Data Driven Power System Modeling and Analysis based on PMU/WAMS

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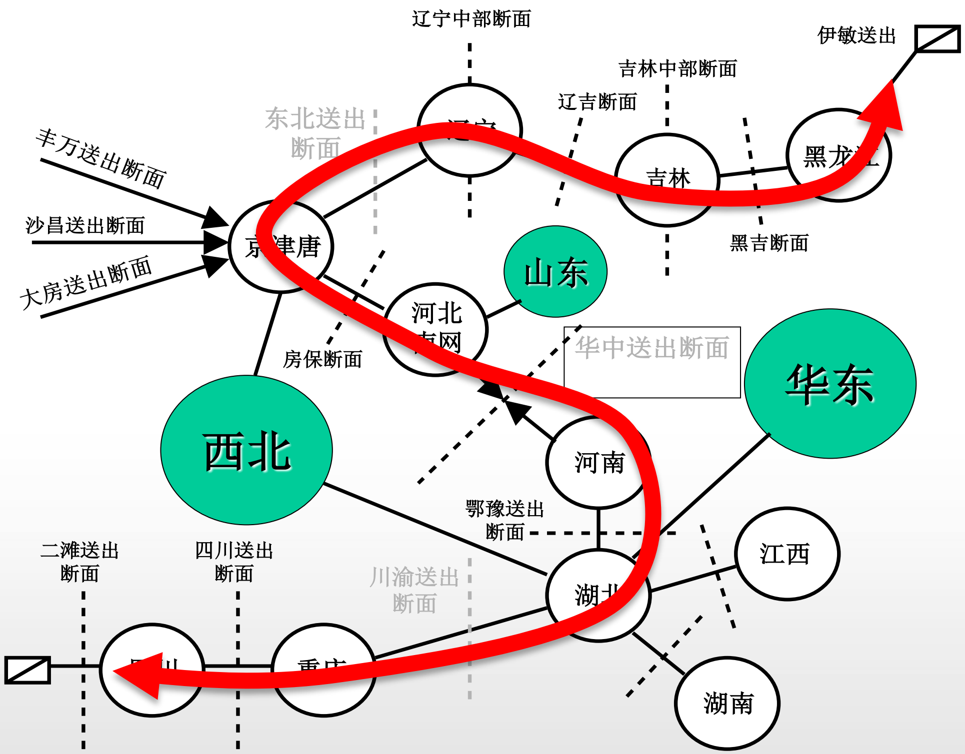
Outlines

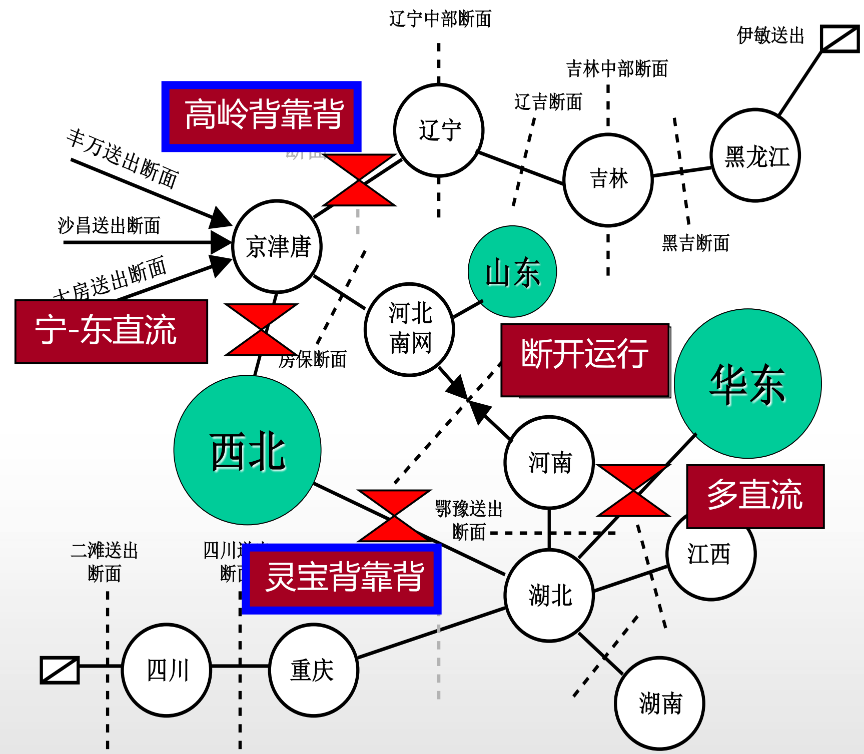
1. Backgrounds
   - Power system oscillation analysis and control
2. Dynamic load parameter identification
3. Online linear state estimation
4. Further Work

1.1 Introduction: low frequency oscillation

- **State Grid, before 2010: difficult to operate a chained AC grid with transmission distance >3000km, because of the low frequency oscillation (0.25~0.3Hz)**



2000~2010, AC grid

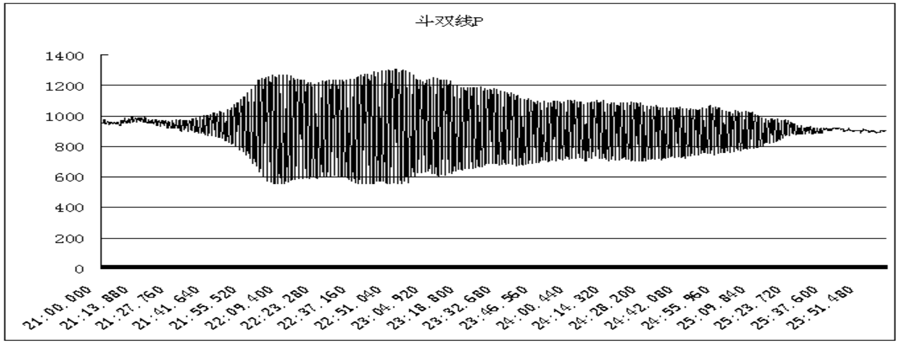


Now, AC/DC system

1.1 Introduction: low frequency oscillation

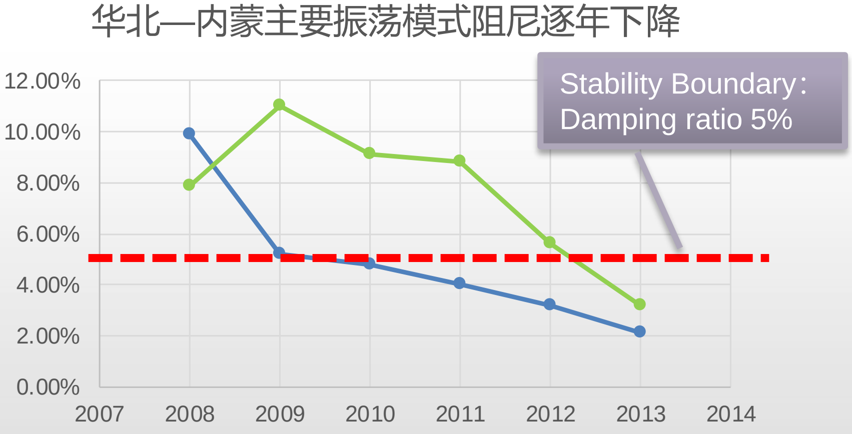
◻ Inter-area low frequency oscillations in State Grid:

Low frequency oscillation events: 2005.10.29, 2006.7.1, 2007.1.29 …



2005.10.29, tie-line power oscillation lasting for 5 minutes

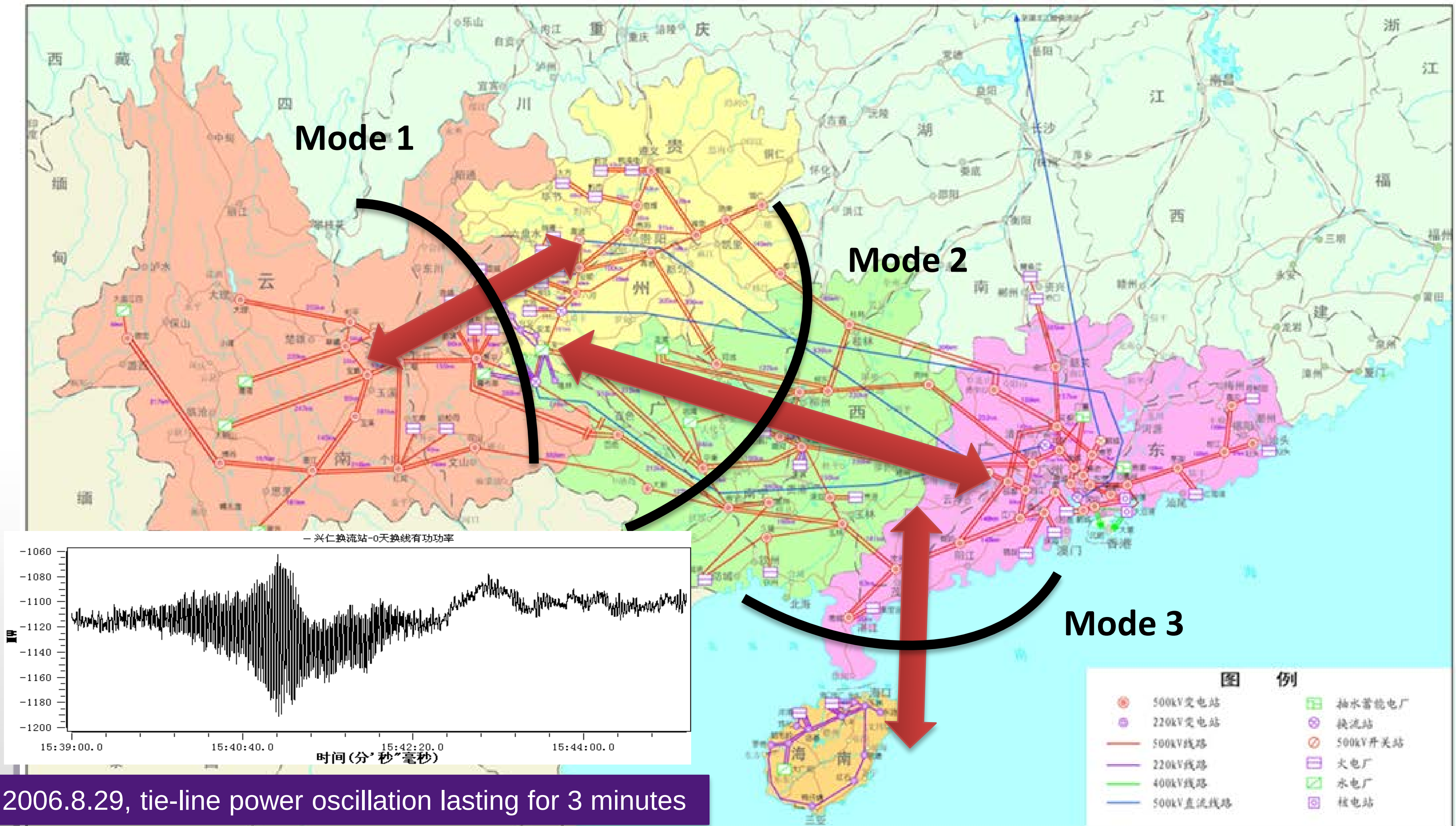
Because huge capacities of wind and thermal power plants are connected through long distance transmission lines, the damping ratio of dominant oscillations keeps declining in the recent years.



