

WAMS Light and Its Applications in China - A New Perspective on Synchronous Monitoring for Power Grids

Hengxu Zhang Ph.D/ Prof.

zhanghx@sdu.edu.cn

School of Electrical Engineering, Shandong University

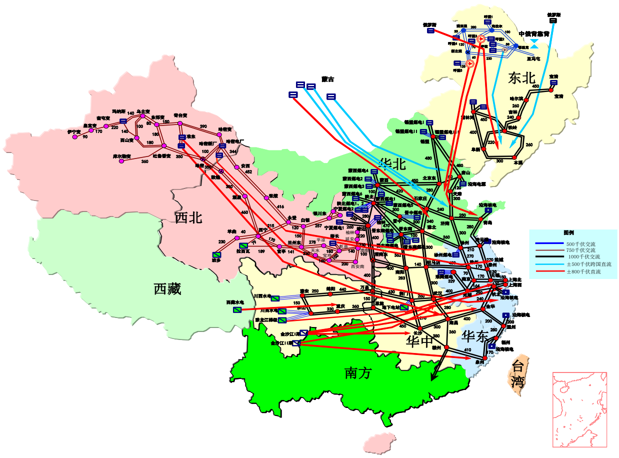
Weihai, 6 July, 2017

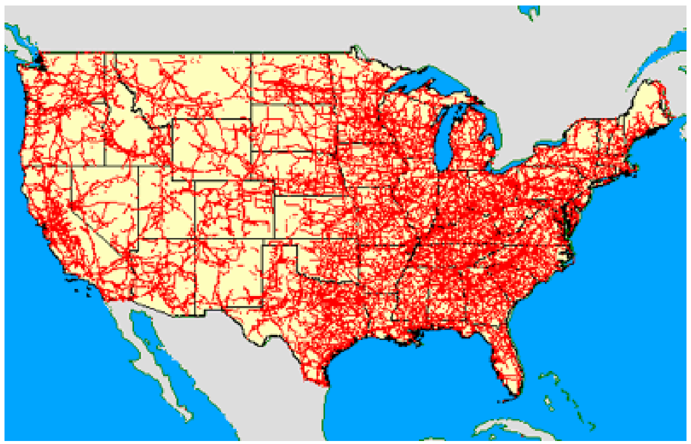
Outlines

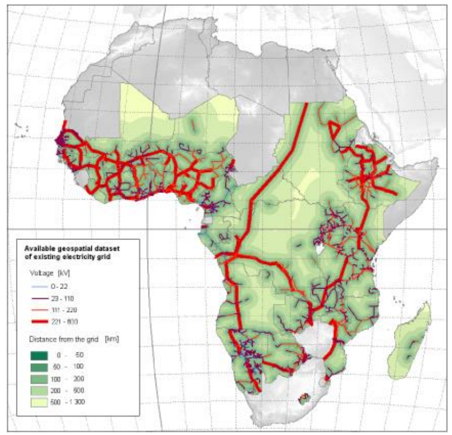
1. Why PMU for distribution network
2. WAMS Light - A New Perspective
3. Applications of WAMS Light
4. Disturbance location with WAMS Light
5. Ongoing works

PMU and WAMS

- In 1893, Charles Proteus Steinmetz presented a paper on simplified mathematical description of the waveforms of alternating current electricity. Steinmetz called his representation a phasor.
- With the great contributions of Dr. Arun G. Phadke and Dr. James S. Thorp, the first PMU was invented in 1988 at Virginia Tech.
- WAMSs are playing a very important role in power systems operation.





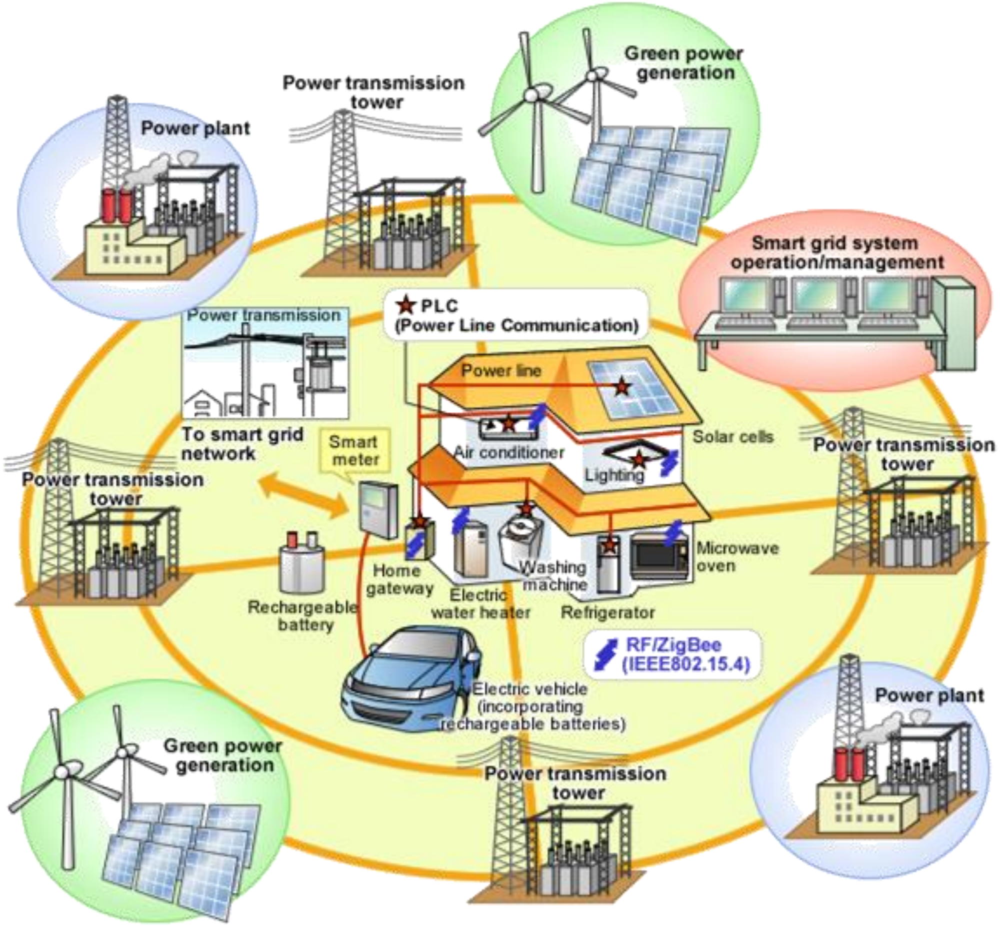


WAMS Deployment in China

In China, more than 2,500 PMUs have been installed, covering almost all the 500kV/1000kV substations and key power stations. So far, most of the WAMSs are deployed in transmission systems, little covering distribution networks.

Driving force of synchronous monitoring for distribution network

- Active Distribution Networks
  - Distributed generations
    - Wind, PV
  - Distributed storage
  - Electric vehicles (EV)
  - Demand response (DR) under market enviroment
  - ...



- Transmission Networks
  - HVDC/HVAC
  - Centralized integration of distributed generations

Challenges of synchronous monitoring for distribution networks

- Relevant phase angle differences in distribution systems are very small, they are not readily measurable with existing synchrophasor technology as is being used on transmission systems.
- High precision requirements vs Low SNR (Signal to Noise Ratio)
- **Large volume data** transmission with weak communication infrastructure and efficiently knowledge learning
- Optimal measurements placement
- Other key applications to enhance the security and stability of distribution networks based on measure data

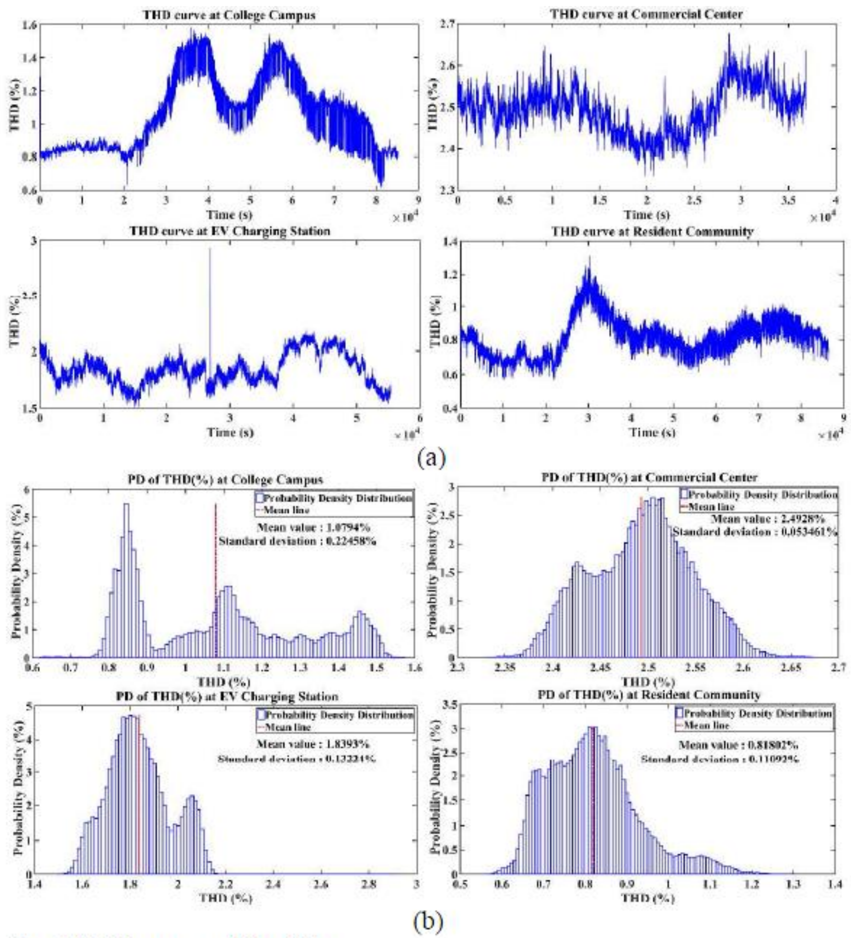
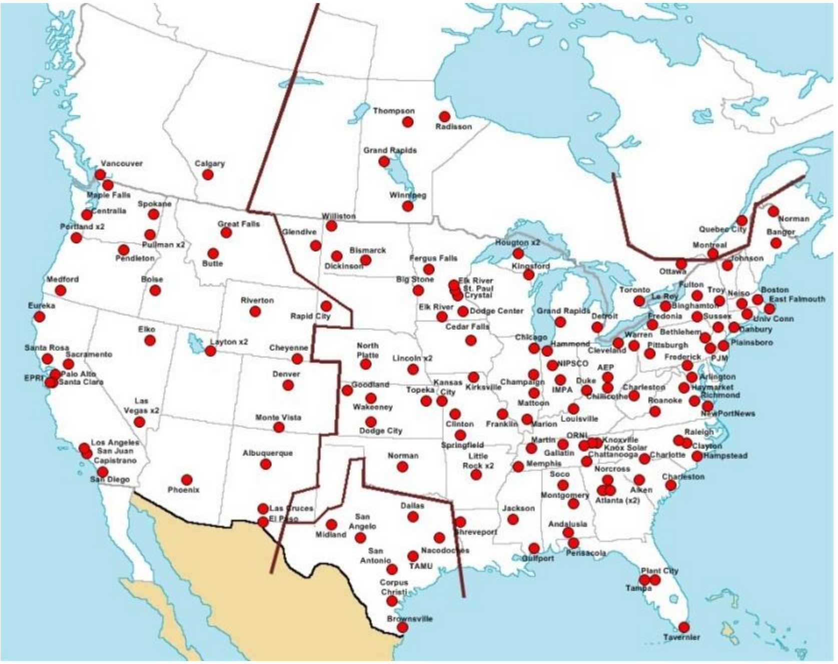
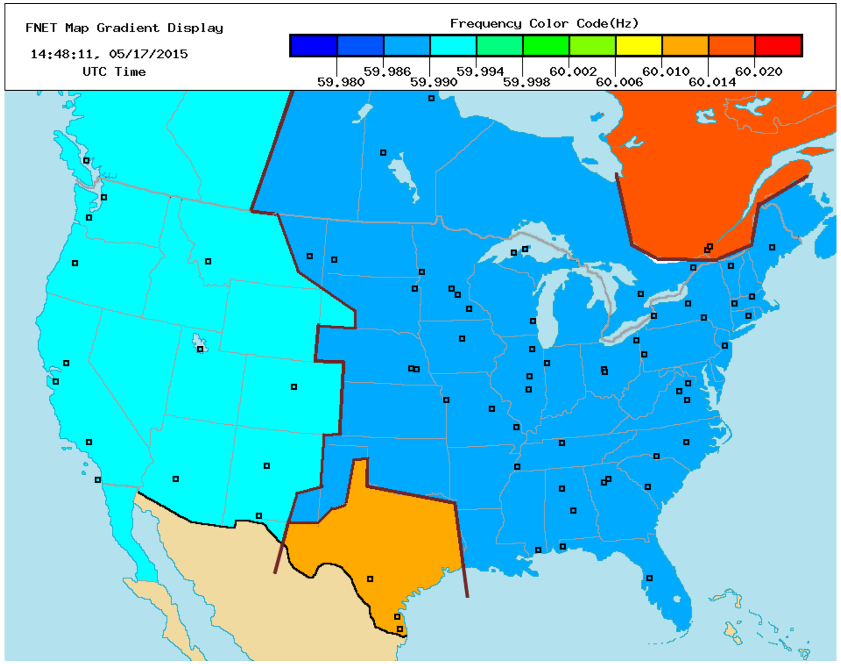


