Situational awareness through WAMS

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India – The energy future

	Population (millions)	TPES (toe/capita)	Electricity (kWh per capita)	CO_2 Emissions (t CO_2 per capita)
World	6,761	1.80	2,730	2.34
OECD	1,225	4.28	8,012	2.30
Asia	2,209	0.66	721	2.16
Africa	1,009	0.67	561	1.38
United States	307	7.03	12,894	16.90
China	1,331	1.70	2,631	5.13
India	**1,155**	**0.58**	**597**	**1.37**

TPES: Total primary energy supply measured using metric tons of oil equivalent (toe)

In 2004-05, proportion of households electrified: rural – 55%, urban – 92%.

Fuel	Production (2007)	Years of Supply at 2007 Production Rate
Coal	457 million t	169
Lignite	34 million t	36
Oil	34 million t	23
Gas + Coal Bed Methane (CBM)	32 billion m^3	75

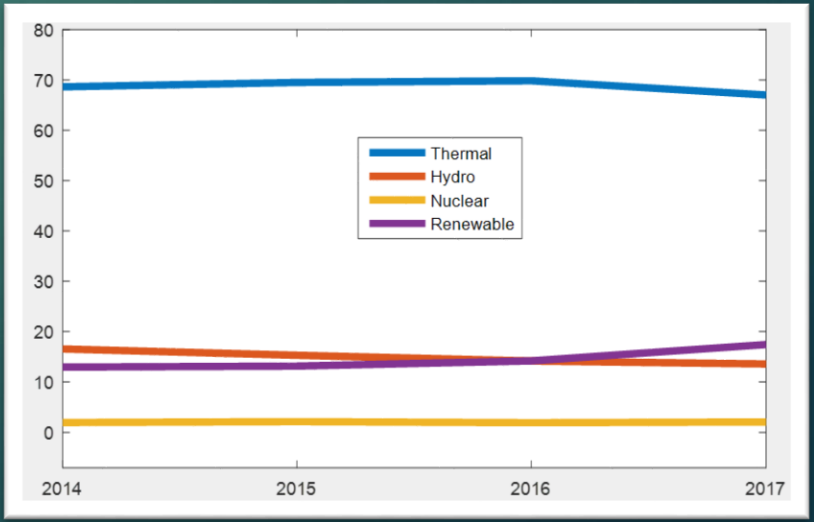
40 years, when rate of increase in consumption is factored in.

Nuclear	400–700 bkWh	Potential by 2030 depending on imports
Hydro	460 bkWh	Assuming full development of 150,000 MW
Wind	80–800 bkWh	Assuming full development of larger potential of 450,000 MW
Solar	6,000 bkWh	Assuming 10 million ha of land at current efficiency levels

3-stage nuclear power program. Vast Thorium reserves, require matured technologies to be useful.

Offshore potential not yet estimated. MNES estimates 45 GW at 20% PLF. Technology almost cost competitive today.

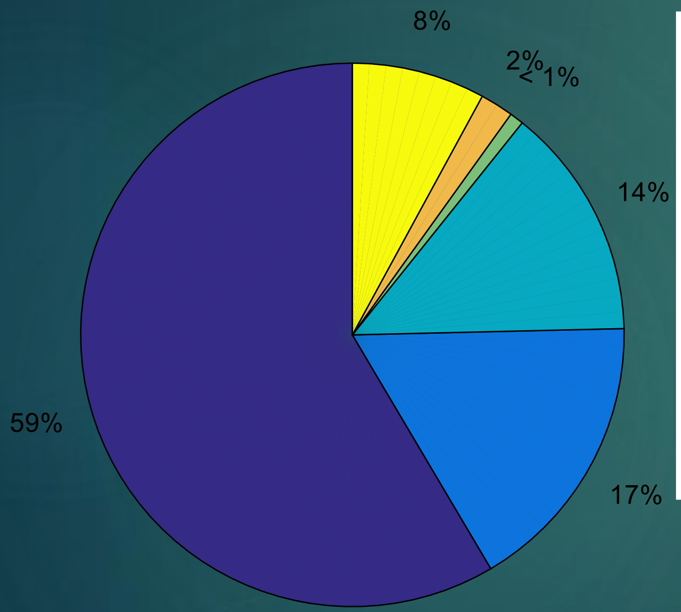
Costly technology. Enormous potential. Less variable than wind.