The damping ratio keeps declining from 2008 to 2013

1.1 Introduction: low frequency oscillation

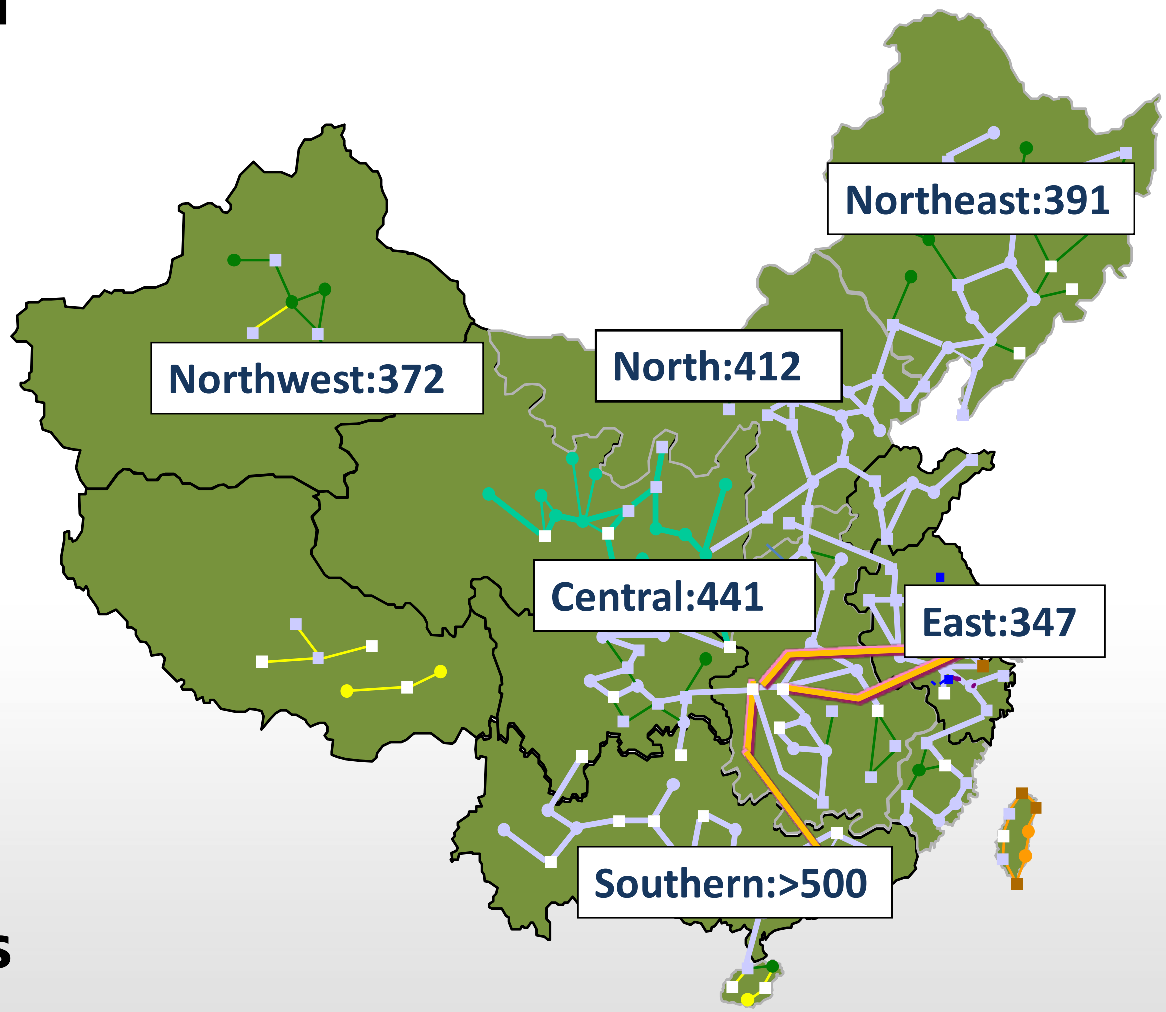
□ China Southern Power Grid, before 2017:



2006.8.29, tie-line power oscillation lasting for 3 minutes

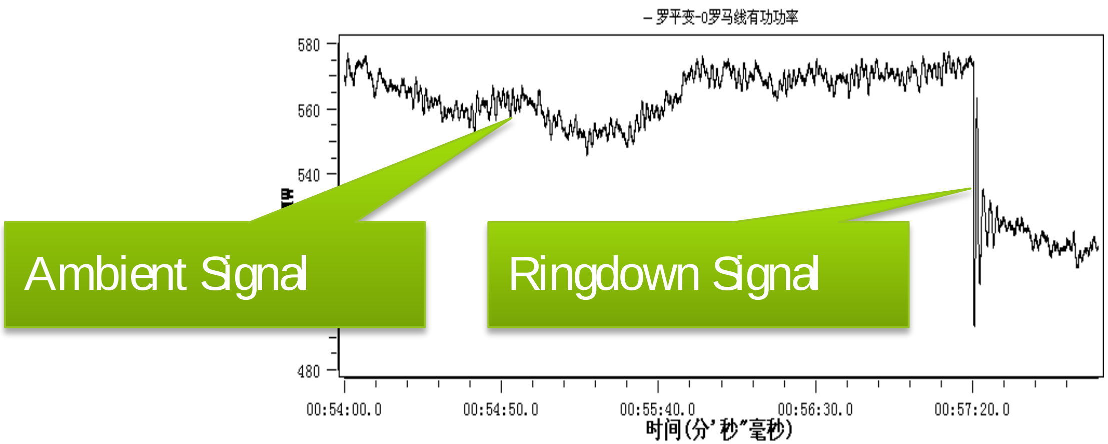
1.1 Introduction: low frequency oscillation

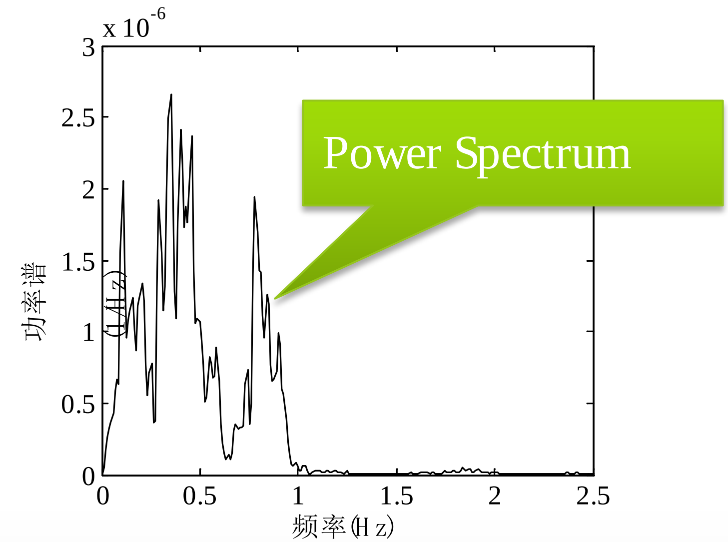
- PMUs were installed in more than 4000 substations and power plans. (2018.12)
- WAMS master stations are deployed in all provincial dispatch centers (>40).
- For damping oscillations, it is efficient to suppress the inter-area modes using PMU/WAMS.



1.2 Introduction：a successful case

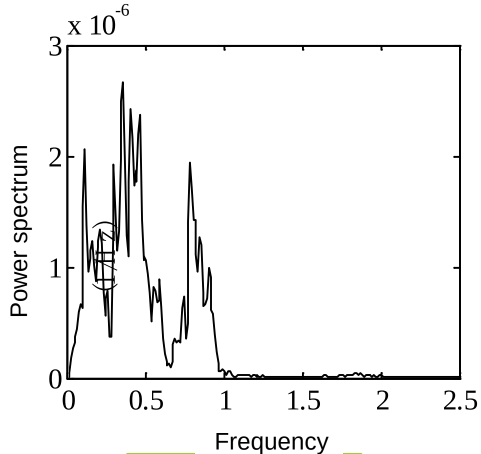
Power system oscillation dynamic ID and control based on PMU/WAMS



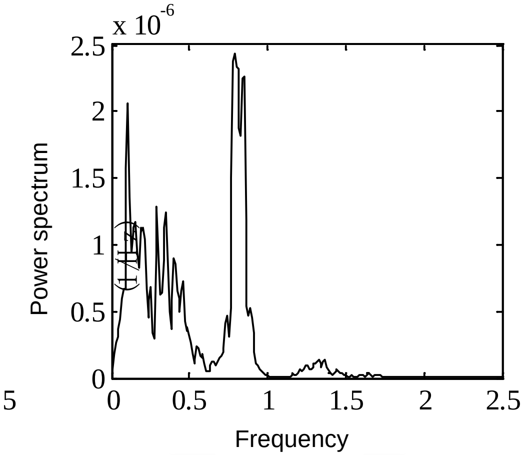


- ID of power system oscillation modes and mode shapes
- ID of oscillation pathway and source
- Optimal power flow improving damping based on sensitivity ID
- Wide-area damping adaptive controller design based on ambient signal ID
- Analysis of the random communication time delays on wide-area control
- Implementation and commission of wide-area control system in real system

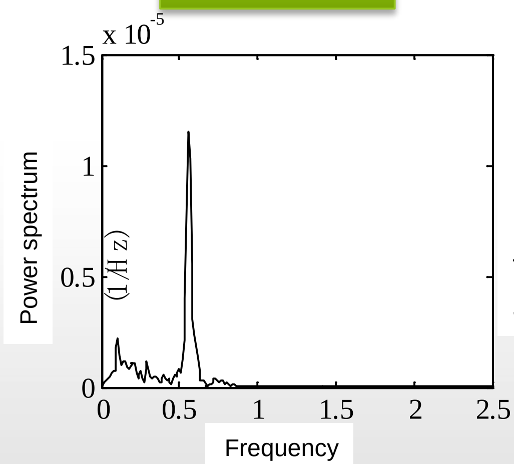
1.2 Oscillation ID based on Ambient Signals



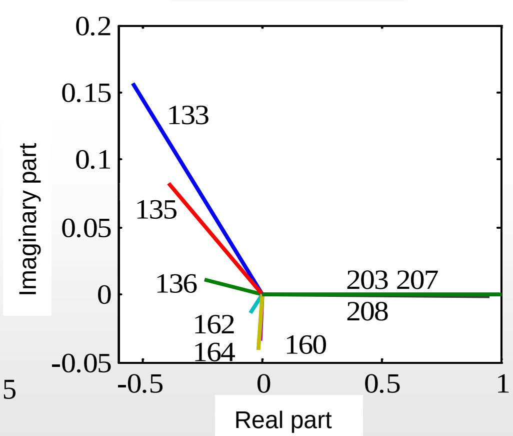
Mode 1



Mode 3



Mode 2

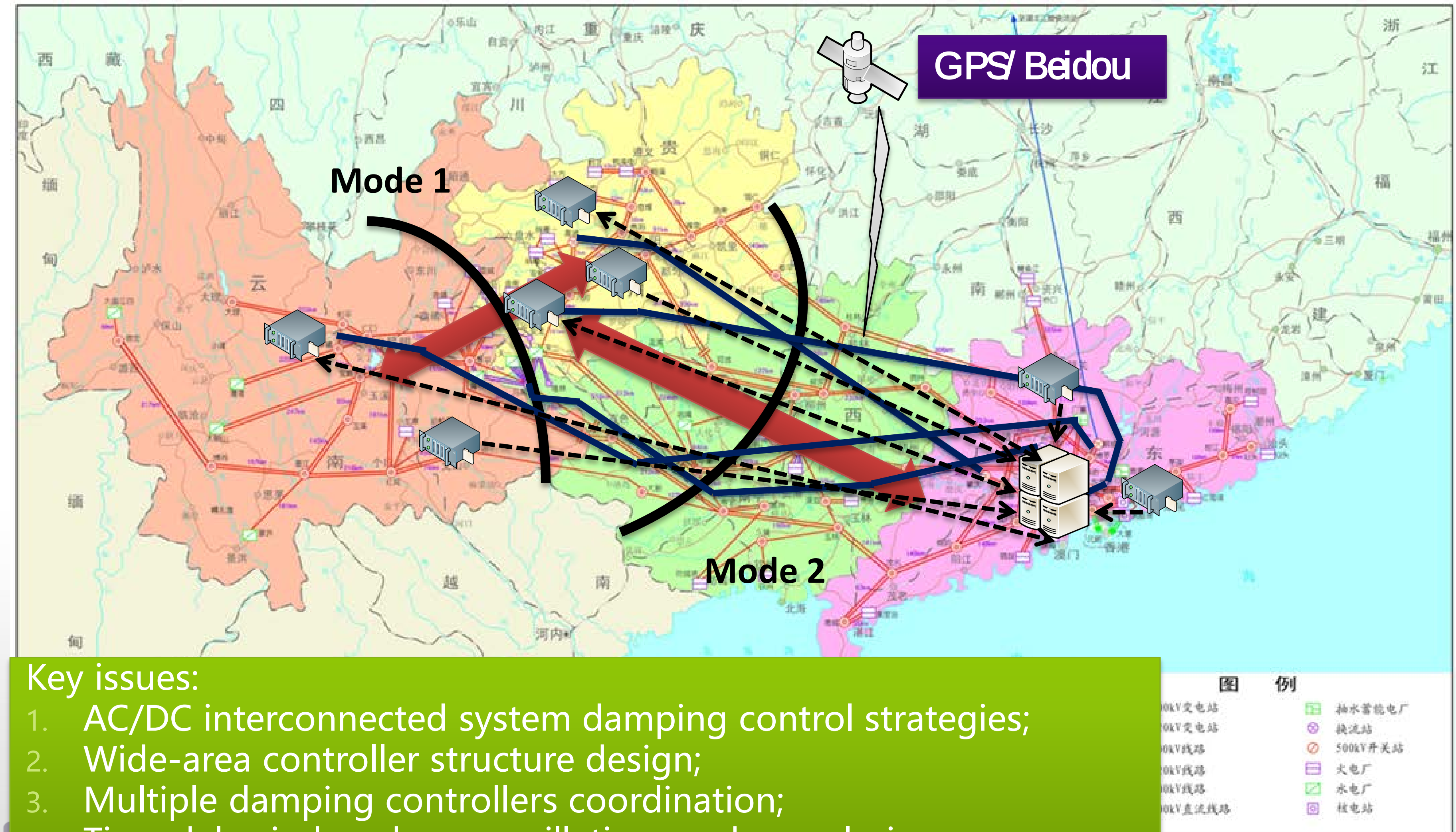


Mode shape 3

Modes	Freq/Hz	DR/%
1 YN/GZ vs. GD	0.402	21.7734
2 YN vs. GZ	0.5616	3.797
3 HN vs. Main Grid	0.8142	3.3102

7*24 monitoring and pre-warning of weakly damped oscillation modes can be realized, not just oscillation detection after it happened.