Fig. 4 THD curve and the PDs

Frequency monitoring NETwork(FNET)

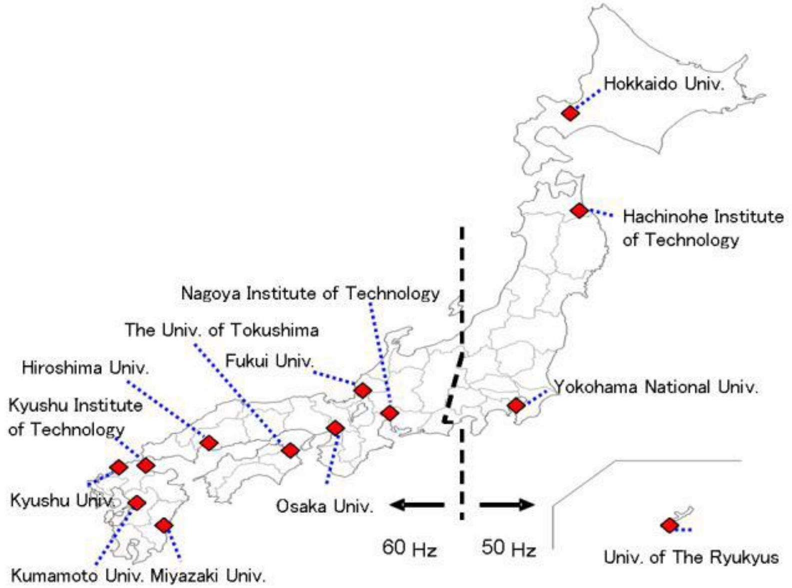
- Frequency disturbance recorder (FDR)
- the frequency monitoring network (FNET)
  http://fnetpublic.utk.edu/

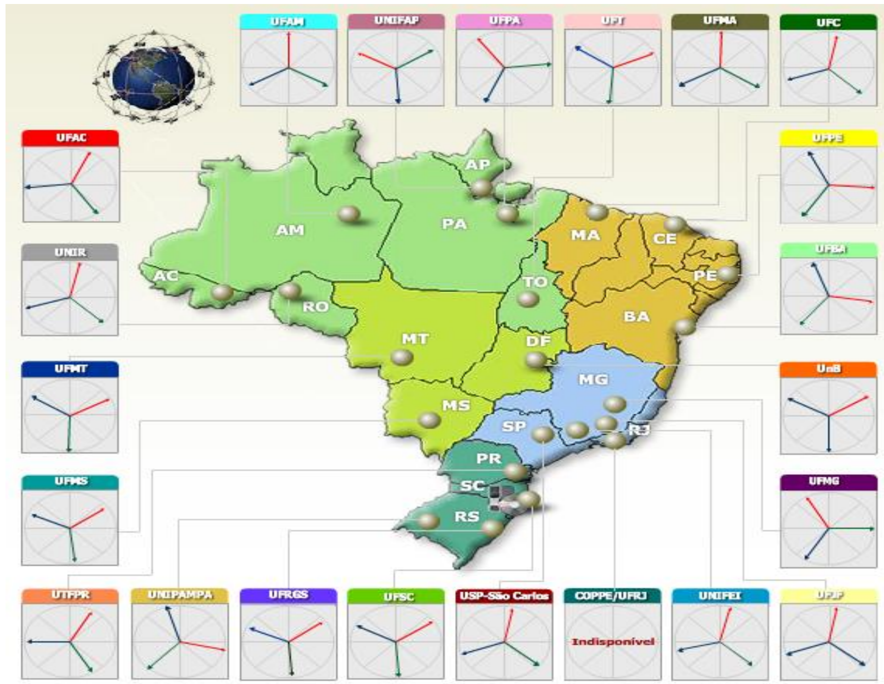




Other monitoring techniques for distribution networks

- Japan: Campus WAMS
  - 12 universities (2014)
  - commercial PMUs at 100V outlets
  - Server
    - Kyushu Institute of Technology
- Brazil: LVPMS
  - 22 universities (2015)
  - Simplified DFR with PMU function
  - Server
    - Federal Univ. of Santa Catarina
    - www.medfasee.ufsc.br/temporeal
- USA: μPMU
  - Monitoring distribution grids
  - Power Standards Lab (PSL) and Lawrence Berkeley National Lab (LBNL),





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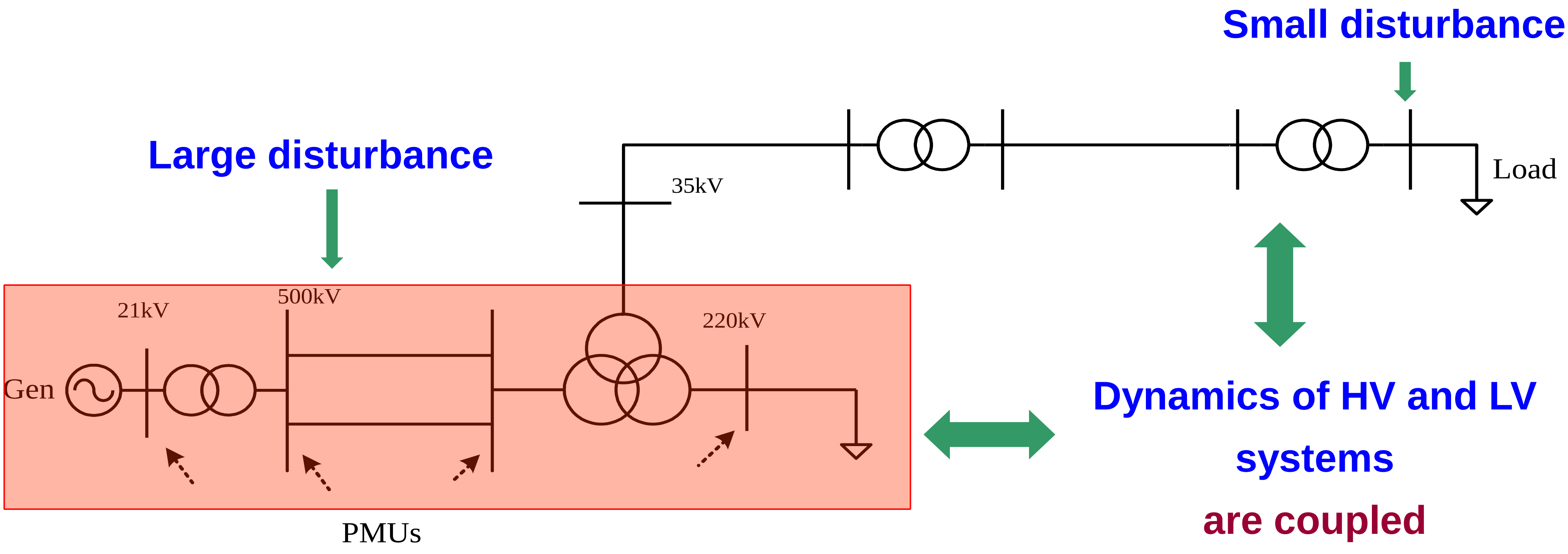
Difference between transmission and distribution networks from monitoring perspective

	HV	LV
Concerns	Angle, voltage, frequency stability. Oscillation	Angle stability is not a key problem, but angle trajectory can give lots information. Voltage is of concern. Frequency monitored for grid operation in isolated mode
Signals	**clean** with little harmonics; not affected by local events at LV side	**polluted** by harmonics, noise; composite of HV dynamics and local events
Number of nodes	**limited** (34 500kV substations for SD)	**numerous**
Device	**PMU** (Costly) (world-widely deployed)	**FDR, PMU Light** **<1/10**
System	**WAMS**	**FNET, WAMS Light, LVPMS, Campus WAMS**

Our pondering on the dynamics of distribution networks



- Dynamics of HV system reflects the overall behavior of the synchronized system, and affects the LV dynamics
- Dynamics of LV system is determined by both HV system and local events

What's Shandong University's focus on?

- Ideas
  - Measure voltage phasor from distribution grid
  - Denoising and decoupling the dynamics of HV and LV grid
  - Get system behaviors and local behaviors at the same time

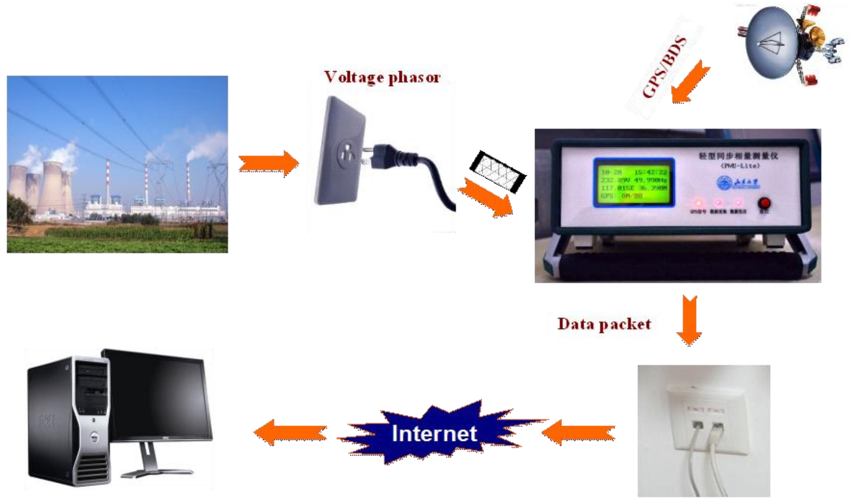
- Solutions
  - Device: PMU Light (Special designed for distribution network)
    - Measured: voltage magnitude, angle, and frequency
    - Unmeasured: rotor angle, transformer tap (until now)
  - System: WAMS Light
    - for data acquisition, processing, and advanced applications based on PMU Light