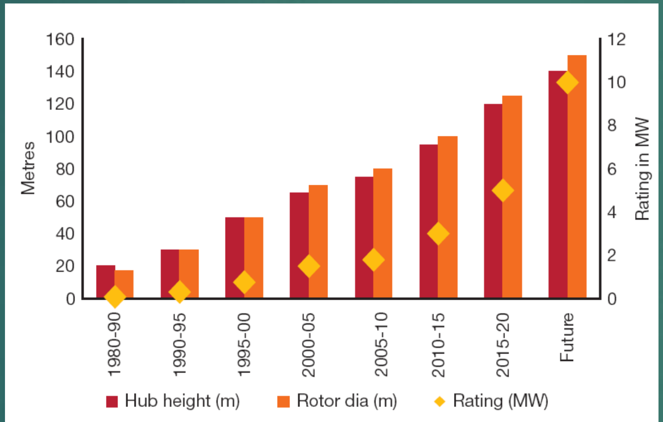


Source: *IEEE Power and Energy Magazine*, May/June 2012

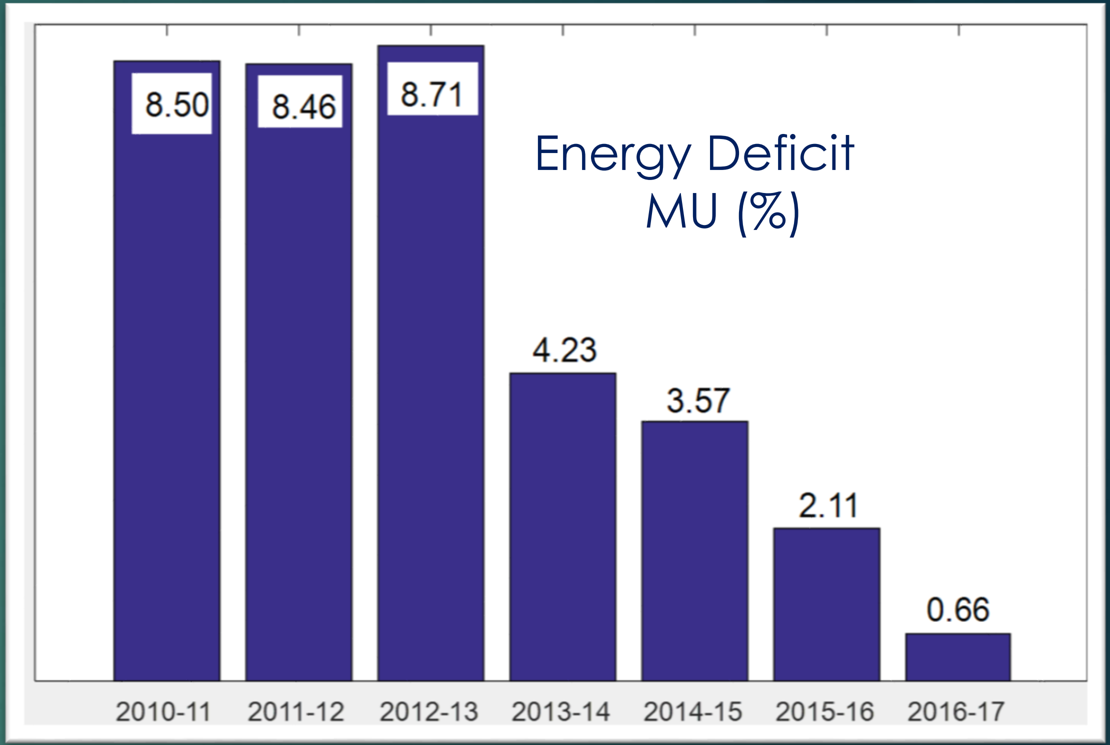
Current status– June 2017

Thermal	Renewable	Hydro	Nuclear	Total
194.4	57.3	44.6	6.8	326.8





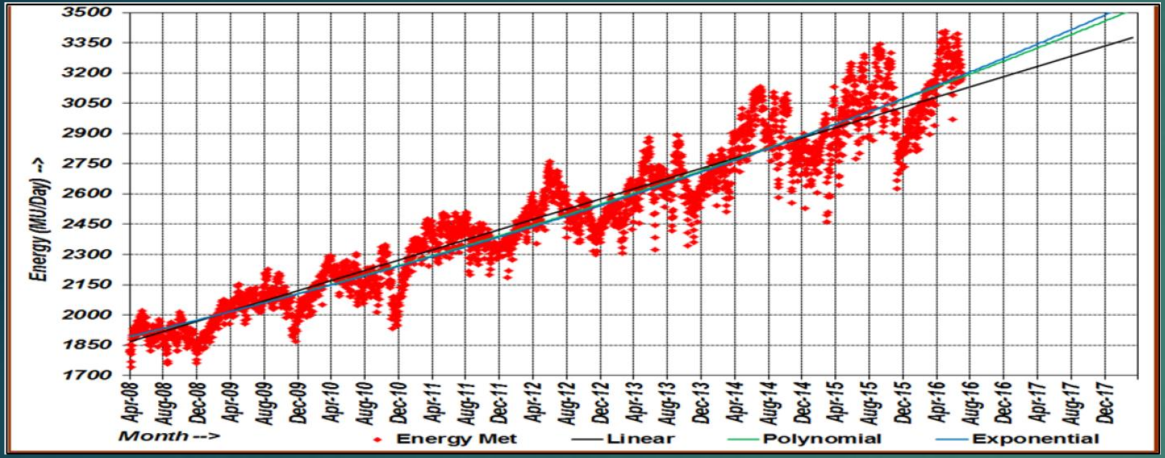
Source: Technology Roadmap–Wind Energy (2013 