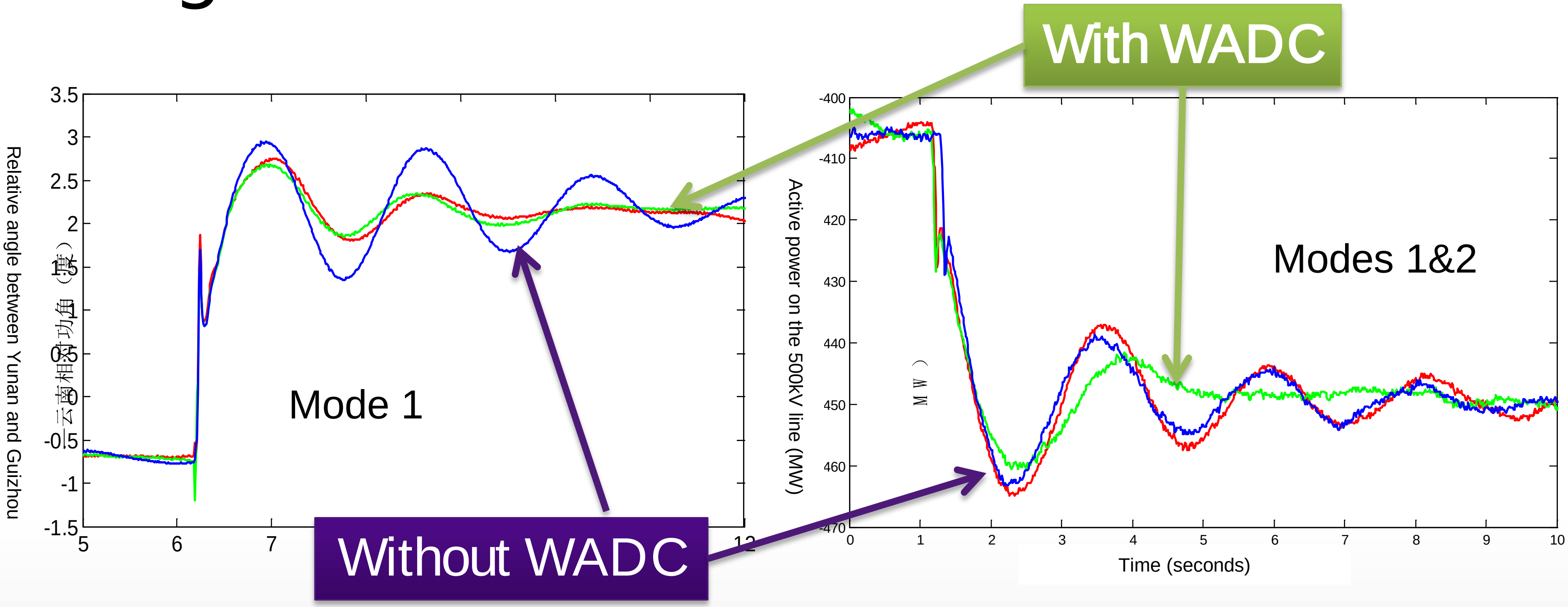
1.3 Wide-area HVDC damping control in CSG



Key issues:

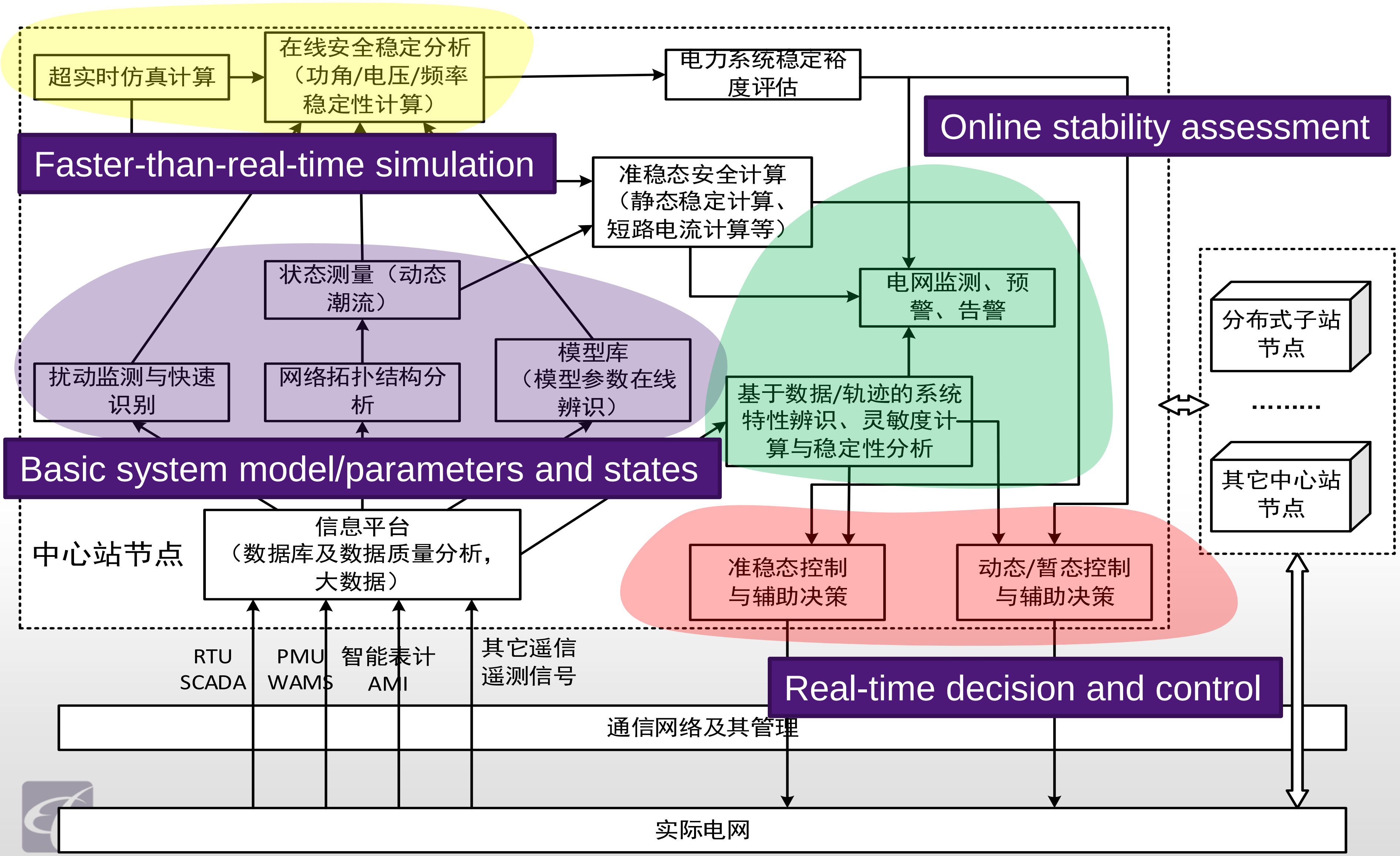
1. AC/DC interconnected system damping control strategies;
2. Wide-area controller structure design;
3. Multiple damping controllers coordination;
4. Time delay induced new oscillation modes analysis;
5. Wide-area random time delay adaptive compensation.

Large Disturbances Field Tests Results



- Multiple disturbances in different conditions:
  - HVDC monopole blocks (700MW)
  - 500kV key inter-area tie-line tripping.

1.4 Proposed Framework



Outlines

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4. Further Work

2.1 Background

The great influence of load model on power system stability

- **Different sets of induction motor parameters**

Type of motors	R_s/pu	X_s/pu	X_m/pu	R_s/pu	X_s	s_0	A	C
Type I motor	0	0.295	3.5	0.02	0.12	2	0.0116	0.15
Type II motor	0	0.120	3.5	0.02	0.12	2	0.0116	0.15
Type III motor	0	0.180	3.5	0.02	0.12	2	0.0116	0.15

- **Composite Load Model**

The composite load model (CLM) is proposed by China Electric Power Research Institute that can fit four large disturbance experiments in Northeast China Power Grid

- **The stability limit of Liaoning-Jinli section (adopting different load models)**

Type of load model	Section stability limit	Limit change (percentage)
50% Type I motor+50% Constant Z	840	Standard
50% Type II motor+50% Constant Z	1510	80
50% Type III motor+50% Constant Z	1390	65
40% Constant Z +60% Constant P	1520	80
30% Constant Z +30% Constant I + 40% Constant P	1540	80
Composite Load Model (CLM)	1470	75

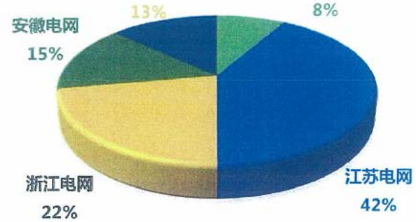
- ✓ The stability limits adopting different load models vary widely.
- ✓ Accurate load modeling is of vital importance for power system stability analysis.

2.1 Background

□ The States of load parameter in Chinese Power Grid

- **CSG load model for simulations :50% Impedance+50% Induction Motor**
- **SG’ s concerns:**

地区	数量
上海	113座
江苏	559座
浙江	302座
安徽	196座
福建	173座



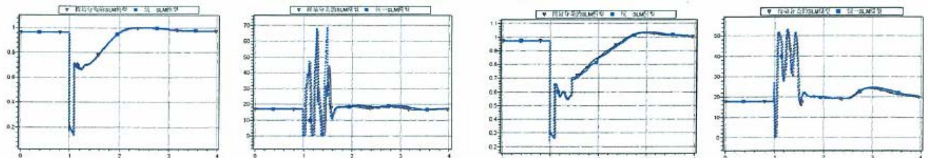
根据对华东5省市1343座220kV负荷站点负荷的普查结果，华东电网工业负荷占比最高，**达到62%**，其次是商业负荷占19%，居民负荷占15%，农业负荷占2%

统一动态模型的参数

Rs	Xs	Xm	Rr	Xr	A	B	Tj	马达比例（%）
0.0331	0.1095	2.9648	0.0192	0.11	0.85	0	2.0372	58%

ZP%	ZQ%	IP%	IQ%	PP%	PQ%	R*	X*
53	53	34	34	13	13	0.004	0.06

统一动态和按站分类动态模型仿真结果比较，基本一致



A 苏州换流站电压　B 锦苏逆变站熄弧角　A 亭卫站母线电压　B 复奉逆变站熄弧角

车坊-木渎三永N-2故障　南桥-亭卫单相开关拒动故障

□ **但是，华东电网“大直流弱受端”的稳定特性，特别是苏州电网等对负荷模型敏感的地区，要求更为精确的负荷模型，能够反映各计算节点不同季节、时段负荷特性和负荷量的变化**

因此，当前的手工建模方法，无法满足华东电网稳定计算需求，迫切需要通过自动化的手段，实现在线负荷建模，及时跟踪负荷特性变化，提高负荷建模工作的时效性。

- More accurate load model is demanded to reflect the changes of loads and the characteristics at different buses, in different seasons & periods of time.
- There is a pressing need to accomplish online load modeling by methods of automation to track the change of load characteristics in time.

Acknowledgement: Eastern China Power Grid

2.1 Background

Research and Progresses of WECC

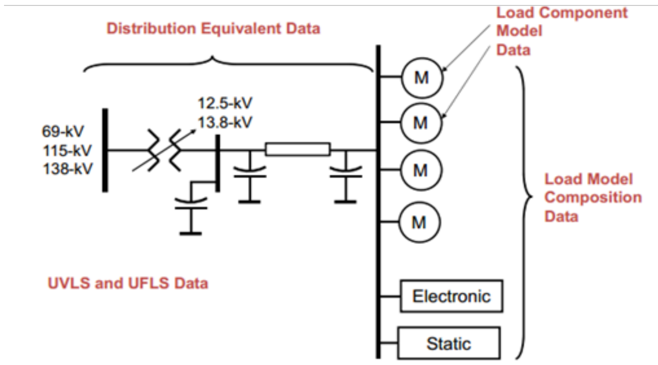


Figure 4-1: composite load model data requirements

A) Distribution Equivalent Data

The approach of constructing the distribution equivalent was developed by **Pacific Gas and Electric (PG&E).**

The distribution equivalent is calculated to meet **the feeder design and performance characteristics**, including: feeder voltage drop, RX ratio, end-use utilization voltage range, distribution losses, and shunt compensation split between the substation and the feeder end.