PMU Light – Synchronous measurement unit for distribution network

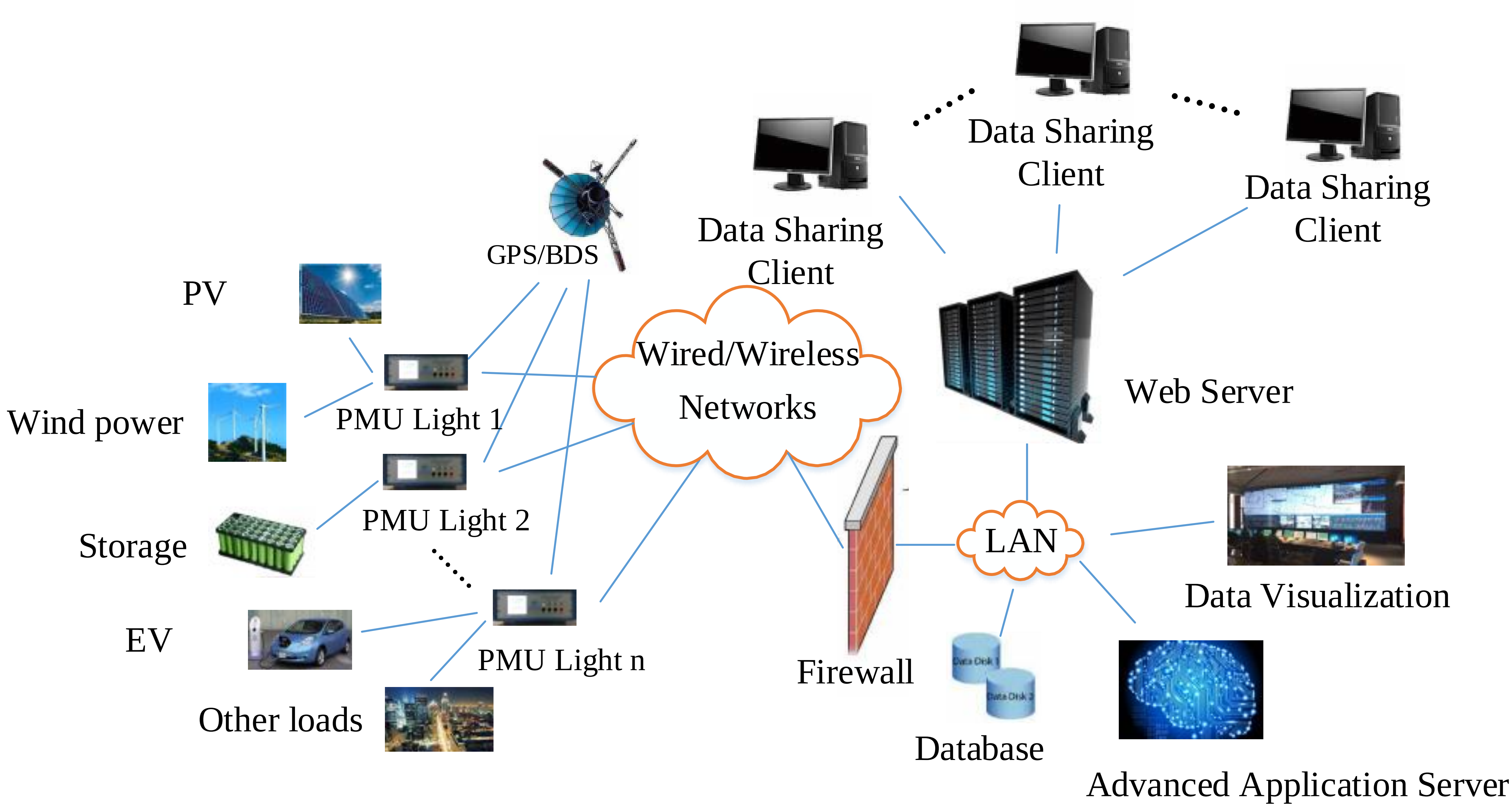
Single-phase device

Three-phase device

- Measure from LV side
- Dual-mode communication
  - Optical fibernternet cable and wireless (4G)
- Dual-mode timing
  - GPS and BDS
- Accurate time keeping when timing signal is unavailable
- High accuracy of frequency and synchrophasor measurement



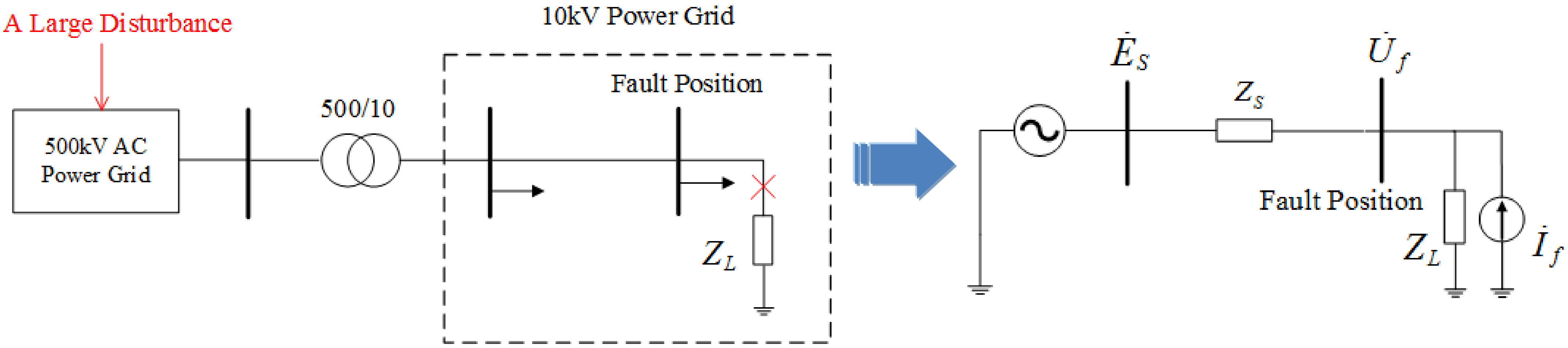
WAMS Light – A synchronous measurement system for distribution network



From 2009

Decoupling of the dynamics captured at LV networks

How the dynamics couple at LV networks?

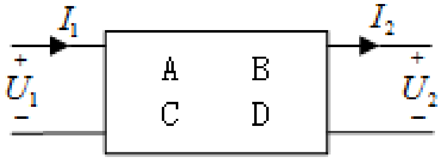


- The voltage $\dot{U}_f$ is the sum of responses of $\dot{E}_S$ and $\dot{I}_f$.
- $\dot{E}_S$ is constantly changing caused by the large disturbance.
- $\dot{I}_f$ is determined by $\dot{E}_S$.(if disturbances in 10kV grid don’t impact the state of 500kV Grid)

Decoupling of the dynamics captured at LV networks

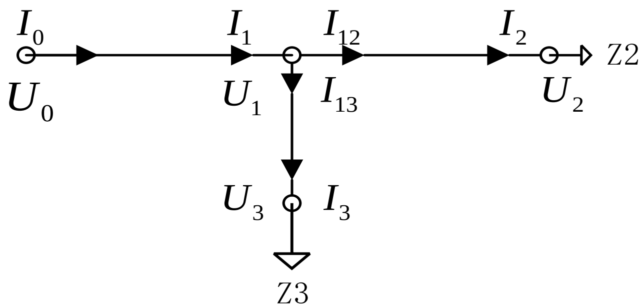
Establish the frequency domain model of each component to derive the two-port transfer matrix of positive sequence

Transmission Lines	Transformers	Load
Bergeron Model	Quasi-Steady-State Model	Constant Impedance Model



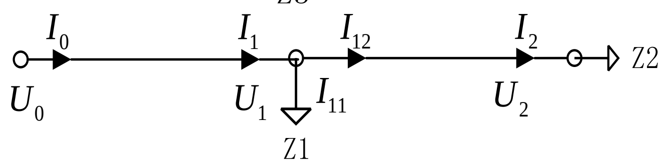
$$\begin{bmatrix} \dot{U}_1 \\ \dot{I}_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \end{bmatrix}$$

Connect the transfer matrixes based on the network structure.
With the boundary condition of the load in the terminal of the grid ,
derive the relationship of the positive voltage phasor in fundamental frequency



$$\begin{cases} \dot{U}_2 = Z_2 \dot{I}_2 \\ \dot{U}_3 = Z_3 \dot{I}_3 \end{cases}$$

$$\begin{bmatrix} \dot{U}_0 \\ \dot{I}_0 \end{bmatrix} = \begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} \begin{bmatrix} \dot{U}_1 \\ \dot{I}_1 \end{bmatrix} = \begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} \begin{bmatrix} A_3 + \frac{B_3}{Z_3} \\ C_3 + \frac{D_3}{Z_3} + (C_2 + \frac{D_2}{Z_2}) \frac{A_3 + \frac{B_3}{Z_3}}{A_2 + \frac{B_2}{Z_2}} \end{bmatrix} \dot{U}_3$$

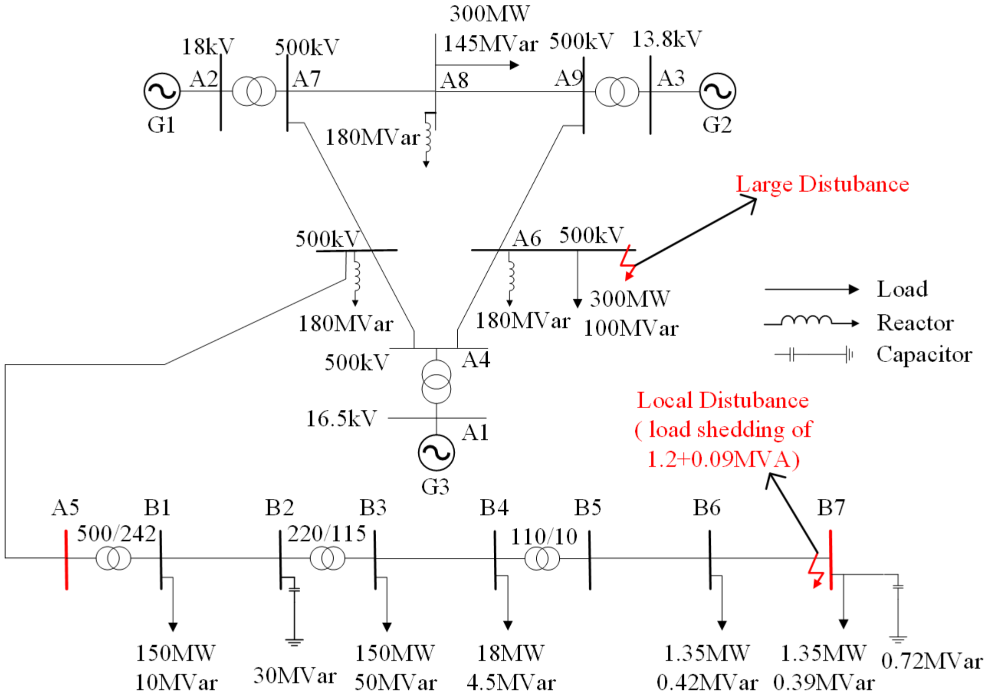


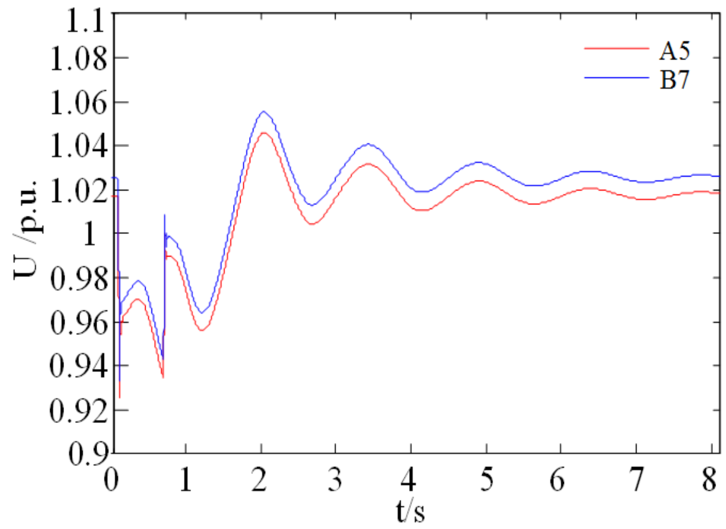
$$\begin{cases} \dot{U}_1 = Z_1 \dot{I}_{11} \\ \dot{U}_2 = Z_2 \dot{I}_2 \end{cases}$$