Edition), IEA; The Economics of Wind Energy, EWEA (2009)

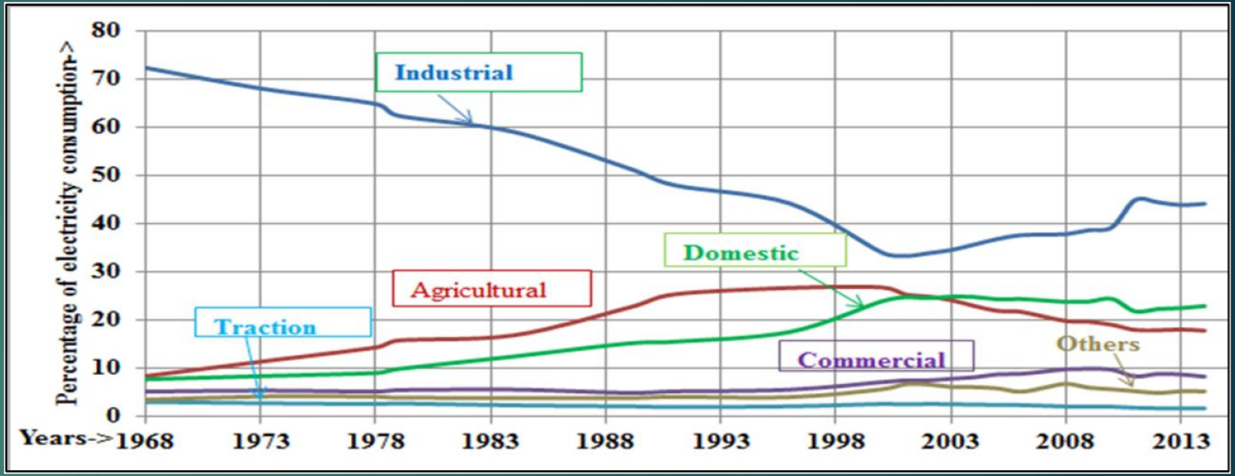


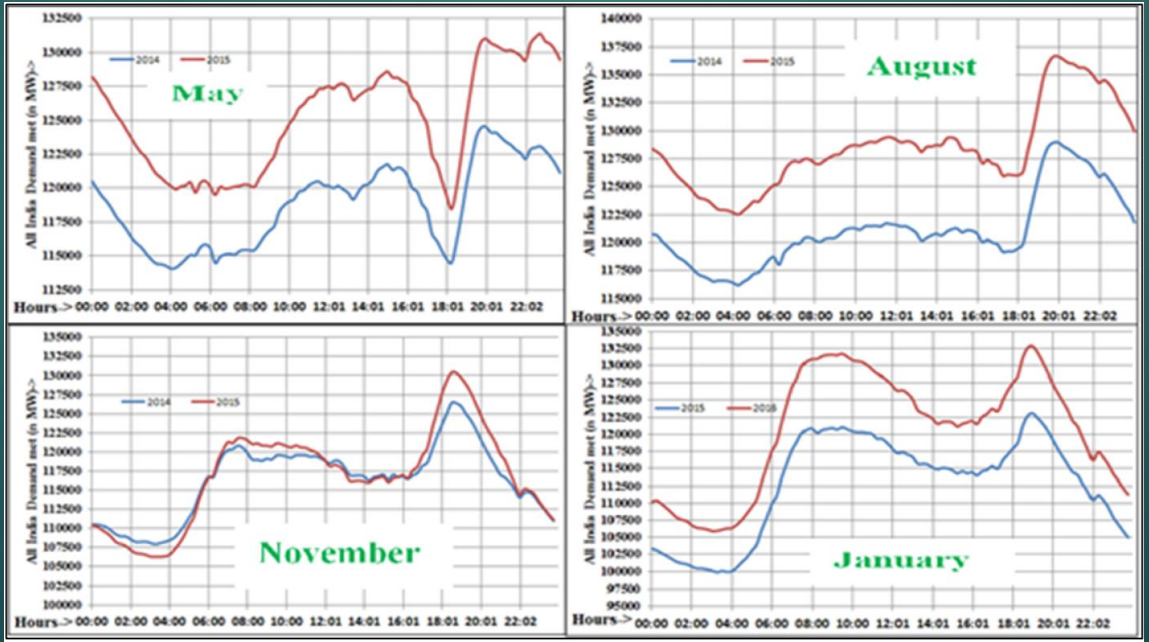
- RE forecasting, SCADA for RE, Scheduling of RE
- Testing of battery technology
- Green energy corridors
- Wide area measurement systems
- Automated metering infrastructure, DSM pilot projects