B) Load Model Fractions / Load Model Composition

WECC LMTF used several sources (several reports) for load composition analysis to develop a simplified version of the load composition model, called **"light" version**.

- ✓ 5 typical days
- ✓ 12 climate zones
- ✓ 4 types of feeder

-Typical summer day
- Hot summer day
- Cool summer day
- Typical shoulder (spring/fall) day
- Typical winter day

ID	Climate Zone	Representative City
NWC	Northwest Coast	Seattle, Vancouver BC
NWV	Northwest Valley	Portland OR
NWI	Northwest Inland	Boise, Tri-Cities, Spokane
RMN	Rocky Mountain North	Calgary, Montana, Wyoming
NCC	Northern California Coast	Bay Area
NCV	Northern California Valley	Sacramento, Fresno
NCI	Northern California Inland	
SCC	Southern California Coast	LA, San Diego
SCV	Southern California Valley	LA, San Diego
SCI	Southern California Inland	LA, San Diego
DSW	Desert Southwest	Phoenix, Riverside, Las Vegas
HID	High Desert	Salt Lake City, Albuquerque, Denver, Reno

ID	Feeder Type	Residential	Commercial	Industrial	Agricultural
RES	Residential	70 to 85%	15 to 30%	0%	0%
COM	Commercial	10 to 20%	80 to 90%	0%	0%
MIX	Mixed	40 to 60%	40 to 60%	0 to 20%	0%
RAG	Rural	40%	30%	10%	20%

2.1 Background

Two ideas of Measurement-Based Method

Large disturbance based load identification

- Load characteristics are fully stimulated. More accurate results can be obtained.

- Highly depend on the emergence of large disturbances. Cannot obtain real-time results.
- Few results & High randomicity in time
- Hard to find the time-varying and spatial distribution characteristics of load

Ambient signal based load identification

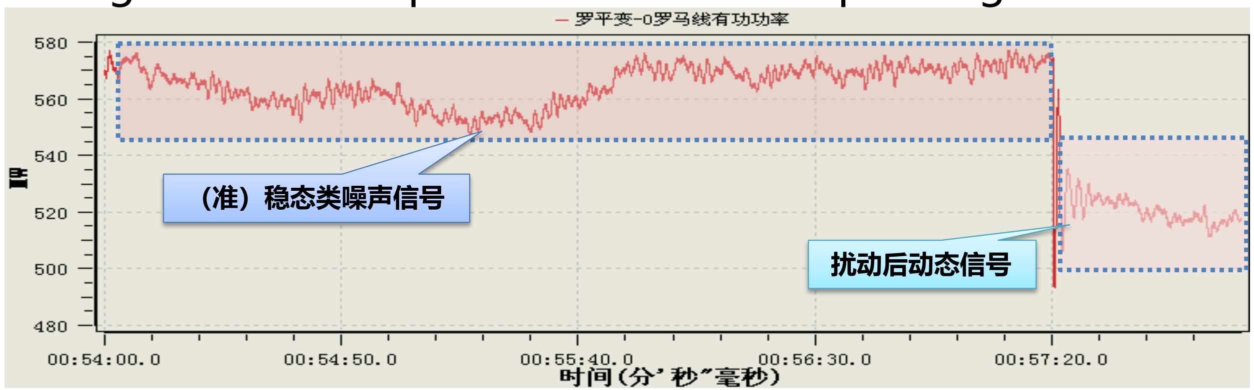
- Load characteristics are not fully stimulated. Measurement error has bigger influence on identification accuracy.

- ✓ Ambient signals exists constantly. Can obtain real-time results.
- ✓ Large Quantity & High coverage both in time and among stations.
- ✓ Provide a foundation for researches on time-varying and spatial distribution characteristics of load.

2.2 Dynamic Load Parameter Identification

2. Ambient Signal Based Load Parameter Identification : Identifiability

ambient signal: A small amplitude fluctuation in response to random changes such as load change in normal operation state of the power grid.



Identifiability Analysis:

1. Obtain the data for identification.
2. Get optimal parameters through DE method.
3. Change parameters successively & Get identifiability curve.
4. Calculate confidence interval and identifiability index.
5. Analyze identifiability by the index.

Parameter	Identifiability Index
X	0.34
X'	0.12
T_{d0}	0.43
R	0.19

- ✓ Identifiability improves as the length of data segment extends
- ✓ Identifiability improves as disturbance amplitude increases
- ✓ Identifiability gets worse as measurement error increases

2.2 Dynamic Load Parameter Identification

Identification Algorithm

- **An on-line identification method combining Prediction Error with Differential Evolution is proposed.**

  - Solve the state variables at time k using PMU data & parameters, then predict the state variables & output variables at time k+1

State Equation

$$E_d(k)=\frac{(P(k)-\frac{U^2(k)}{R})X'U_q(k)-Q(k)X'U_d(k)}{U^2(k)}+U_d(k)$$

$$E_q(k)=\frac{-Q(k)X'U_q(k)-(P(k)-\frac{U^2(k)}{R})X'U_d(k)}{U^2(k)}+U_q(k)$$

$$s(k)=\frac{\dot{E}(k)-\dot{E}(k-1)}{T}+\frac{(-\dot{E}(k-1)+j(X-X')\dot{I}(k-1))*T_{d0}}{j\dot{E}(k-1)\omega_0}$$

  - Using DE to optimize the load parameters to minimize the sum of deviations squares between predicted and measured power

Objective Function

$$A=\sum(P_p(k)-P(k))^2+(Q_p(k)-Q(k))^2$$

Optimization Problem

$$z=\sum\left(y_p-y_m\right)^2$$

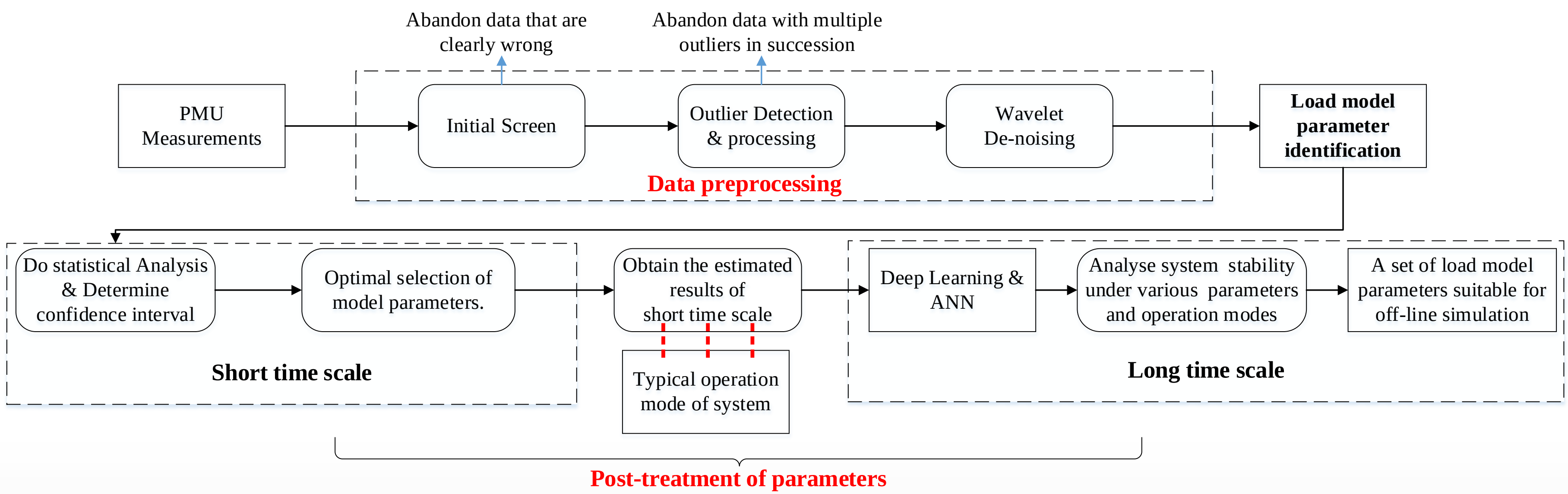
$$X=\{X_1,X_2,T_{d0},H_2,R\}$$

$$X_0,\quad s.t.\quad z=\min(z)$$

2.2 Dynamic Load Parameter Identification

Data preprocessing & Parameter post-treatment

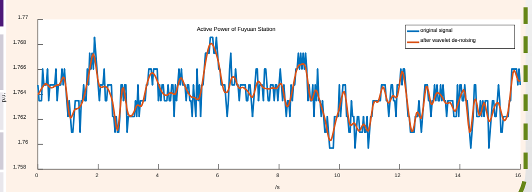
Overall framework



Data preprocessing

Preprocessing Method	Identifiable percentage
Without preprocessing	16.9%
Low pass filtering	20.3%
EMD	20.0%
Wavelet de-noising	27.3%

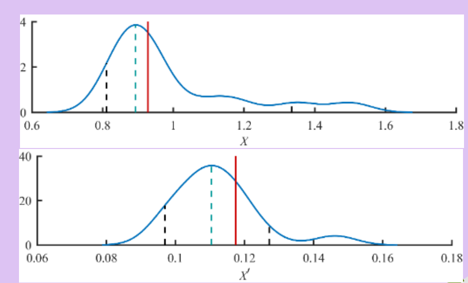
- Wavelet de-noising result:



Post-treatment of parameters

- KSD estimation for the PDF of parameters.
- Criterion for optimal parameter selection:

$$\min_{j} \sum_{i=1}^{N} (\|P_i - P_p(U_i,\theta_j)\| + \|Q_i - Q_p(U_i,\theta_j)\|) + \|\theta_j - \theta_e\|$$

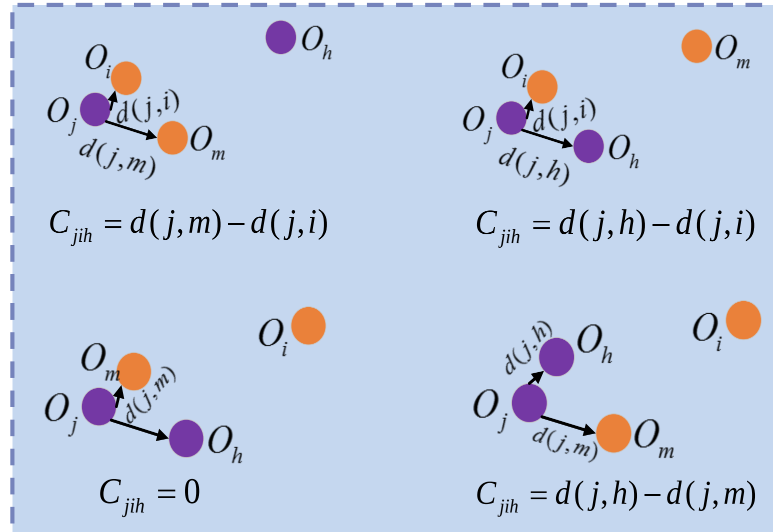


2.2 Dynamic Load Parameter Identification

Modified K-Medoids Clustering For Load Model Parameter Extraction

Targets for Load Model Parameter Extraction

- Solve the time-varying characteristics of power load.
- Get typical load model parameters under typical operation modes.



The Pseudo-code of the Partitioning Around Medoids Algorithm

Algorithm*: *K-medoids

Input: Dataset with n samples
Number of clusters k
Output: Class labels of all samples
(1) **for** $i = 1$ to N **do**
(2) initialize cluster centers
(3) **repeat**
(4) assign the sample to its closest center
(5) calculate the cost (C) of replacing a center sample with a non-center sample
(6) **if** $C<0$
(7) update the new cluster center
(8) **endif**
(9) **until** all the center samples and non-center samples are considered
(10) **endfor**

Algorithm modifications

- The distance between each sample is defined as the fitness of the center sample parameters and the non-center sample measurements:

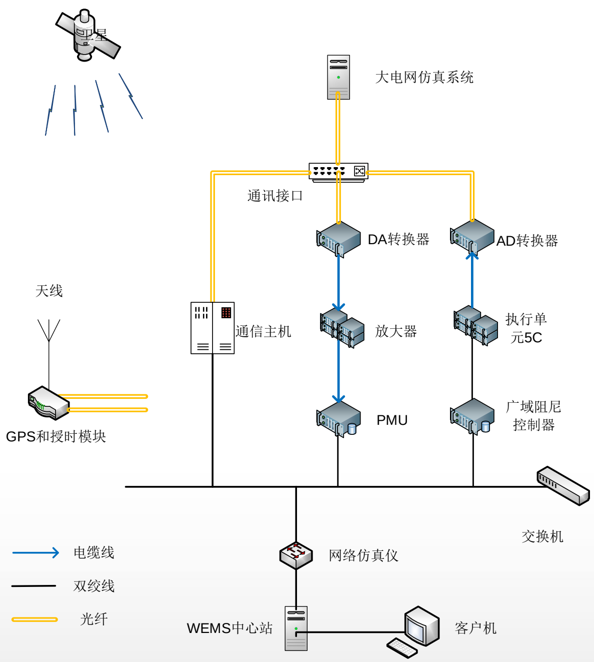
$$fit = 1 - \frac{1}{2}\left(\frac{\|P_p - P\|^2}{\|P - mean(P)\|^2} + \frac{\|Q_p - Q\|^2}{\|Q - mean(Q)\|^2}\right) \qquad C_{ih} > 0$$

- The update criterion of the center sample:
- the results with the largest fitness will be the final cluster results.