Boundary Conditions

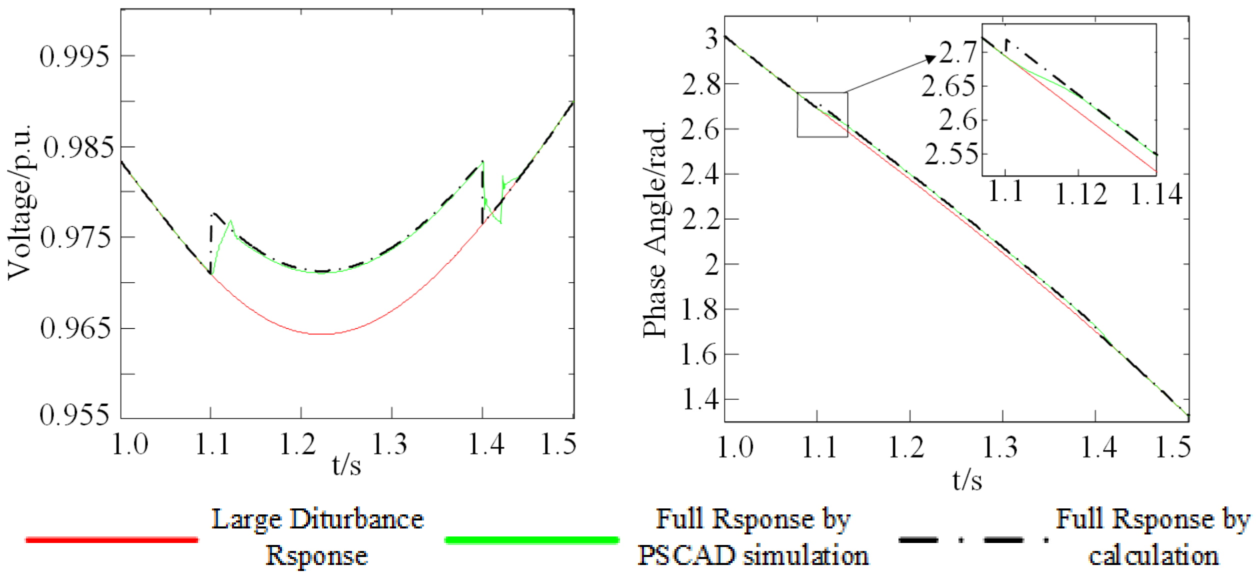
$$\begin{bmatrix} \dot{U}_0 \\ \dot{I}_0 \end{bmatrix} = \begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} \begin{bmatrix} \dot{U}_1 \\ \dot{I}_1 \end{bmatrix} = \begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} \begin{bmatrix} A_2 + \frac{B_2}{Z_2} \\ C_2 + \frac{D_2}{Z_2} + \frac{A_2 + \frac{B_2}{Z_2}}{Z_1} \end{bmatrix} \dot{U}_2$$

Decoupling of the dynamics captured at LV networks – Case studies

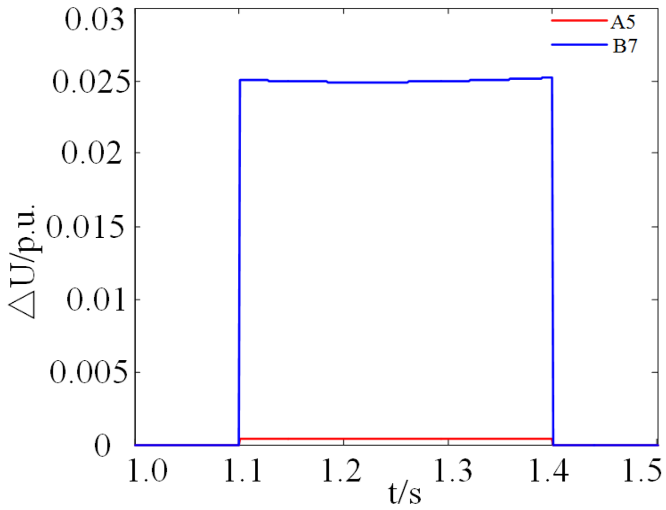




Large Disturbance Response

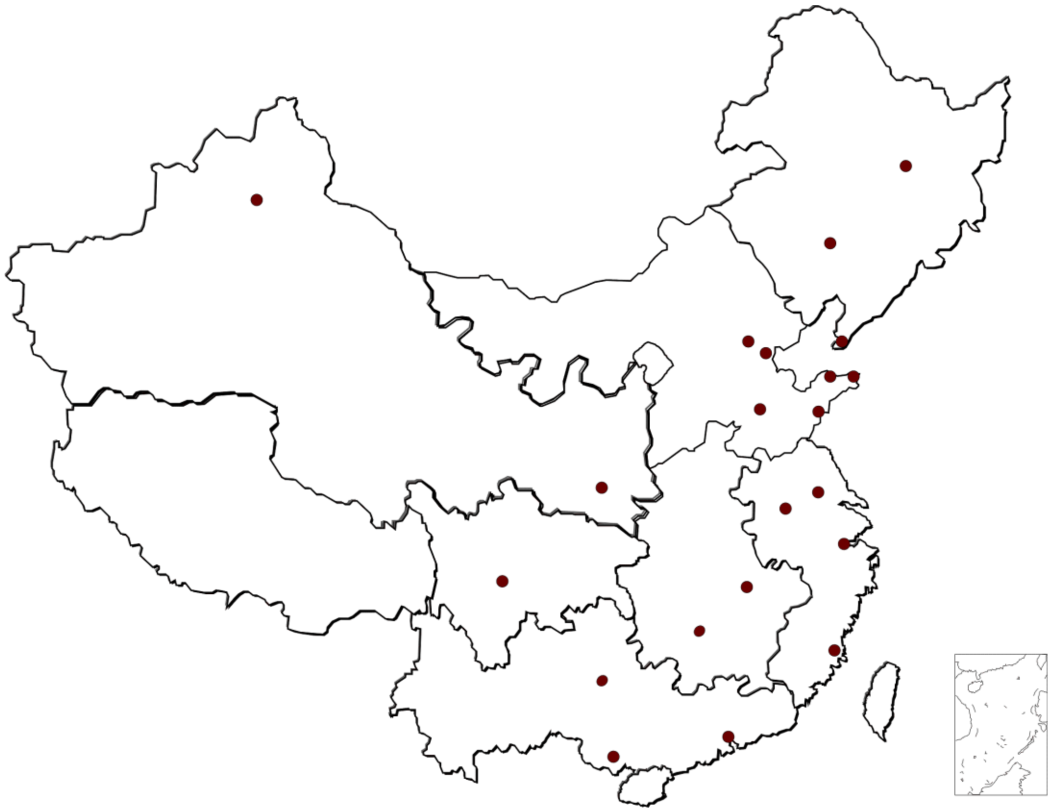


Full Response



Local Disturbance Response

Ongoing Deployment of WAMS Light in China



http://wamslight.sdu.edu.cn/

- More PMU Light will be deployed to monitor the grid dynamics
- Demonstration with some smart grid projects

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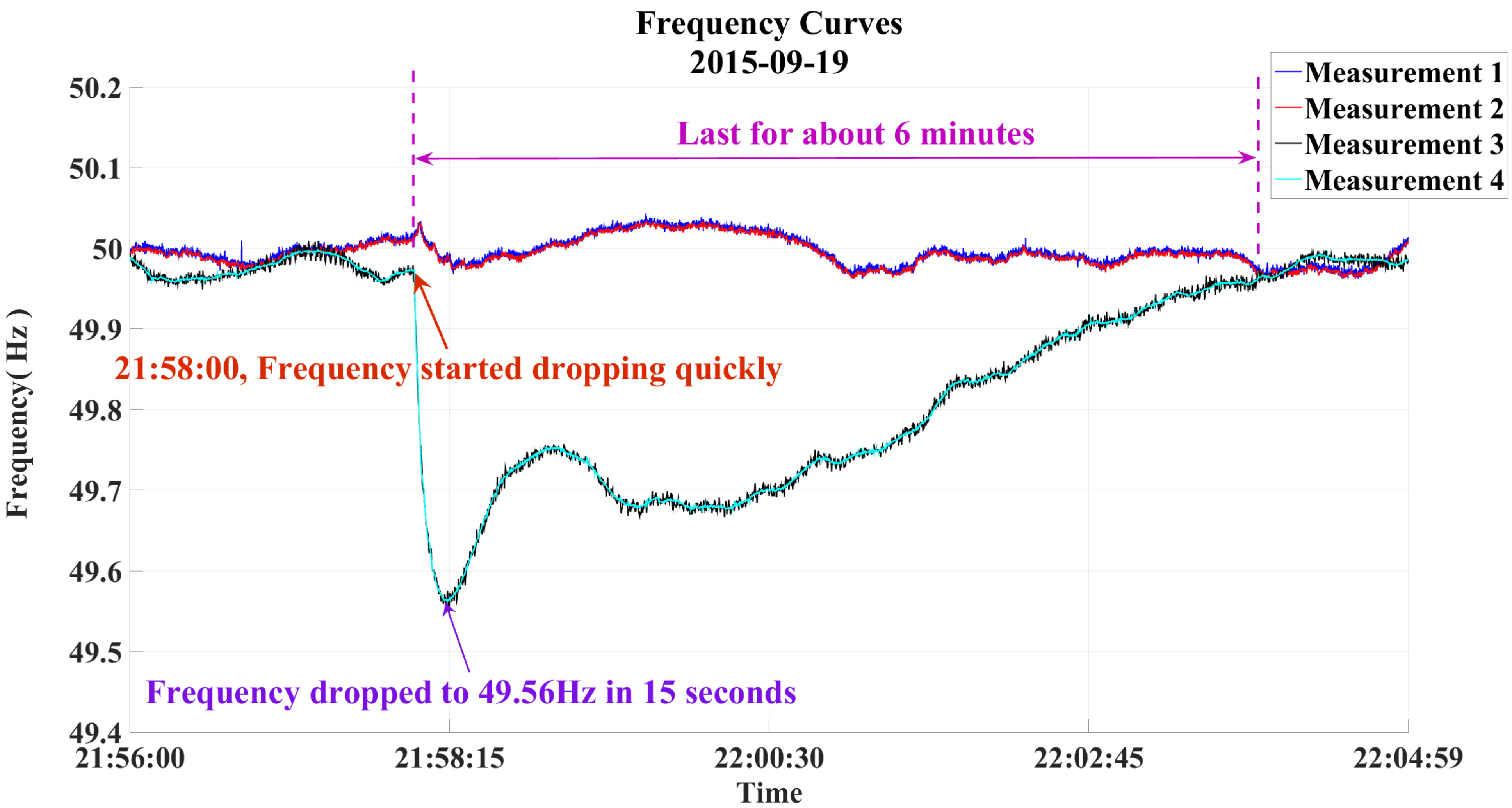
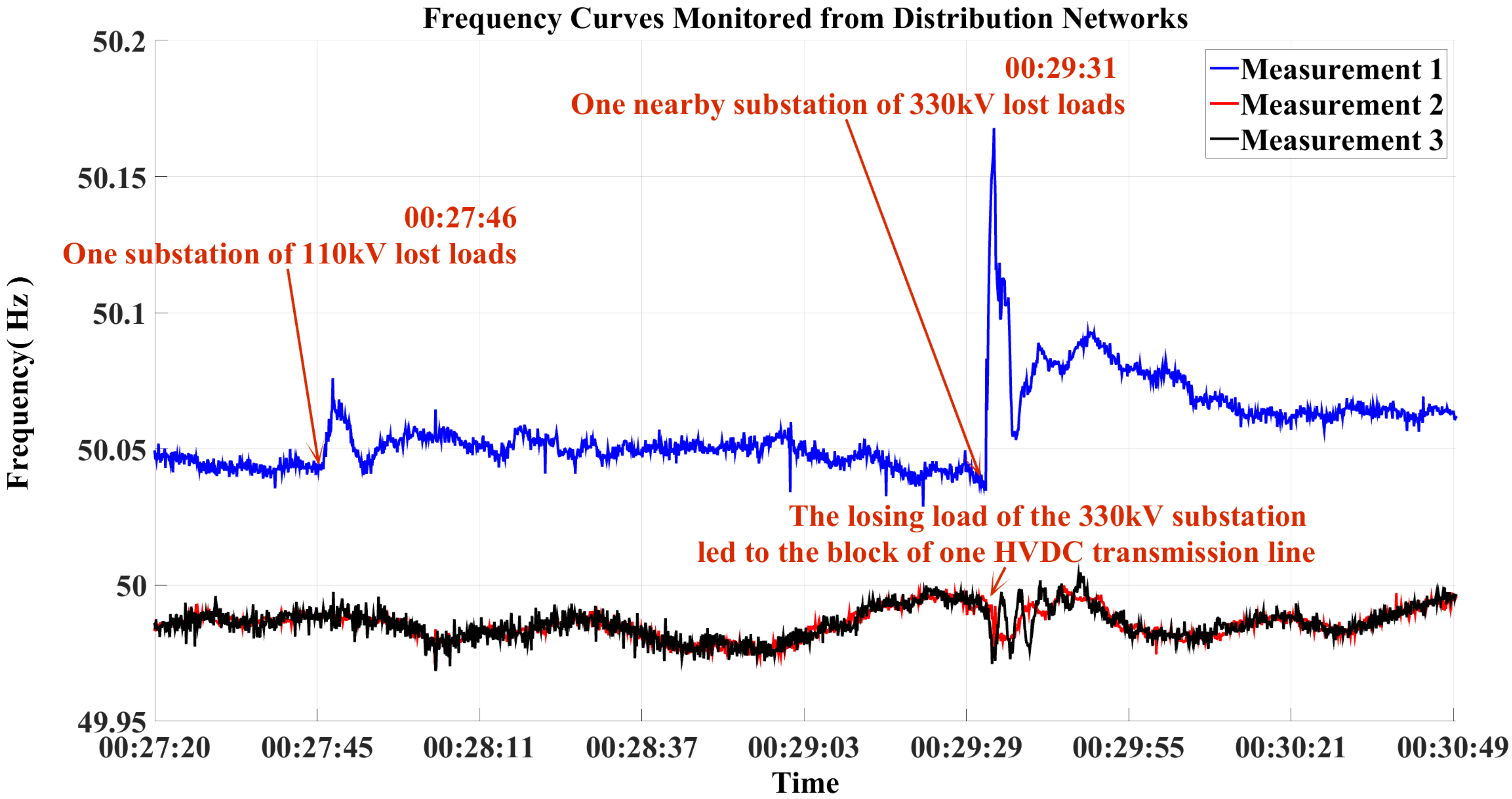
Applications of WAMS Light