Source: *Central Electricity Authority 2016, PricewaterhouseCoopers India*

India – load growth







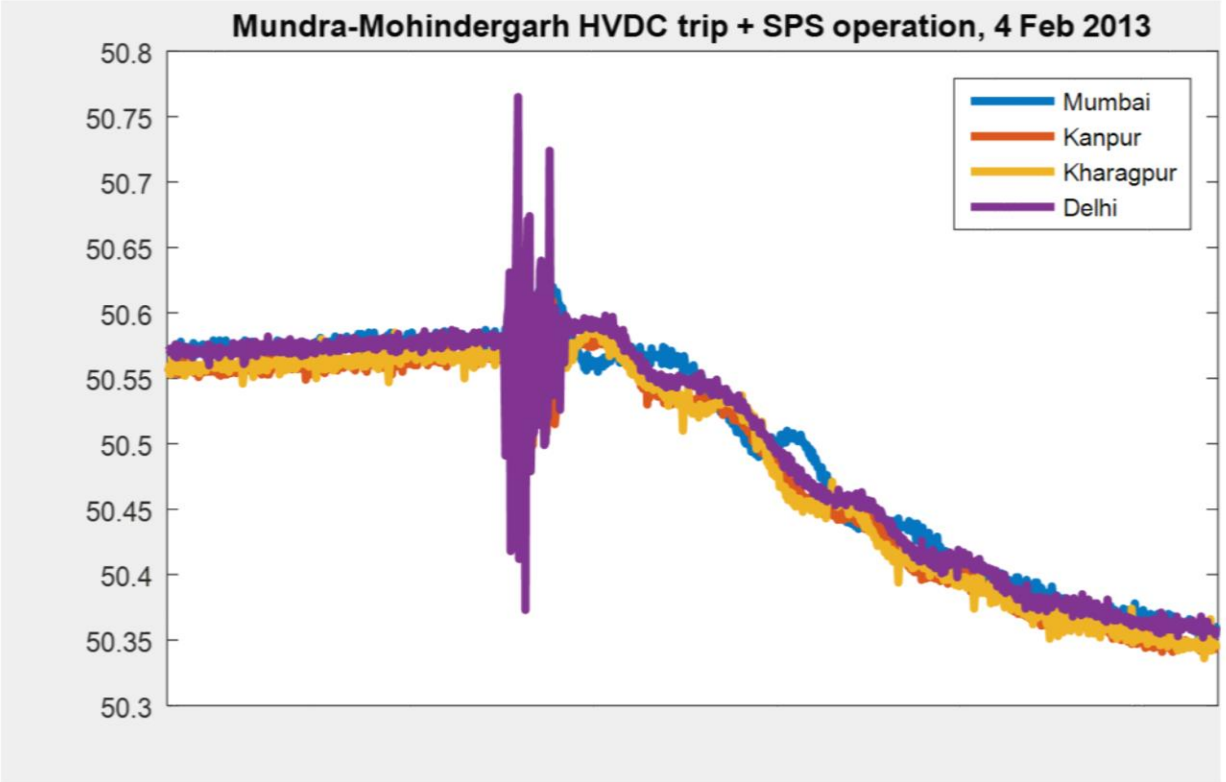
Source: POSOCO

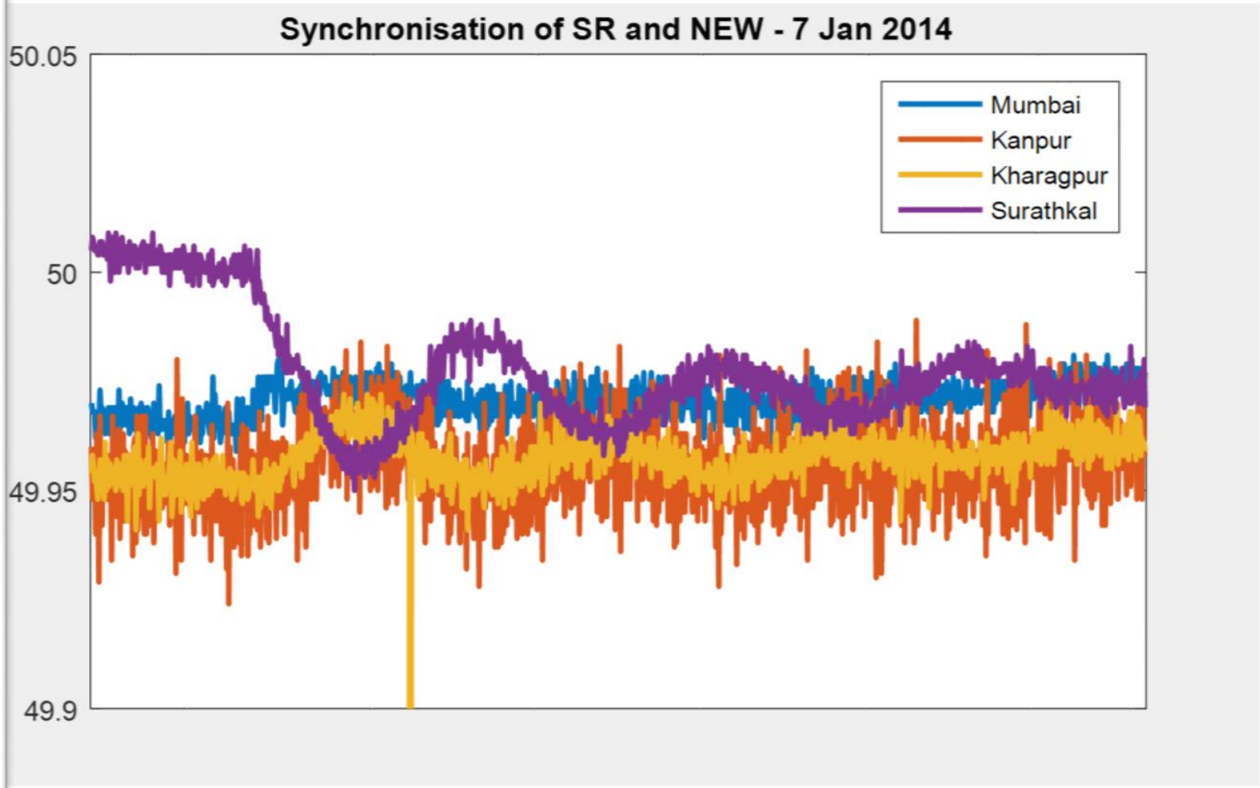
URTDSM project

- Placing PMUs on buses > 400 kV, generator connections at 220 kV etc.
- Phase 1 – 1600 PMUs, Phase 2 – 620 PMUs
- Immediate targets
  - Analysis of grid incidents
  - Detection and analysis of grid oscillations
  - Post despatch analysis
  - Enhancing situational awareness
- Future applications
  - Line parameter estimation
  - Vulnerability assessment of distance relays
  - Linear/dynamic state estimator
  - CT/CVT calibration
  - Supervision of zone-3 protection
  - Control schemes for grid security