2.3 Test and Implementation

2. Hybrid Real-time Simulation Test

✓ **Large Grid Simulation System Based Experimental Platform**



✓ **Hybrid Simulation Platform:** Simulation System、Communication Network、PMU, etc.

Identified parameters with systematic error

系统误差(%)	X	X'	T_{d0}	R	拟合度
0	0.727	0.282	0.161	0.460	1
0.2	0.731	0.284	0.161	0.463	0.999
0.5	0.716	0.279	0.160	0.453	0.971
1.0	0.750	0.273	0.162	0.448	0.952

Identified parameters with random error under different disturbance amplitudes

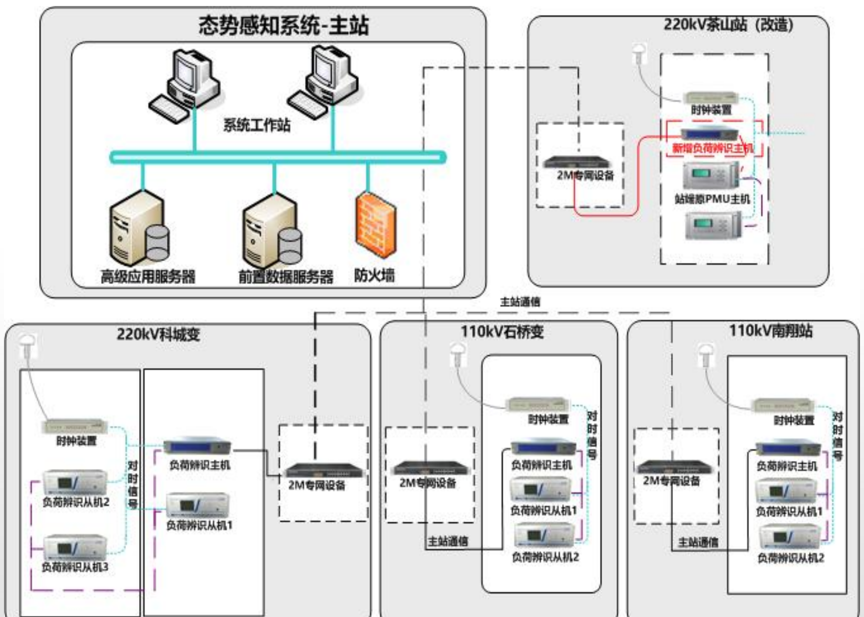
扰动幅值（%）	$\mu(X)$	$\mu(X')$	$\mu(T_{d0})$	$\mu(R)$
真实值	0.727	0.282	0.161	0.460
1	0.698	0.284	0.123	0.440
2	0.726	0.284	0.147	0.455
3	0.724	0.282	0.154	0.458
4	0.726	0.282	0.159	0.460

✓ High tolerance for systematic error.
✓ Accurate identification results can be obtained from small disturbances.

2.3 Test，Implementation & Verification

System Implementation and Verification: CSG Pilot Project

- ✓ 4 substations have completed field installation ,commissioning and operation.
- ✓ Substations are connected to the master station through a dedicated channels. Results and data are uploaded in real time. The measurement, identification and communication are operating normally.
- ✓ On October 18, 2018, the Power Dispatch and Control Center of China Southern Power Grid approved the formal commission of this system.



Cabinets at project site

2.3 Test，Implementation & Verification

Typical Results

✓ **Overall Situation Analysis：t**ake the identification results of October 10, 2018 at 15:30 as an example, 50/58 500kV Stations can obtain effective results, the coverage ratio is 86.2%.

No.	Plant	Device	Time	X	X'	T_{d0}	R	$slip$
1	香山站	#2B-高	2018-10-10 15:30:38	**0.686**	**0.179**	**0.072**	**0.142**	**0.034**
2	横沥站	#4B-高	2018-10-10 15:29:18	**1.328**	**0.408**	**0.065**	**0.176**	**0.043**
3	香山站	#1B-高	2018-10-10 15:30:37	**0.680**	**0.173**	**0.078**	**0.145**	**0.034**
4	花都站	#2B-高	2018-10-10 15:28:54	**1.018**	**0.172**	**0.165**	**0.155**	**0.015**
5	砚都站	#2B-高	2018-10-10 15:31:29	**2.107**	**0.545**	**0.057**	**0.346**	**0.047**
6	横沥站	#3B-高	2018-10-10 15:29:17	**1.546**	**0.444**	**0.171**	**0.195**	**0.014**
7	库湾站	#3B-高	2018-10-10 15:31:03	**1.434**	**0.421**	**0.104**	**0.295**	**0.019**
8	加林站	#4B-高	2018-10-10 15:30:24	**2.213**	**0.373**	**0.369**	**0.233**	**0.029**
9	玉城站	#2B-高	2018-10-10 15:28:52	**2.908**	**0.236**	**0.108**	**0.589**	**0.019**
10	香山站	#3B-高	2018-10-10 15:27:49	**1.286**	**0.203**	**0.138**	**0.184**	**0.014**
11	崇文站	#4B-高	2018-10-10 15:30:31	**2.575**	**0.442**	**0.216**	**0.296**	**0.010**
12	祯州站	#3B-高	2018-10-10 15:30:20	**1.410**	**0.326**	**0.091**	**0.582**	**0.003**
13	福园站	#3B-高	2018-10-10 15:31:23	**2.425**	**0.507**	**0.607**	**0.424**	**0.057**

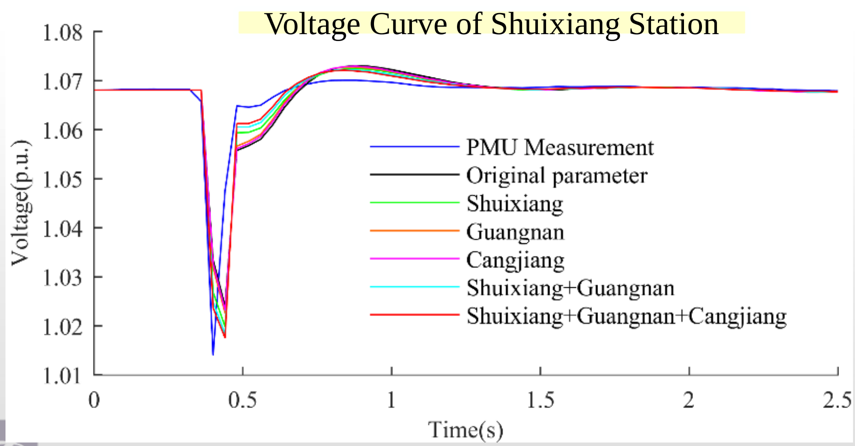
2.3 Test, Implementation & Verification

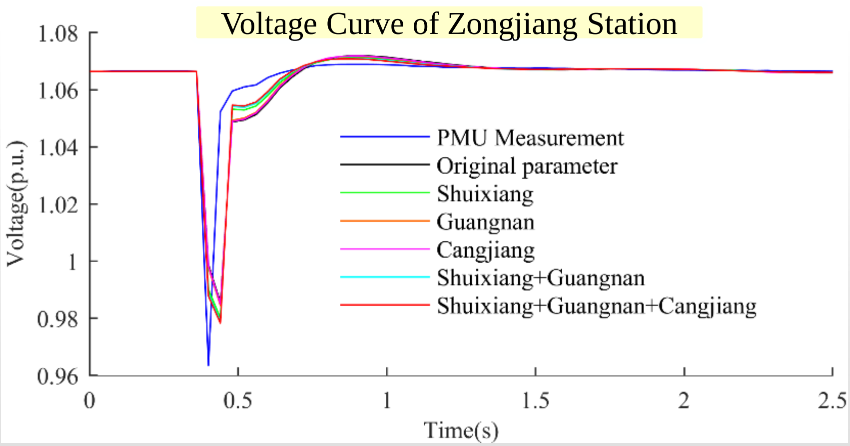
Application and Verification of Load Identification Parameters

- At 16:03:20 on August 19, 2018, the 500 kV Shuixiang-Guancheng Line A tripped due to short circuit. The parameters of different load nodes at 220kV in BPA simulation are replaced by the parameters equivalented from 500kV load parameters identified with PMU measurement.

Multiple-Area Replacement of Load Parameters

Simulation Results using actual Identification model are closer to actual measurements.





2.3 Test，Implementation & Verification

广东省分区		X	X′	T′d0	R	pct	PCT
广州区域	广南站	1.793	0.144	0.335	2.222	0.57	0.71
	木棉站	1.840	0.148	0.362	3.457	0.70	
	狮洋站	1.056	0.300	0.994	4.385	0.89	
东莞区域	水乡站	0.747	0.224	1.236	2.577	0.77	0.75
	横沥站	0.927	0.299	1.174	2.663	0.81	
	纵江站	1.621	0.129	0.681	4.219	0.72	
惠州区域	福园站	8.429	0.470	0.563	1.515	0.87	0.88
	博罗变	6.555	0.390	1.445	2.018	0.89	
汕头区域	汕头变	2.414	0.195	0.340	1.410	0.54	0.72
	胪岗站	1.992	0.760	0.566	2.679	0.87	
清远区域	贤令山	6.860	1.563	0.824	1.309	0.91	/
云浮区域	卧龙变	2.133	0.103	0.451	1.134	0.56	/
总加权 pct							0.74

广西省分区	X	X′	T′d0	R	pct	PCT
崇左变	2.472	0.934	2.625	2.159	0.87	0.78
逢宜变	5.888	0.456	0.161	2.678	0.81	
海港站	1.549	0.482	1.185	1.194	0.75	
平果站	1.374	0.464	1.122	0.613	0.58	

云南省分区	X	X′	T′d0	R	pct	PCT
永丰变	0.740	0.138	0.830	2.959	0.79	0.83
多乐站	1.717	0.551	1.299	3.526	0.91	
草埔站	1.967	0.580	1.120	2.284	0.82	

贵州省分区	X	X′	T′d0	R	pct	PCT
福泉站	1.020	0.391	0.524	1.493	0.70	0.71
施秉变	0.938	0.180	0.418	1.706	0.52	
息烽变	4.579	0.822	1.710	2.015	0.87	
铜仁站	2.511	0.216	0.473	0.971	0.55	

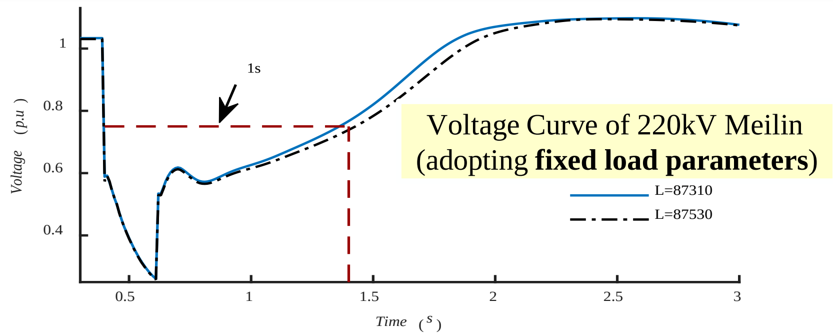
PCT in the tables is the static load ratio. The actual identification of the motor range in this area is 15~30%, which is much smaller than the current 50% of the typical load parameters，showing that conservation of typical load parameters is great!