◆ Monitor dynamics with major disturbances

Severe frequency disturbance

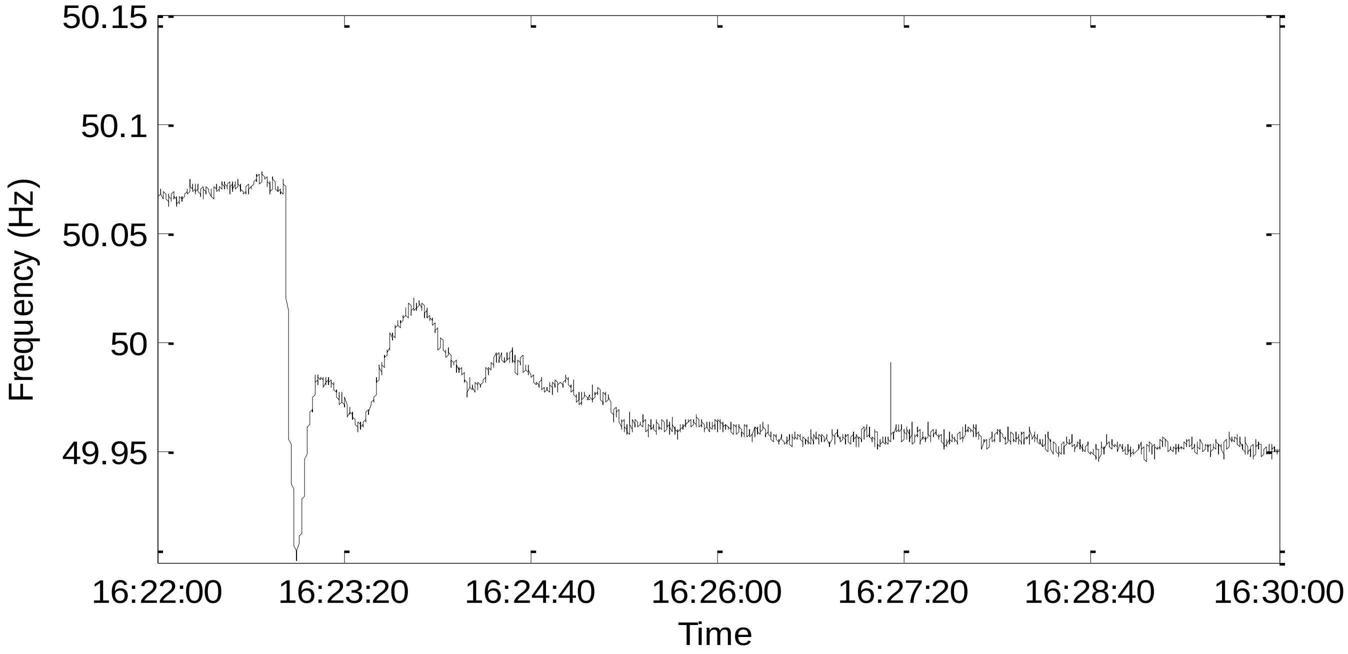


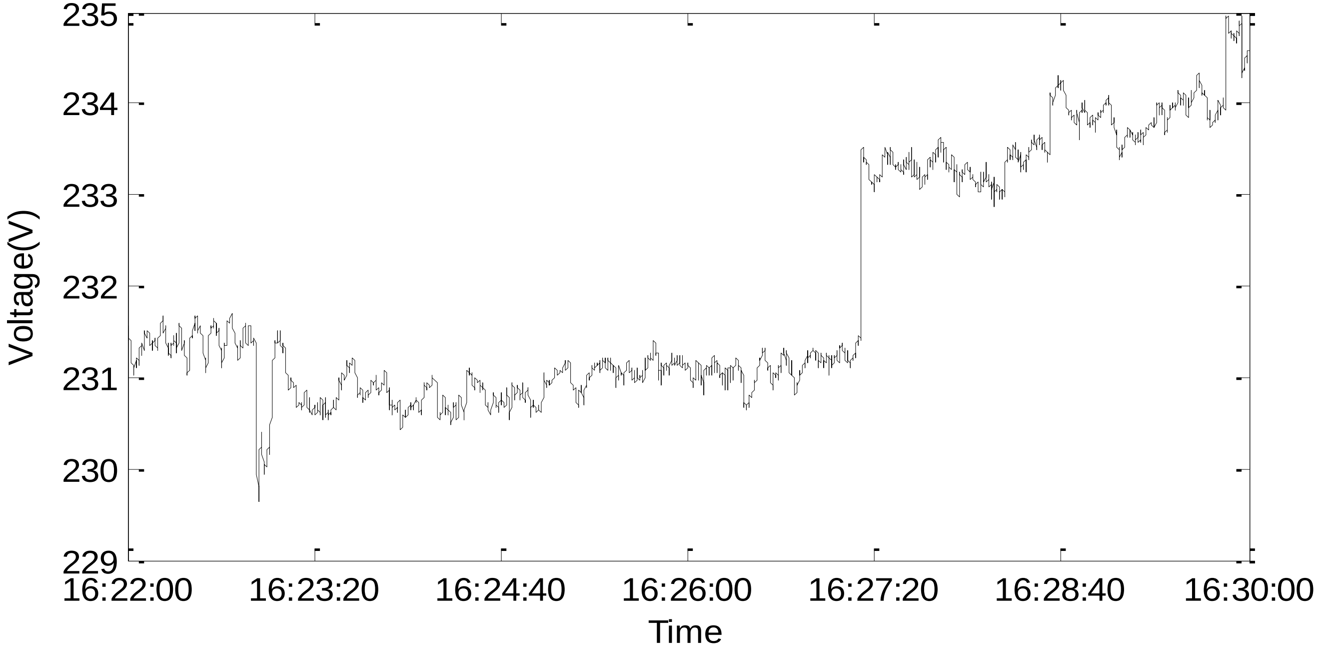
Driving force of synchronous monitoring at LV side



This event indicated that there is a risk of dynamic propagating from LV network to transmission system, even threatening the inter-area stability.

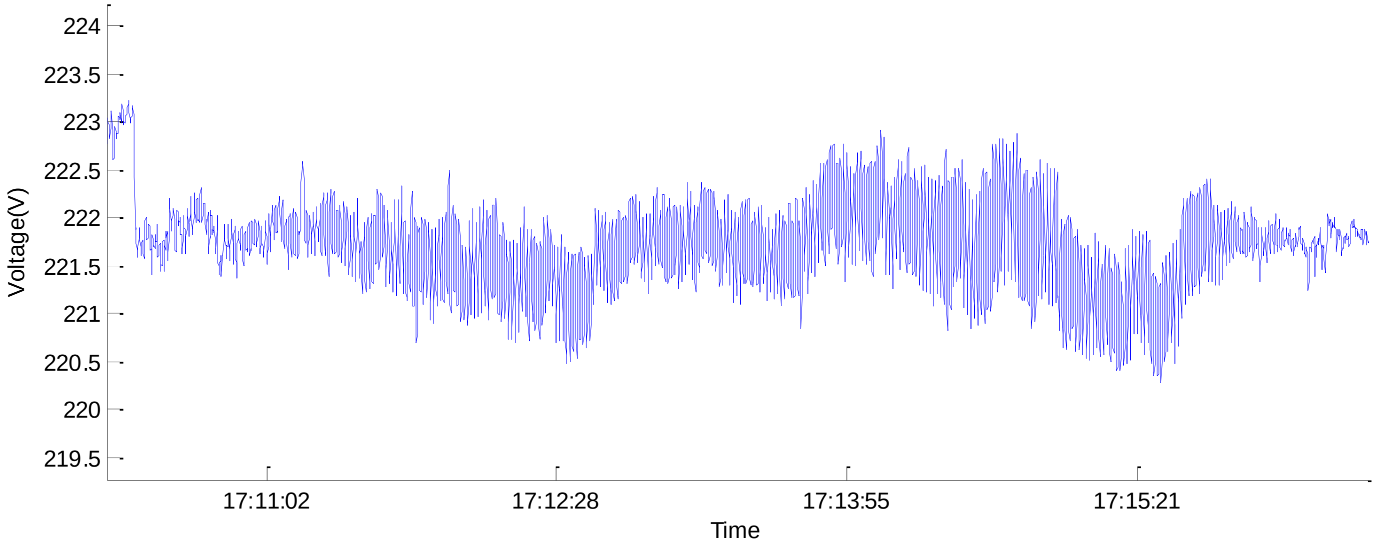
Disturbance recording: ±800kV Ultra-HVDC monopole blocking