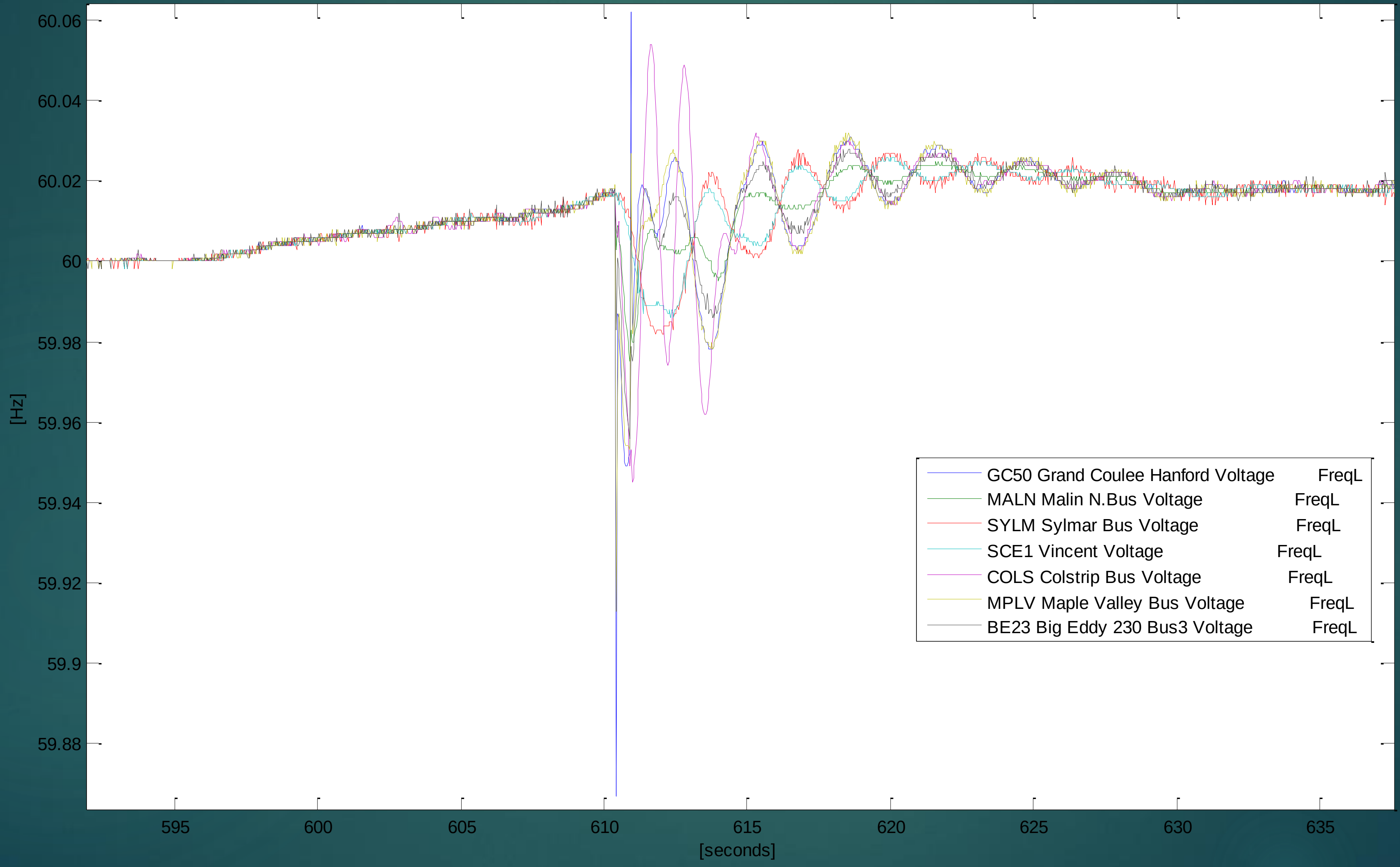
Source: URTDSM Report 2012, Synchrophasors Initative 2013 - POSOCO