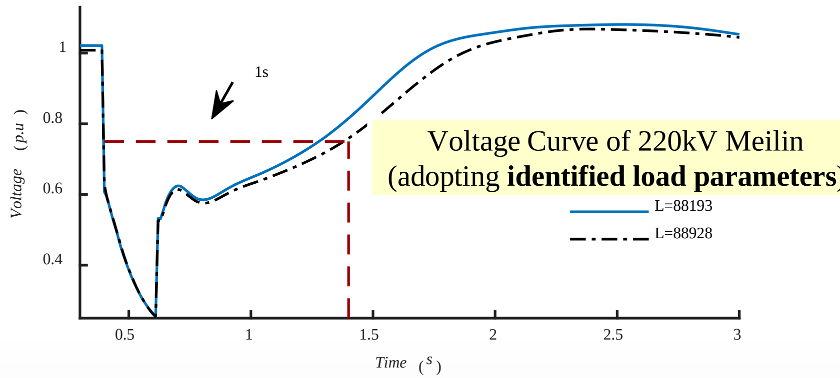
2.3 Test，Implementation & Verification

Further verification from the view of stability limit

- Use the operation condition of CSG on 2018.8.19.
- Set up a three phase short-circuit fault on Baoan-Pengcheng A-line.
- Shenzhen area is a low voltage area after the fault occurs. Based on the engineering criterion of transient voltage stability of CSG, the transmission stability limit of Guizhou-Guangdong section can be obtained by observing the voltage curve of 220 kV Meilin station.

Guizhou-Guangdong Section	AC Lines	DC Lines
	黎平-桂林 Liping-Guilin	高坡-肇庆（高肇直流） Gaopo-Zhaoqing
	独山-柳东 Dushan-Liudong	兴仁-宝安（兴安直流） Xingren-Baoan





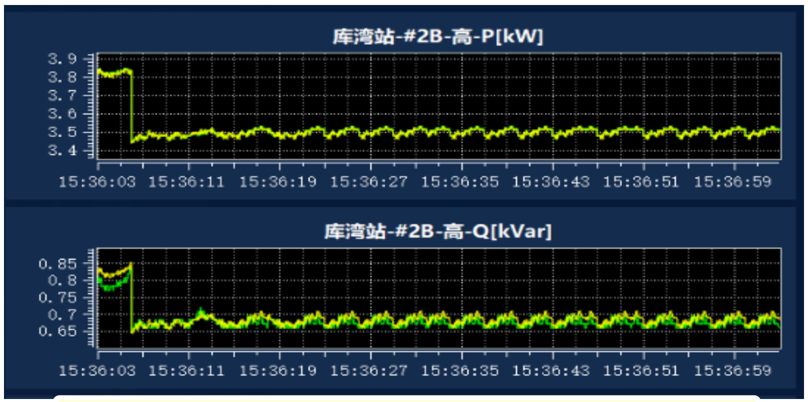
Section Stability Limit	Fixed Load Parameters	Identified Load Parameters
	5748MW	7179MW

✓ The transmission stability limit increases by about 20% while using identified load parameters.

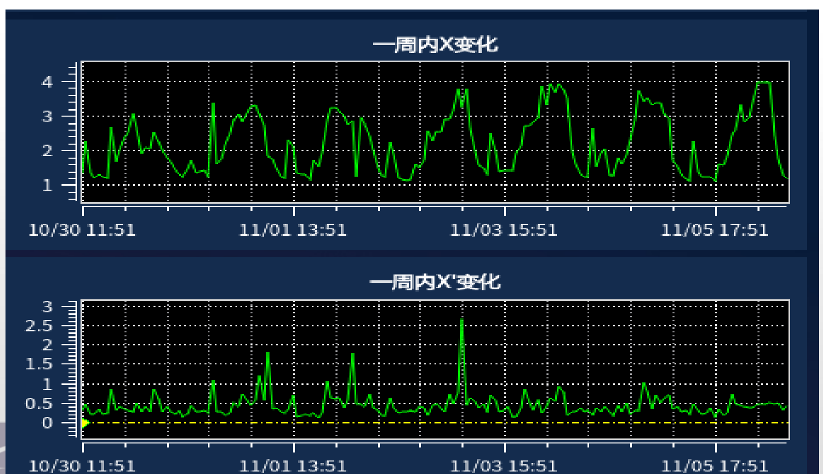
2.3 Test，Implementation & Verification

3. Temporal Statistics of Load Identification Results

✓ **Identification Results of Kuwan (2018.10.10)**

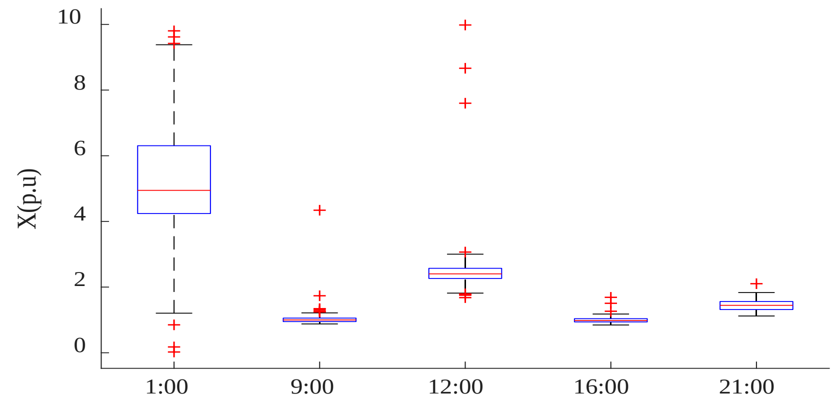


Output value fits well with measurement.

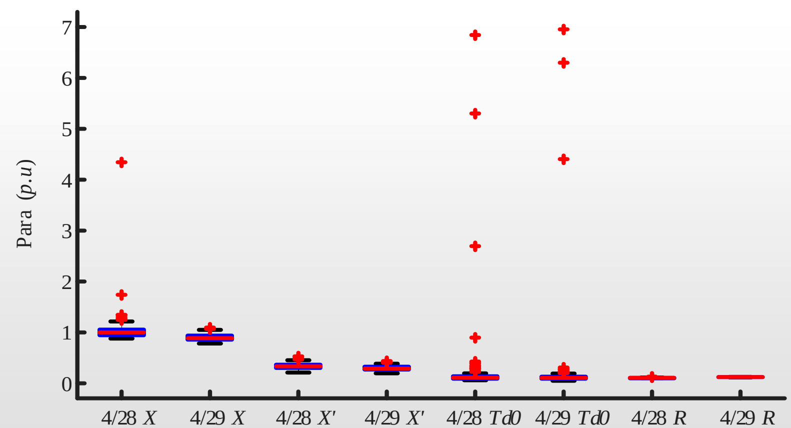


The periodicity of the parameters in a week.

✓ **Identification Results of Chashan (2018.4.28 & 4.29)**



Distribution of parameter X within 4.28



The distribution of parameters is similar in the same hour within 4.28&29

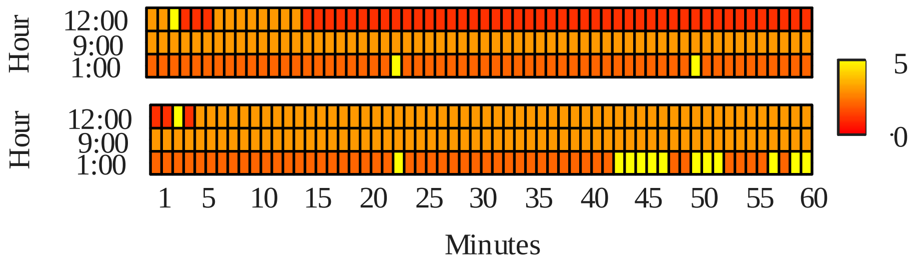
2.3 Test, Implementation & Verification

Modified K-Medoids Clustering For Load Model Parameter Extraction

✓ **Cluster Results of Chashan 220kV substation identification parameters**

Parameter identification for Modified K-Medoids Cluster

- PMU data with 20ms sample interval are studied.
- A 1080-set (60×3×6=1080) is identified at 01:00, 09:00, 12:00 on April 28th and 29th. For each minute, the identification process is conducted 3 times
- The number of cluster centers is set as 3.



The cluster results of the load characteristic on April 28th and 29th

Conclusions

- ✓ Identified parameters in the same time are grouped into the same cluster.
- ✓ The center parameter of each cluster is from different hours.
- ✓ Both the results in the figure and the chart on the right side indicates the effectiveness of the modified k-medoids method.

The Cluster Centers of the 1080-set Load Model Parameters Identified on April 28th and 29th

X	X'	T_{d0}'	R	*Time*
2.3912	0.7519	1.1683	0.1307	April 28th 12:29
2.6696	3.7616	2.4936	0.1912	April 29th 01:58
0.9363	0.4060	6.9526	0.1233	April 29th 09:16

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Outlines

1. Backgrounds

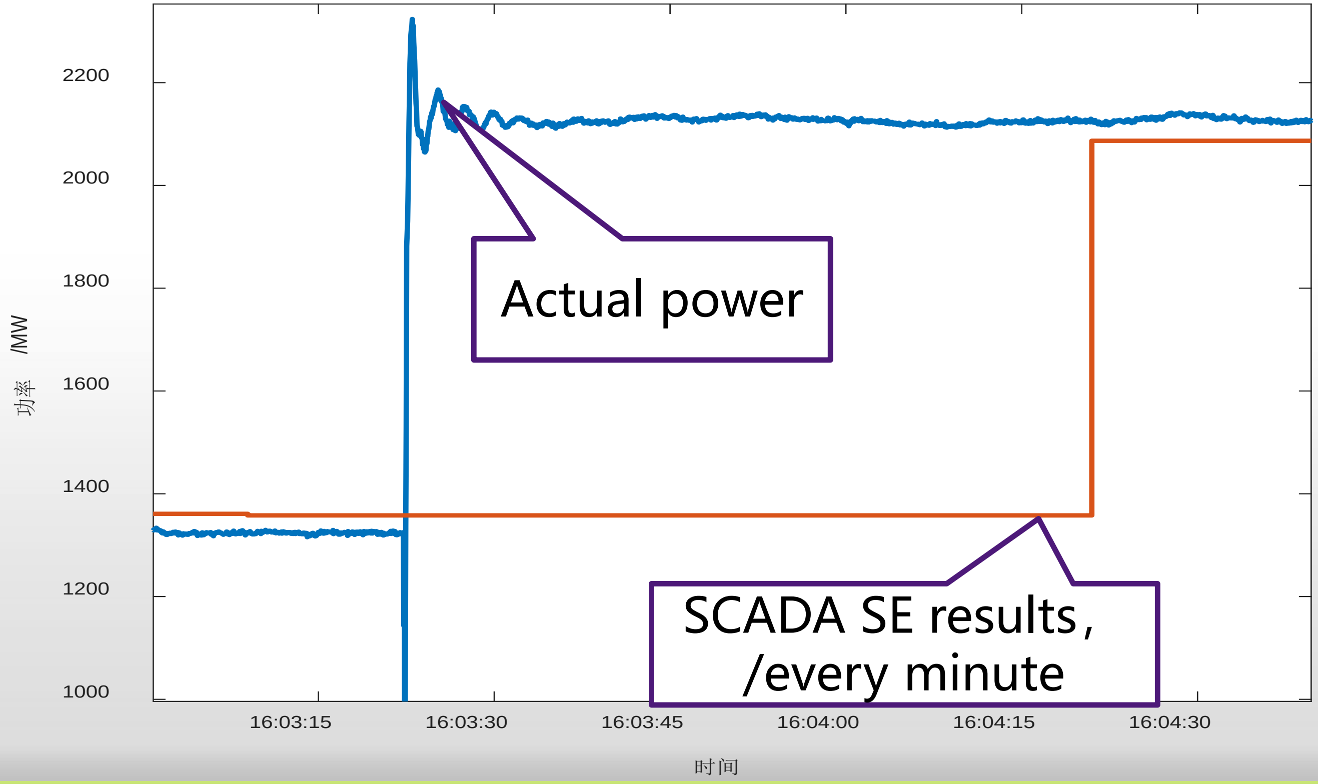
   Power system oscillation analysis and control

2. Dynamic load parameter identification
3. Online linear state estimation (SE)
4. Further Work

3.1 Background

Problem of traditional State Estimation —— A Case in CSG

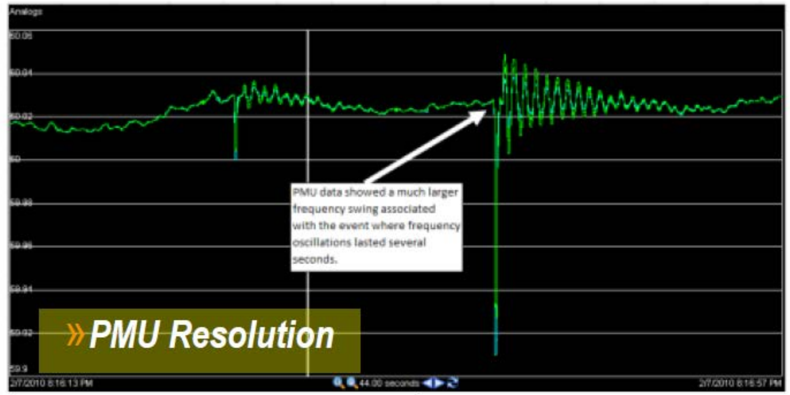
- On August 19, 2018, around 16:03:22, there was an outage in the 500kV Line A between Shuixiang and Guancheng (水莞甲线) because of an inter-phase short-circuit fault.
- Because the fault of Line A, The power flow had transferred to Line B. Thus, Line B had a large increase in power with multiple cycles of oscillations. There were more than 1-minute time when the actual line transmission power has risen to more than 2100 MW but the SCADA-based SE results are less than 1400 MW.