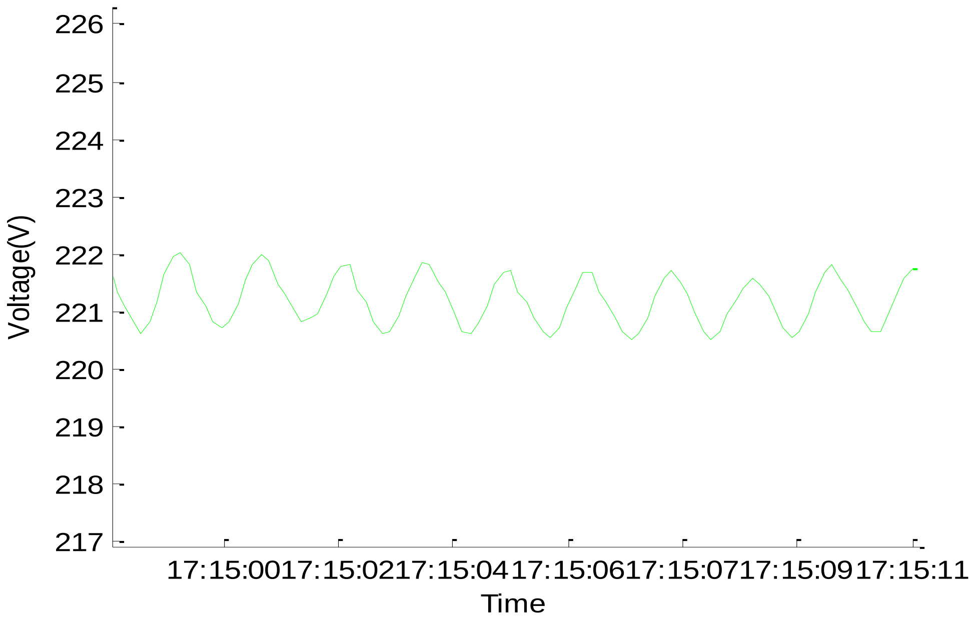


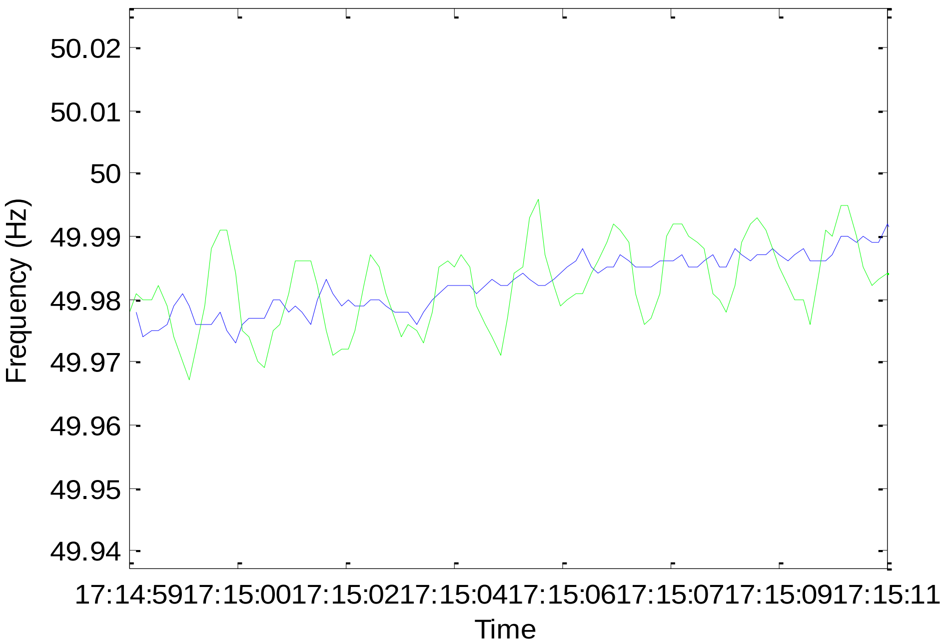


Recorded by PMU Light in Nanning

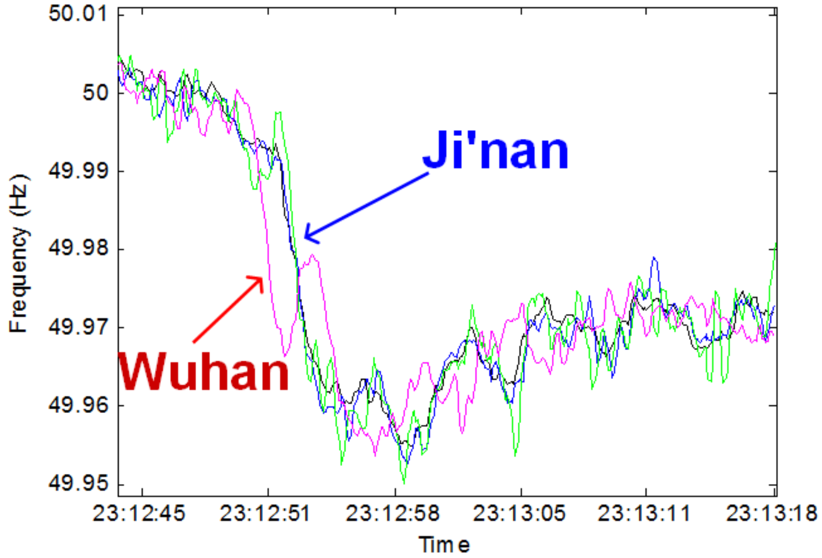
Online low frequency oscillation detection

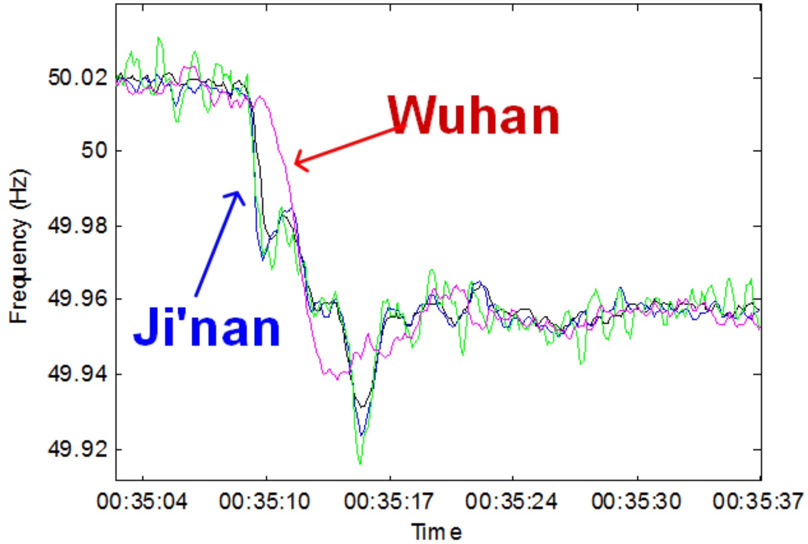






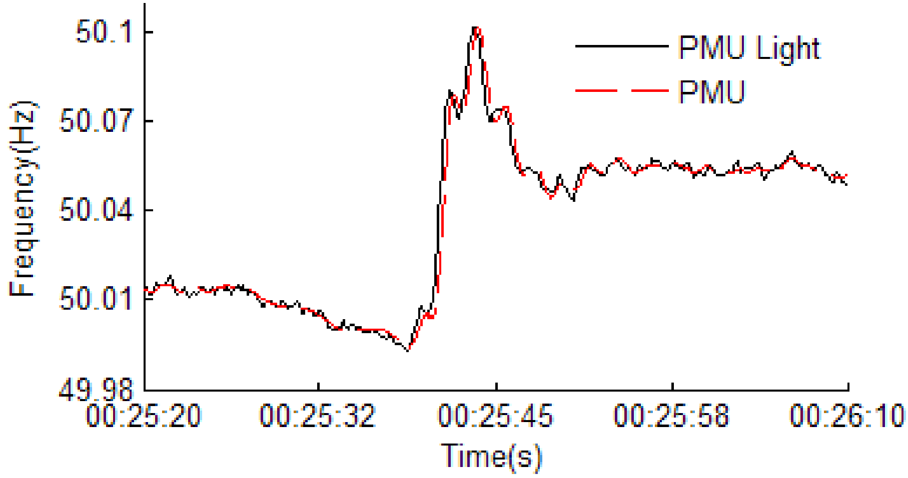
Space-time distribution of frequency dynamics

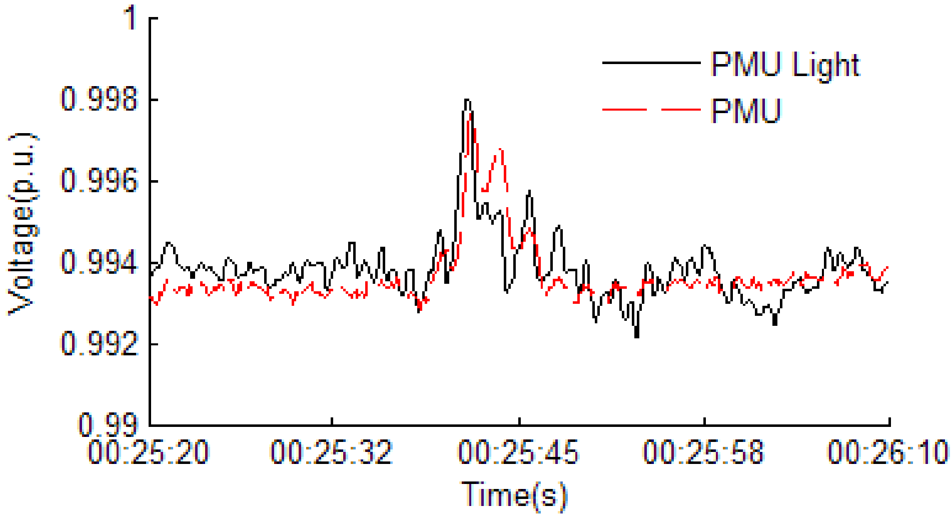


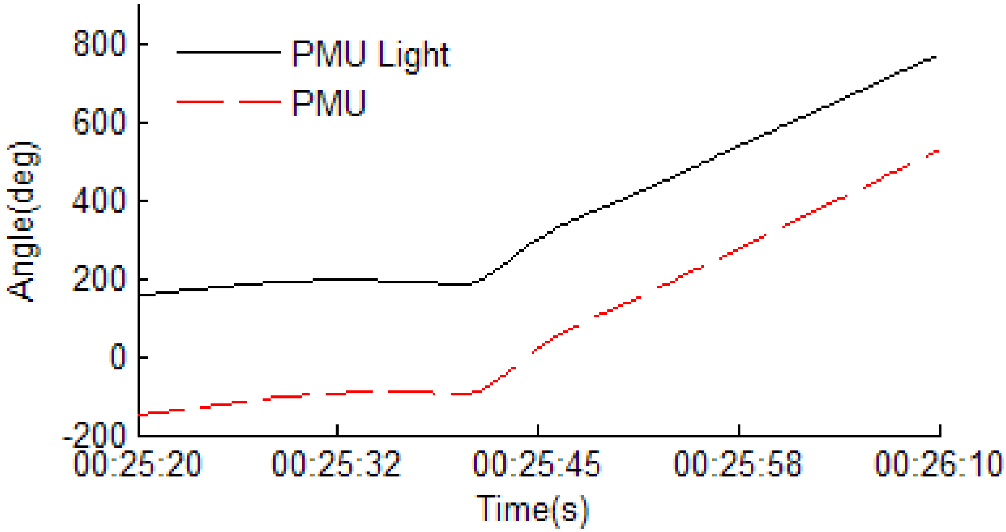


Frequency response pattern identification based deep-learning (ongoing work)

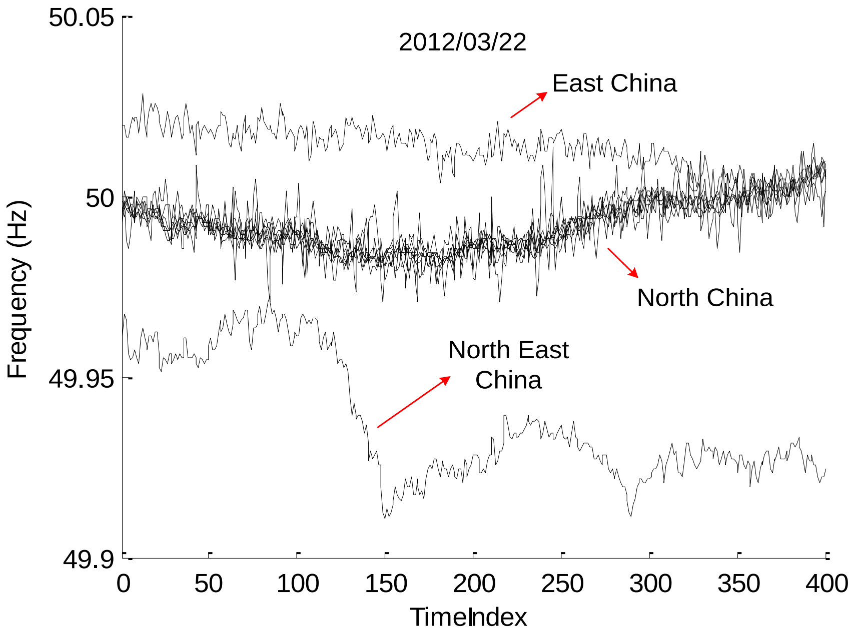
Line trip event can be detected by PMU Light even 1000km away