WAMS data - India



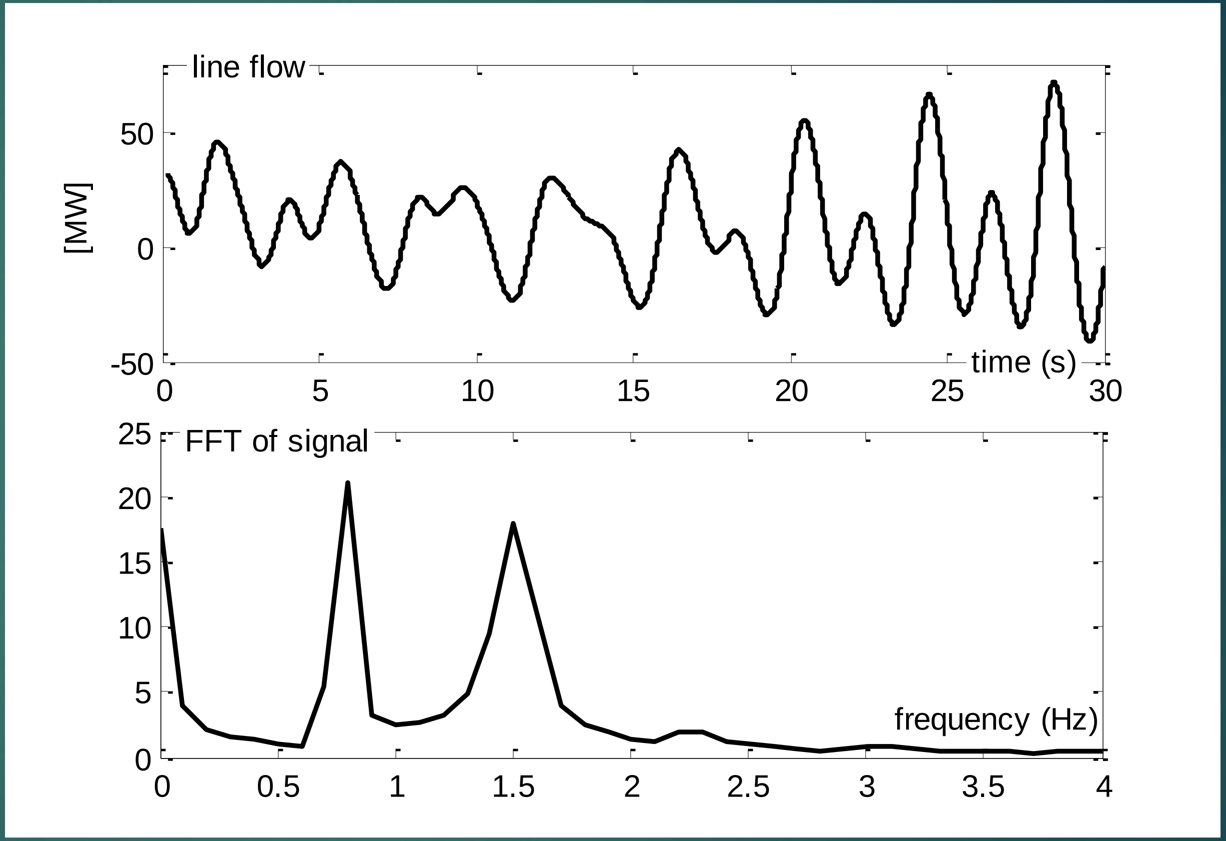


WAMS data - USA



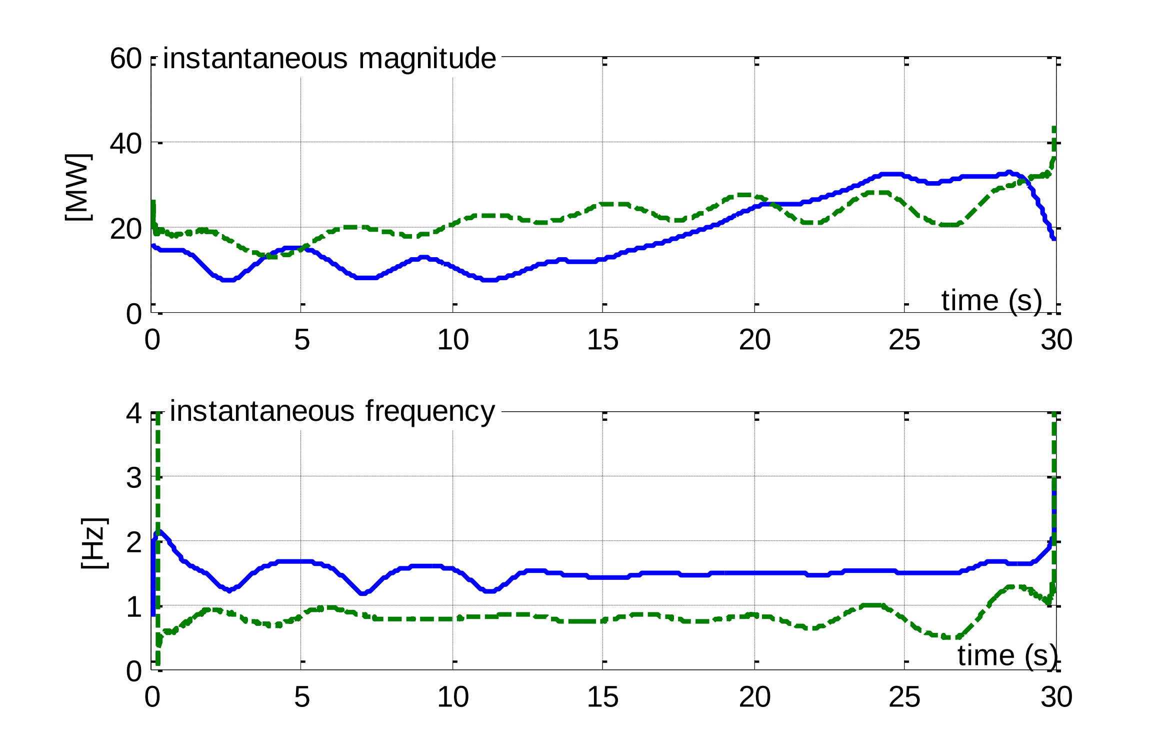
Mexican Power System

- Oscillations in the real power flow on the 230 kV MPD-MCD transmission line in response to tripping of Laguna Verde 650 MW unit.
- FFT reveals prominent modal frequencies at 1.5 and 0.8 Hz.