3.1 Background

- **SCADA based state estimation is the general approach to obtain power flow, But**

- SCADA Measurements of individual snapshots are weakly synchronized;
- The SE solutions may suffer from divergence problems and it might turn out not to be the available power flows because of nonlinearity of the estimation model.
- The estimation intervals usually are minute-long, which cannot satisfy the requirement of tracking system dynamics;
- SE calculations/results depend on network parameters and topology, but gird network parameters and topology is actually derived by measurements, which may be incorrect.

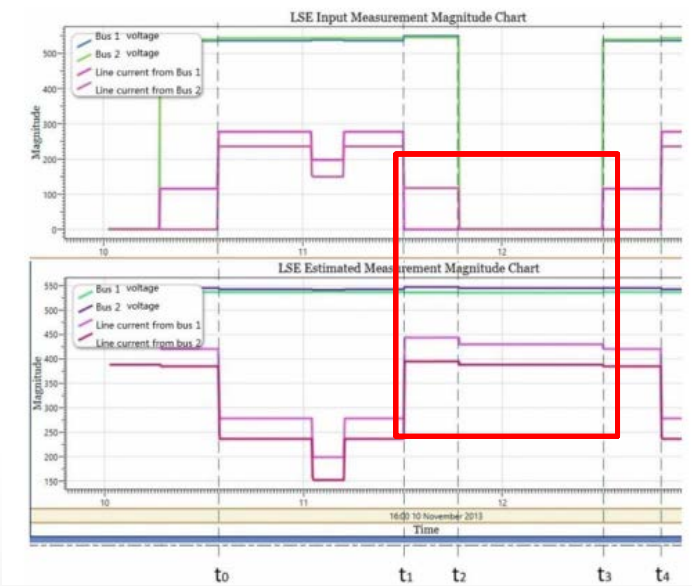


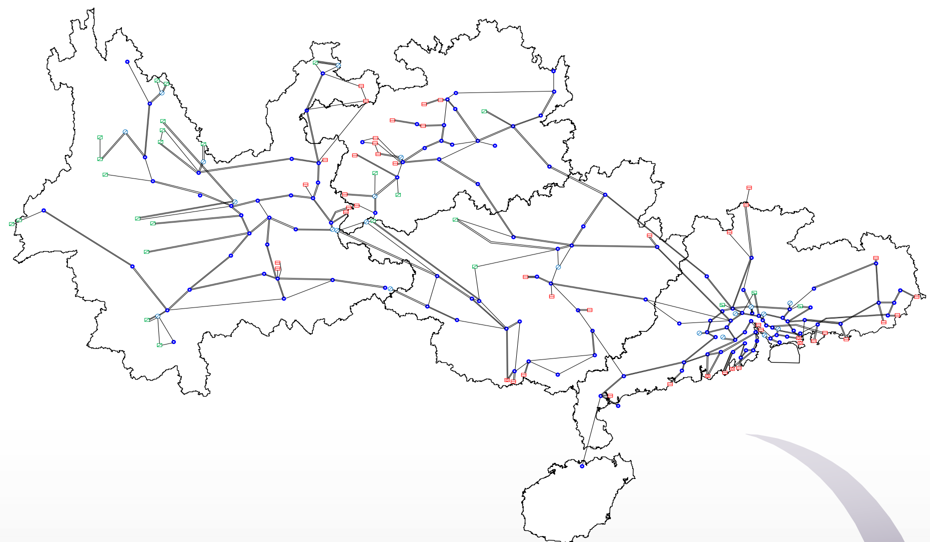
- Modern power systems are becoming more complicated and challenging. For the sake of comprehension of system dynamic behaviors and further analysis, assessment and control, it is quite urgent to quickly obtain accurate dynamic power flows of the whole system

3.1 Background

Problem of traditional State Estimation —— A Case in CSG

- Topology analysis is completed based on switch/breaker measurements. The operation interval is usually 5 minutes or more, which cannot quickly reflect the real-time change of the grid topology.





- Transmission Line parameters are usually offline obtained using specific instruments during construction or maintenance. Thus Timeliness is poor and there may be errors:
  - Measurements Errors
  - Managements Errors

id	name	r	x	bch
249181	花从乙线	0.0023	0.485	119.6212
249184	花从甲线	0.0229	0.49	122.3776

3.2 PMU-Based State Estimation

- We systematically develops a PMU-based real-time state estimation theory and system in a realistic large-scale power grid, including an improved linear state estimation algorithm, a real-time topology analysis approach based on PMU measurements, a practical bad data identification method and so on.

Background	Key Algorithms	Advantages
PMU raw measurement data still has large errors	**Bad Data Detection and Processing**	Free of rely on specific distribution assumptions, deal with leverage measurements and multi-correlation bad data.
Traditional SE methods are lacking in speed, accuracy, and robustness.	**Real-time Linear State Estimation**	Quick and accurate access to real-time states of power grids, better numerical stability and computational efficiency
There is no effective way to identify topology and parameter changes in real time.	**Online Tracking of Parameter and Topology**	Considering the complexity and variability of modern grids, real-time rapid acquisition of system parameters and network topology
Power system states and network & parameters are interdependent	**Joint State Estimation**	Simultaneous estimation of power system states, line parameters and network topology

3.2 PMU-Based State Estimation

- **Error Characteristic of Phasors :**

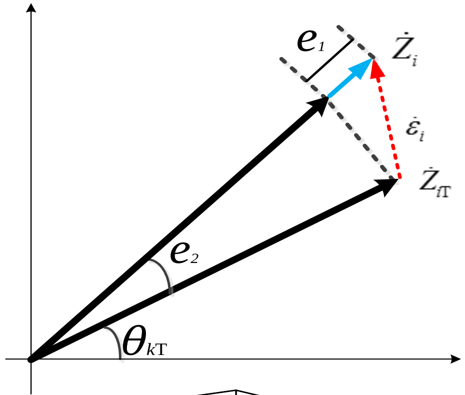
$$|\dot{\varepsilon}_i| = |\dot{Z}_{i\mathrm{T}} - \dot{Z}_i| = |Z_{i\mathrm{T}} e^{j\theta_{i\mathrm{T}}} - (Z_{i\mathrm{T}} + e_{i1}) e^{j(\theta_{i\mathrm{T}} + e_{i2})}| = Z_{i\mathrm{T}} \sqrt{2(1+e_{i1})(1-\cos e_{i2}) + e_{i1}^2}$$

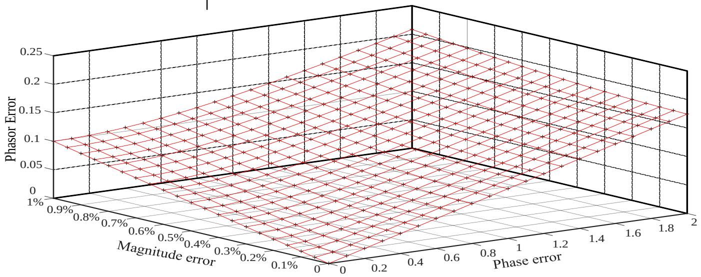
$$E(|\dot{\varepsilon}_i|) = Z_{i\mathrm{T}} E\left(\sqrt{2(1+e_{i1})(1-\cos e_{i2}) + e_{i1}^2}\right) = t_i Z_{i\mathrm{T}}$$

$$D(|\dot{\varepsilon}_i|) \approx Z_{i\mathrm{T}}^2 (\sigma_1^2 + \sigma_2^2 - t_i^2)$$

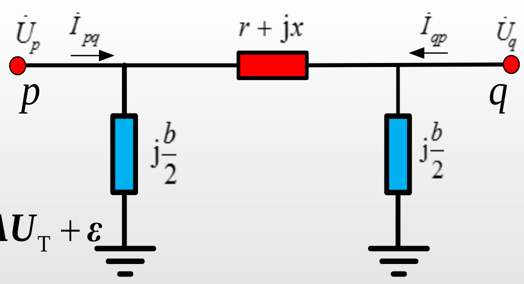
$$t_i = E\left(\sqrt{2(1+e_{i1})(1-\cos e_{i2}) + e_{i1}^2}\right)$$

Phase measurement error e_{i2} contributes more to $|\dot{\varepsilon}_i|$ than magnitude error e_{i1}





- **The complex-domain state estimation method**



π equivalent circuit

$$\begin{cases} \dot{I}_{pq} = Y_{pp}\dot{U}_p + Y_{pq}\dot{U}_q \\ \dot{I}_{qp} = Y_{qp}\dot{U}_p + Y_{qq}\dot{U}_q \end{cases}$$

Measurement Equation

$$\boldsymbol{Z}_\mathrm{m} = \begin{bmatrix} \boldsymbol{U}_\mathrm{m} \\ \boldsymbol{Y}_\mathrm{b}\boldsymbol{U}_\mathrm{T} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\varepsilon}_\mathrm{U} \\ \boldsymbol{\varepsilon}_\mathrm{I} \end{bmatrix} = \begin{bmatrix} \boldsymbol{E} & \boldsymbol{0} \\ \boldsymbol{Y}_\mathrm{b1} & \boldsymbol{Y}_\mathrm{b2} \end{bmatrix} \boldsymbol{U}_\mathrm{T} + \begin{bmatrix} \boldsymbol{\varepsilon}_\mathrm{U} \\ \boldsymbol{\varepsilon}_\mathrm{I} \end{bmatrix} = \boldsymbol{A}\boldsymbol{U}_\mathrm{T} + \boldsymbol{\varepsilon}$$

Objective Function

$$J_\mathrm{CWLS}(\boldsymbol{U}) = \sum w_i |\dot{\varepsilon}_i|^2 = \boldsymbol{\varepsilon}^\mathrm{H}\boldsymbol{W}\boldsymbol{\varepsilon}$$

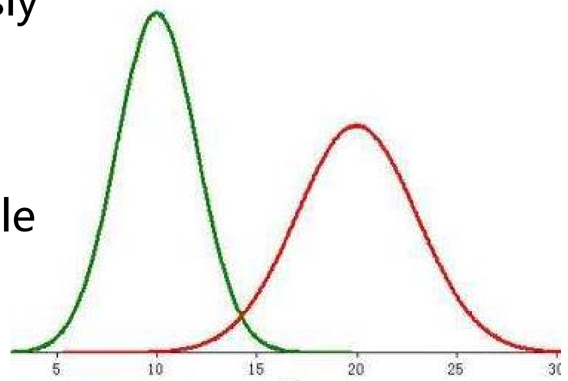
Optimal solution

$$\boldsymbol{U}_\mathrm{e} = (\boldsymbol{A}^\mathrm{H}\boldsymbol{W}\boldsymbol{A})^{-1}\boldsymbol{A}^\mathrm{H}\boldsymbol{W}\boldsymbol{Z} = \boldsymbol{G}\cdot\boldsymbol{Z}_\mathrm{m}$$

3.2 PMU-Based State Estimation

☐ Joint identification and correction of erroneous parameters and bad data

- The identification and correction are performed simultaneously using normalized Lagrangian multiplier (LM) and normalized residuals (rN), and the iterative state estimation is performed until there is no abnormality.
- Basic idea: statistical hypothesis test, probabilistically separable indicator



$$\begin{cases} \min & J(x, p_e) = \frac{1}{2} r(x, p_e)^T R^{-1} r(x, p_e) \\ s.t. & p_e = 0 \end{cases}$$

$$L(x, p_e, \lambda) = \frac{1}{2} r^T R^{-1} r - \lambda^T p_e$$

$$\lambda = -H_p^H R^{-1} r$$

First order optimal

$$\begin{aligned} r &= \Delta z - \Delta \hat{z}' \\ &= \Delta z - K \Delta z - S H_p p_e \\ &= S(\Delta z - H_p p_e) \\ &= S(H \Delta x + e - H_p p_e) \\ &= Se - S H_p p_e \end{aligned}$$

$$\begin{aligned} \lambda &= -H_p^H R^{-1} r \\ &= -H_p^H R^{-1}(Se - S H_p p_e) \\ &= -H_p^H R^{-1} Se + H_p^H R^{-1} S H_p p_e \\ &= \Lambda p_e + Ae \end{aligned}$$

$$\Lambda = H_p^H R^{-1} S H_p$$

LM Sensitivity matrix

$$\lambda_i^N = \frac{\lambda_i}{\sqrt{\Lambda_{ii}}} \sim N(0,1)$$

normal distribution

$$p_{corr,i} = p_{bad,i} - \frac{\lambda_i}{\Lambda_{ii}}$$

Simulation Results on Guangdong 500kV Grid

Table 1 The average time of completing state estimation

Method	WLS	CLS	CWLS	CRLS
time	0.004847	0.000233	0.001447	0.001387

Table 2 The TVE index of the four method

Method	WLS	CLS	CWLS	CRLS
Magnitude	1.482106	16.309487	1.264982	1.415835
Phase	0.277303	0.523769	0.279085	0.272706
TVE	0.153488	1.083342	0.139669	0.146323