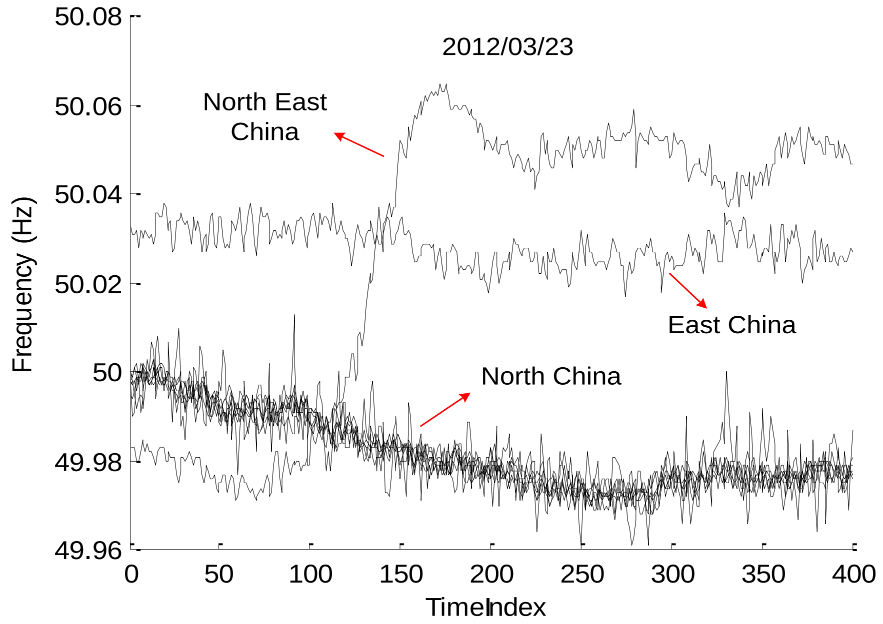


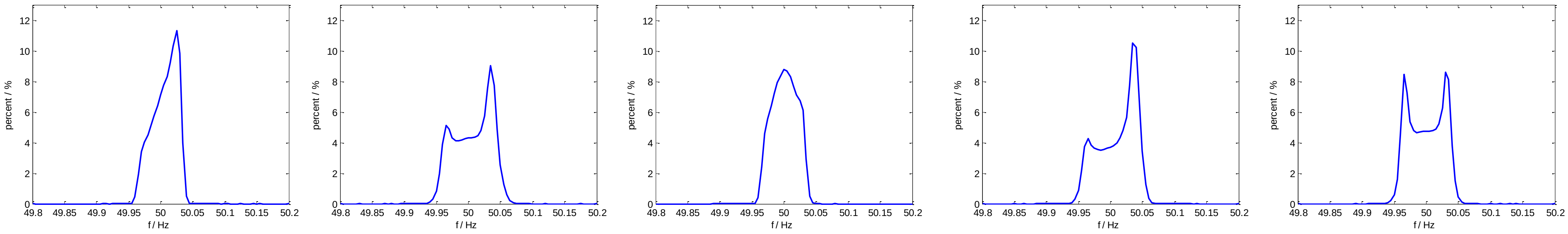




Statistical analysis of frequency regulation

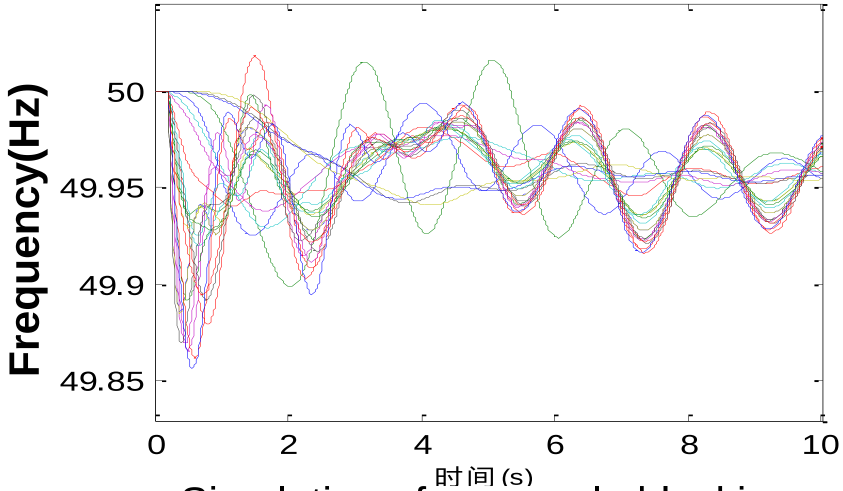






Model validition

Numerical simulation

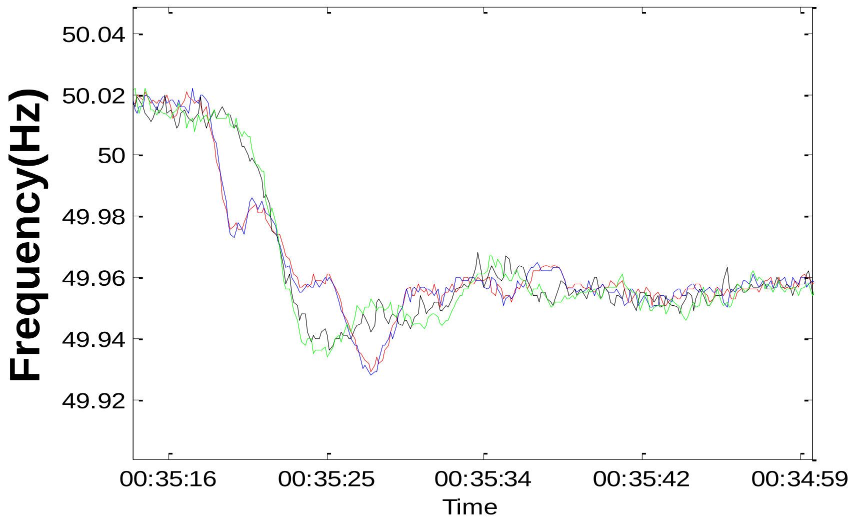


Simulation of monopole blocking

Model Validiton

Monitor dynamics with major disturbances

Measured dynamics



Measurement of monopole blocking

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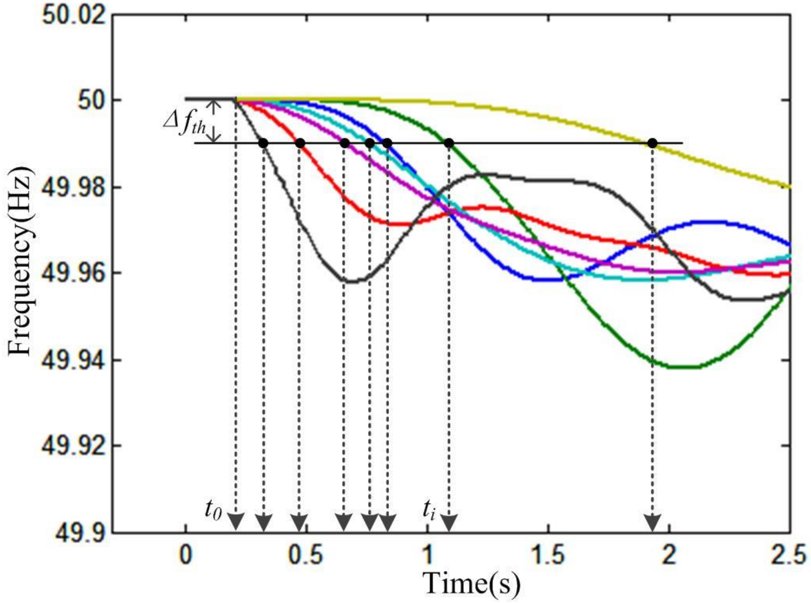
Disturbance location problem

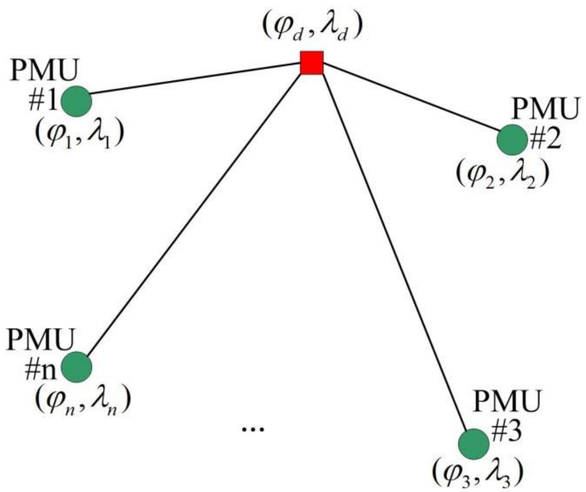
- Large disturbance in a power system can be observed system-widely, e.g., with frequency at different locations



Problem: How to estimate the disturbance location with measured frequency response?

Disturbance location estimation model (Reference)

- Assumption: uniform frequency propagation speed



$$\begin{cases} (x_1 - x_d)^2 + (y_1 - y_d)^2 - v^2(t_1 - t_d)^2 = 0 \\ (x_2 - x_d)^2 + (y_2 - y_d)^2 - v^2(t_2 - t_d)^2 = 0 \\ \cdots \\ (x_n - x_d)^2 + (y_n - y_d)^2 - v^2(t_n - t_d)^2 = 0 \end{cases}$$

$$F = \sum_{i=1}^{n}((x_i - x_d)^2 + (y_i - y_d)^2 - v^2(t_i - t_d)^2)^2$$

$$\begin{aligned} s.t. \quad & x_{\min} < x_d < x_{\max} \\ & y_{\min} < y_d < y_{\max} \\ & 0 < t_d < t_i, \quad \forall i \in \{1, 2, \ldots, n\} \end{aligned}$$

- In fact, frequency deviation propagates to different locations at different speeds.
- Problem: How to improve the disturbance location with the anisotropy of FPS?

Improved disturbance location estimation model

$$\begin{cases} (x_1 - x_d)^2 + (y_1 - y_d)^2 - v^2(t_1 - t_d)^2 = 0 \\ (x_2 - x_d)^2 + (y_2 - y_d)^2 - v^2(t_2 - t_d)^2 = 0 \\ \cdots \\ (x_n - x_d)^2 + (y_n - y_d)^2 - v^2(t_n - t_d)^2 = 0 \end{cases}$$

$$\begin{cases} (x_1 - x_d)^2 + (y_1 - y_d)^2 - v_1^2(t_1 - t_d)^2 = 0 \\ (x_2 - x_d)^2 + (y_2 - y_d)^2 - v_2^2(t_2 - t_d)^2 = 0 \\ \cdots \\ (x_n - x_d)^2 + (y_n - y_d)^2 - v_n^2(t_n - t_d)^2 = 0 \end{cases}$$

