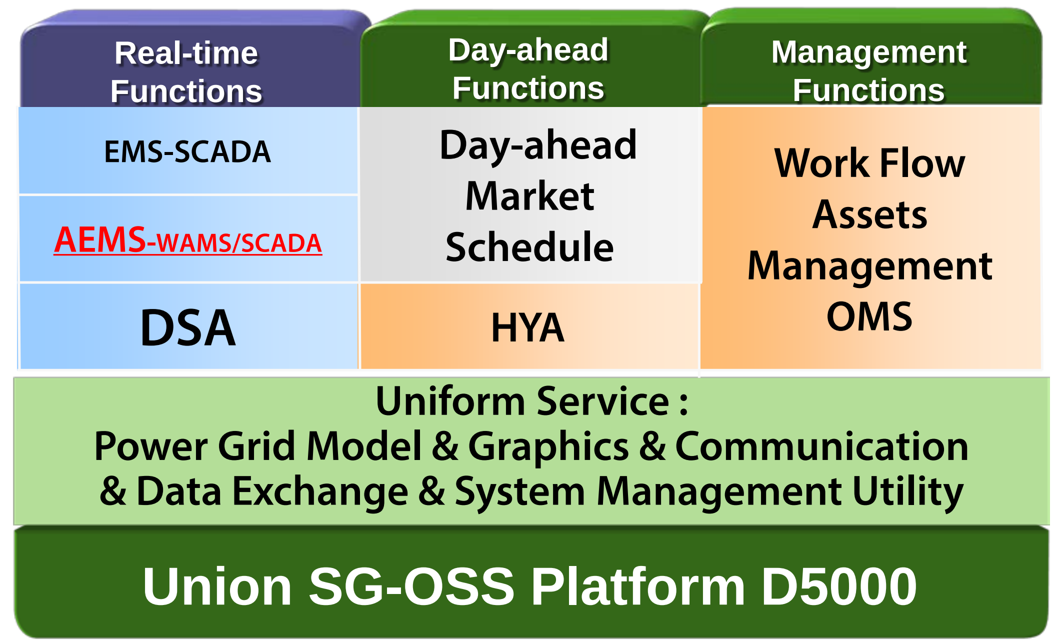
WAMS Application Platform

An Advanced EMS is being framed and developed with more sophisticated data, SCADA + WAMS

Before



Now & Future



Openness, Standardization, Visualization, Service Oriented, Reliability, Security.

Summary

- An online power system parameter screening tool has been developed and implemented.
- A novel PMU data calibration approach & system has been developed and implemented.
- Significance of contribution: online PMU data calibration without knowing accurate system model (by-product: more accurate system models & parameters).
- Future work includes:
  - Extending the work to simultaneous calibration of multiple PMUs
  - Parallelizing the algorithm to improve computational efficiency

Thank you!