Table 3 The TVE index under different level of noise

	WLS	CLS	CLWS	CRLS
Test 1	0.282221	2.045667	0.251195	0.272447
Test 2	0.109075	0.550314	0.103528	0.100756
Test 3	0.164529	1.026709	0.146293	0.151672

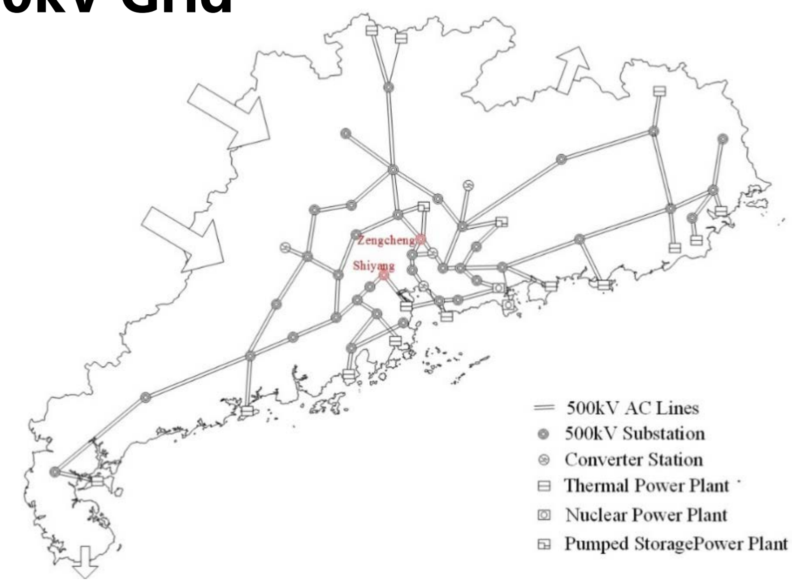


Fig.1 The realistic GD provincial 500kV power grid

- The computational efficiency and robustness of the CWLS algorithm are better than that of the WLS algorithm.
- The CWLS algorithm can improve the accuracy of the measurements especially the phase angle measurements.

Fig.2 TVE curves with numbers of bad data

3.2 PMU-Based State Estimation

- **Joint Identification of bad parameter and data**
  - IEEE case: verify the validity of the maximal normalized Lagrangian multiplier (NLM), add 20% error simulation error parameters to the specified branch parameters, no bad data,

	IEEE 14		IEEE 57		IEEE 118	
Wrong parameter	r1-2	x2-5	r4-6	x12-13	r19-20	x79-80
Max NL	6.236	25.546	5.097	22.3456	4.596	44.568
Identifed data	r1-2	x2-5	r4-6	x12-13	r19-20	x79-80
Estimated Value	0.0192	0.1694	0.0427	0.0576	0.0635	0.0688
True Value	0.0194	0.1739	0.0430	0.0580	0.0630	0.0704
Relative Error	1.33%	2.09%	0.75%	0.64%	0.95%	2.34%

  - 500kV CSG Case: Multiple parameters and bad data exist at the same time, and there is strong correlation, 4 bad parameters ([r77; x111; b239; x300]) and 3 bad data (U20, U77, U165), The results of the identification are as follows:

No.	Identified Data	max r/λ	Estimated Value	True Value	Relative Error
1	b239	12.603421	0.313029	0.284660	0.099660
2	b239	6.289312	0.298827	0.284660	0.049769
3	r77	5.192040	0.000195	0.000195	-0.000242
4	x300	4.591293	0.002575	0.002640	-0.024444
5	x111	4.284585	0.004183	0.004300	-0.027096
6	b239	3.147370	0.291733	0.284660	0.024847
7	U20	3.030690	1.008320	1.007722	0.000594
8	U77	3.033639	0.864652	0.864335	0.000366
9	U165	3.038104	0.927477	0.927560	-0.000089

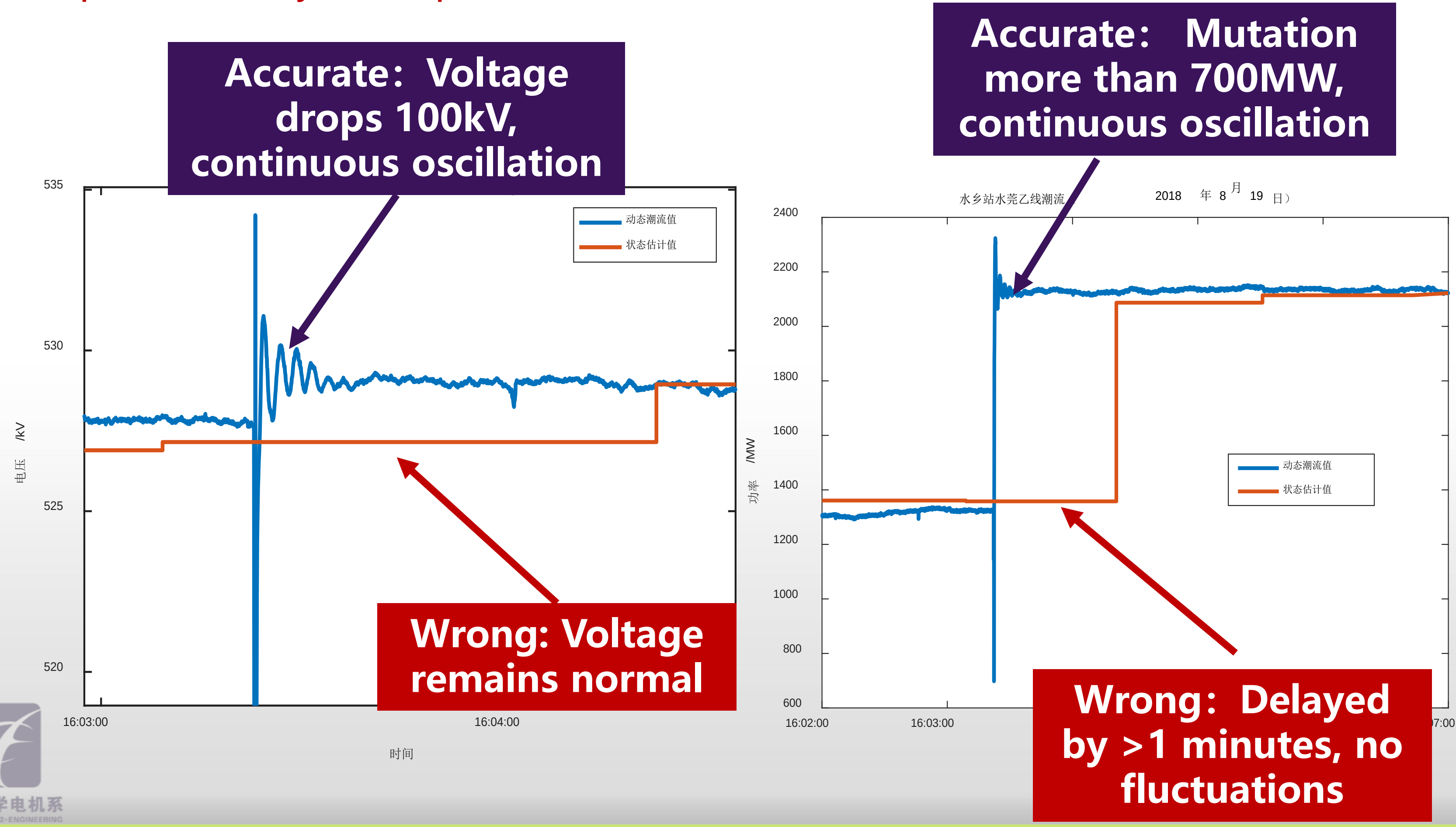
3.3 PMU-based SE Project in CSG

Implementation of PMU-based real-time SE in 500kV network of CSG with the interval of 40ms.

3.3 PMU-based SE Project in CSG

Field Results under Fault Circumstances

- The figures shows Line B’ s voltage and power 5-minute traces of the PMU-based SE and the traditional SCADA-based SE during the fault On August 19, 2018 .
- At the moment of disturbances/faults, the PMU-based SE quickly and accurately captures the dynamic process that the traditional SE cannot track.



Outlines

1. Backgrounds

    Power system oscillation analysis and control

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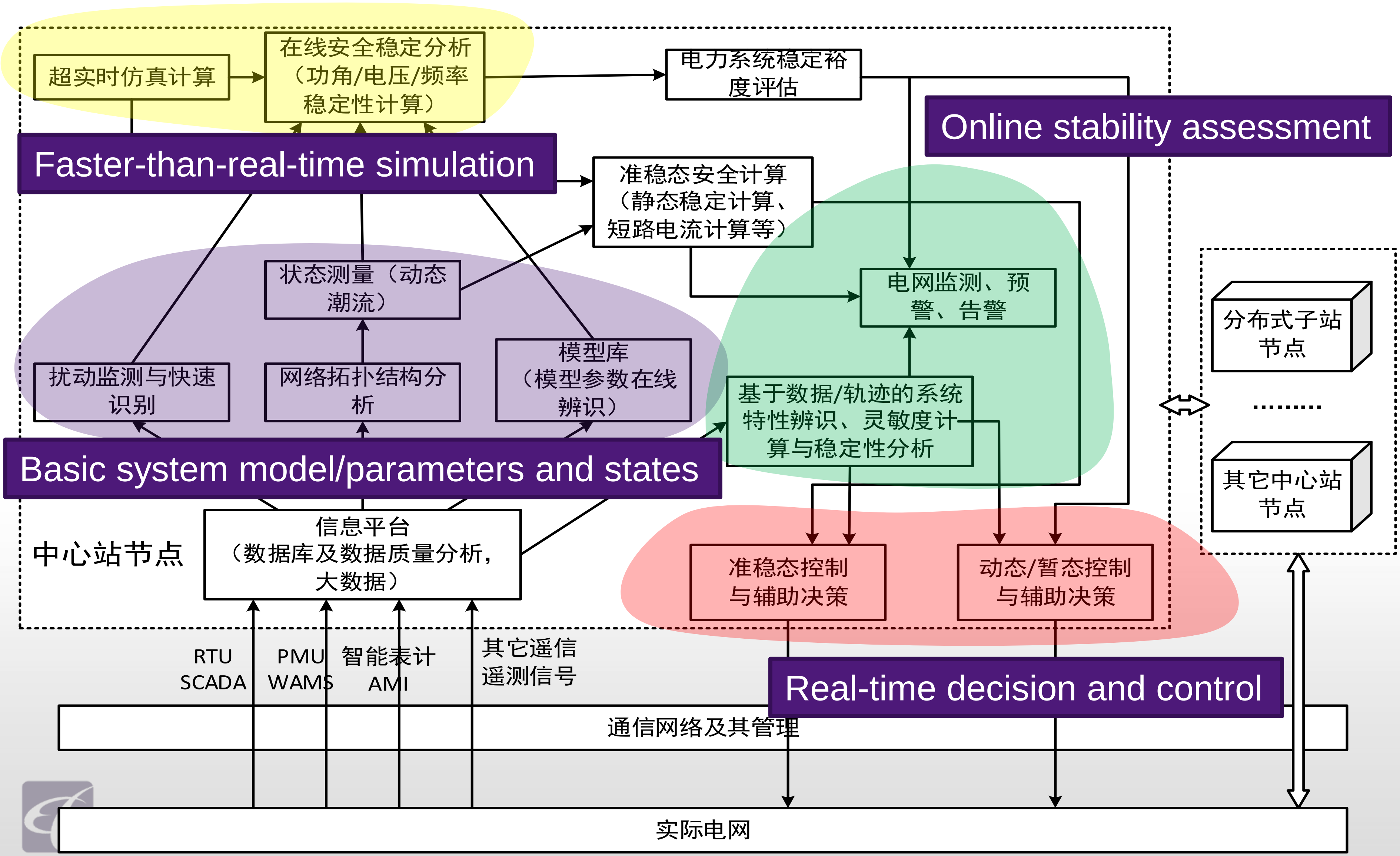
4. Further Work



Thanks for your attentions!