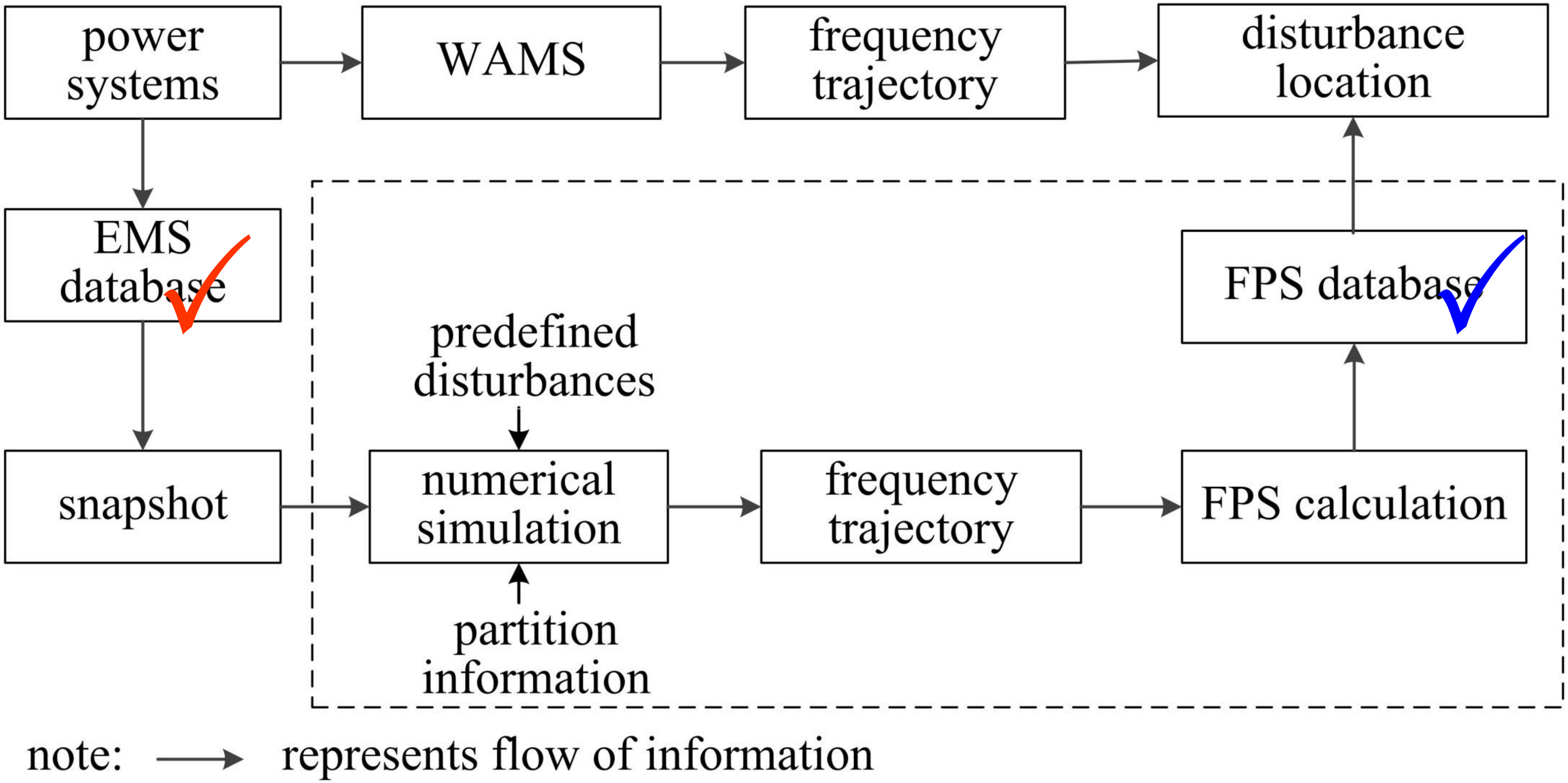
$$F = \sum_{i=1}^{n} ((x_i - x_d)^2 + (y_i - y_d)^2 - v_i^2(t_i - t_d)^2)^2$$

$$\begin{aligned} s.t. \quad & x_{\min} < x_d < x_{\max} \\ & y_{\min} < y_d < y_{\max} \\ & 0 < t_d < t_i, \quad \forall i \in \{1, 2, ... n\} \end{aligned}$$

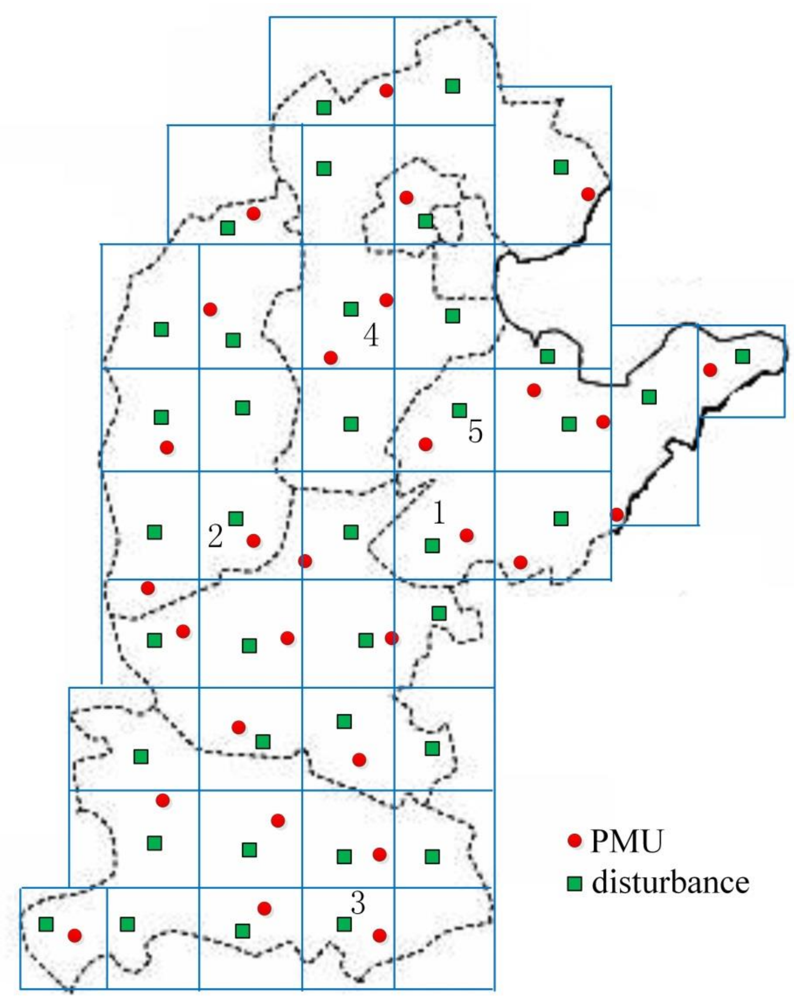
under-determined equations

Adaptive online disturbance location

The key issue is the FPS database is changing.

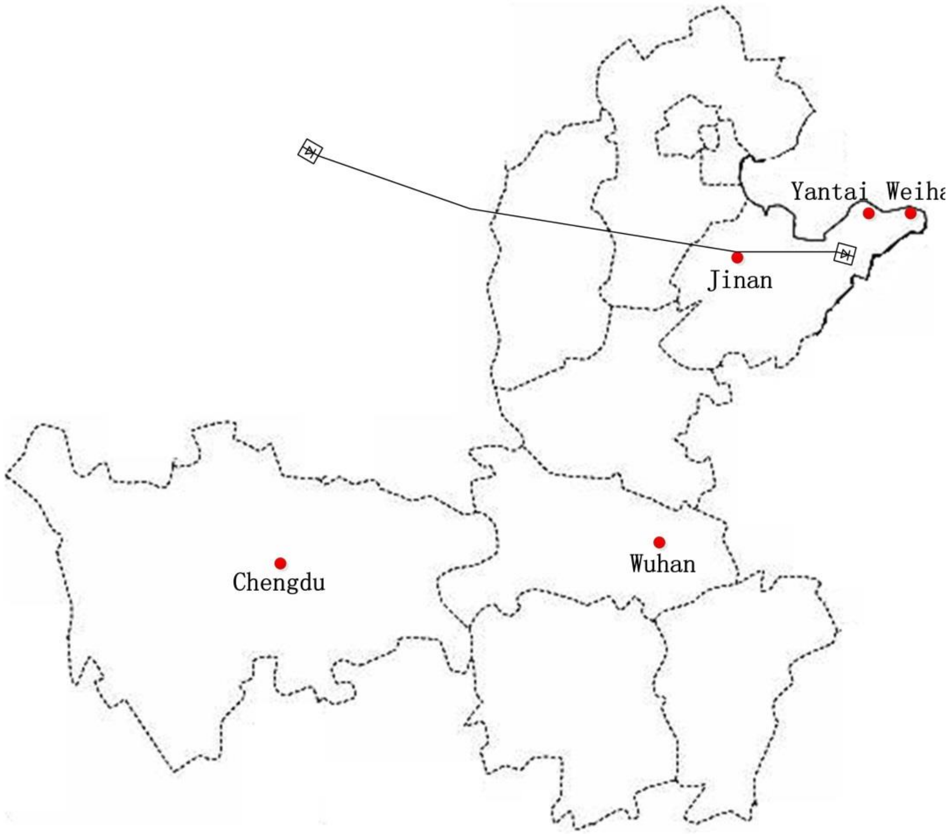


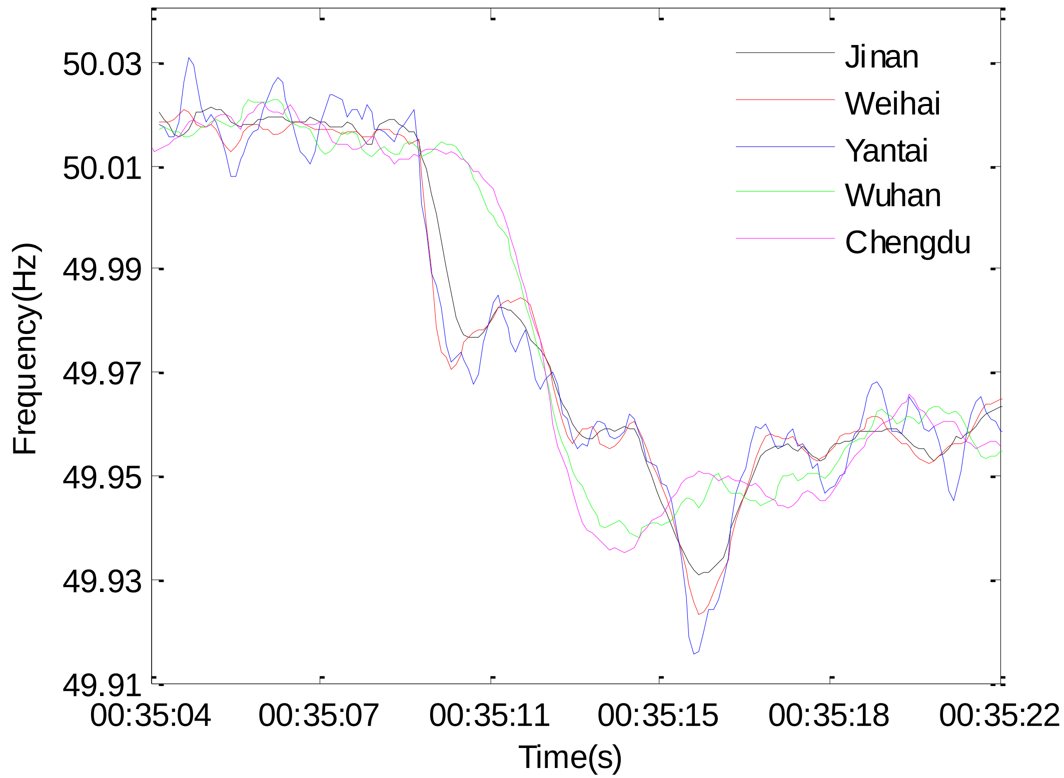
Simulation of North and Central China Power Grid



Case Index	Improved model		Old model	
	Location error (km)	Relative error (%)	Location error (km)	Relative error (%)
1	27.9	1.74	66.4	4.15
2	30.3	1.89	89.1	5.57
3	35.6	2.23	81.7	5.11
4	21.5	1.34	65.8	4.11
5	29.6	1.85	73.5	4.59

Measuremend data of HVDC monopole blocking





Improved model		Old model	
Location error (km)	Relative error (%)	Location error (km)	Relative error (%)
45.3	2.27	131.2	6.56

Adaptive Online Disturbance Location Considering Anisotropy of Frequency Propagation Speeds. IEEE Trans. on Power Systems, 2016

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Ongoing works on WAMS Light

- Improving the hardware and software systems
- Low frequency oscillation monitoring and early warning
- Distribution network fault diagnosis based on synchronous data
- Synchronous data visualization
- Data driven knowledge learning and distribution power system analysis and control

Thanks for your attention!
Questions?