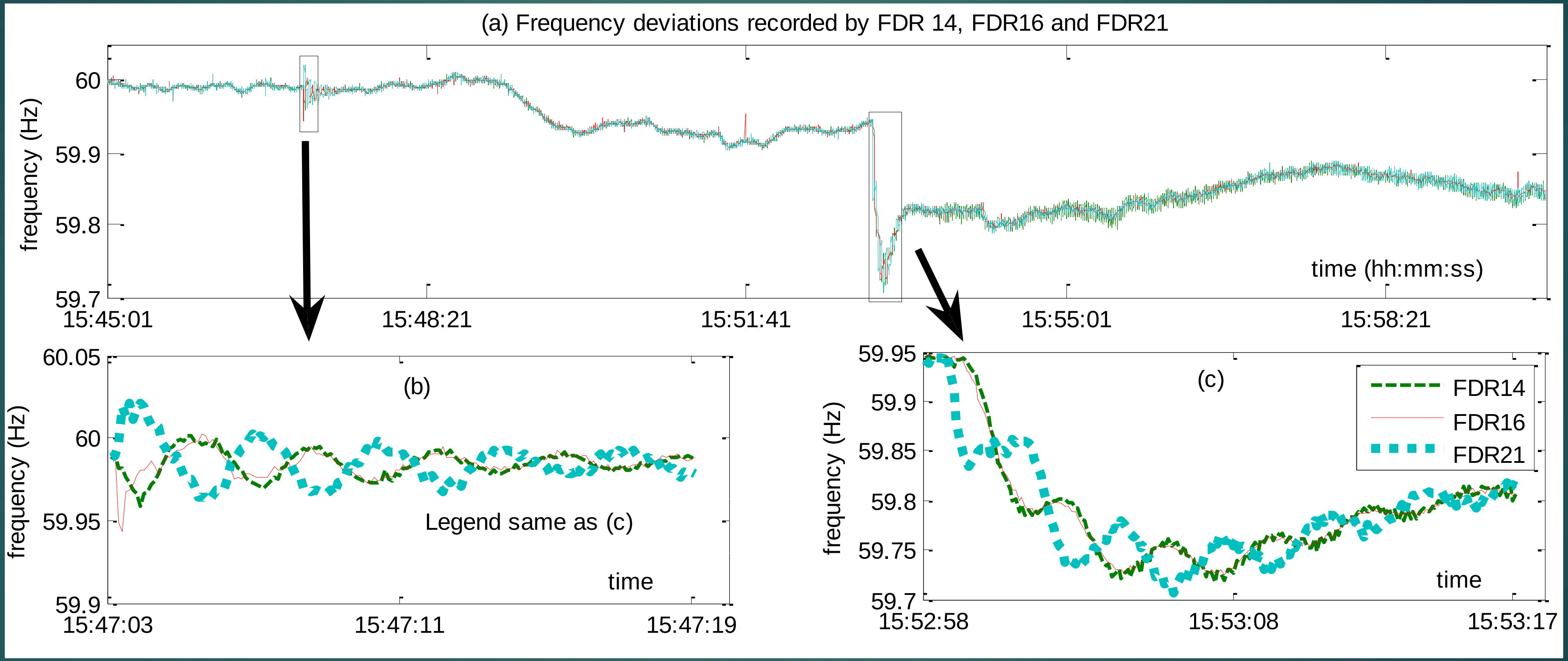


Mexican Power System

- Instantaneous frequency and amplitudes of the two most prominent modes extracted from oscillations in the line flow of the 230 kV MPD-MCD line.
- Note the monotonic rise in amplitude over time signifying undamped oscillations

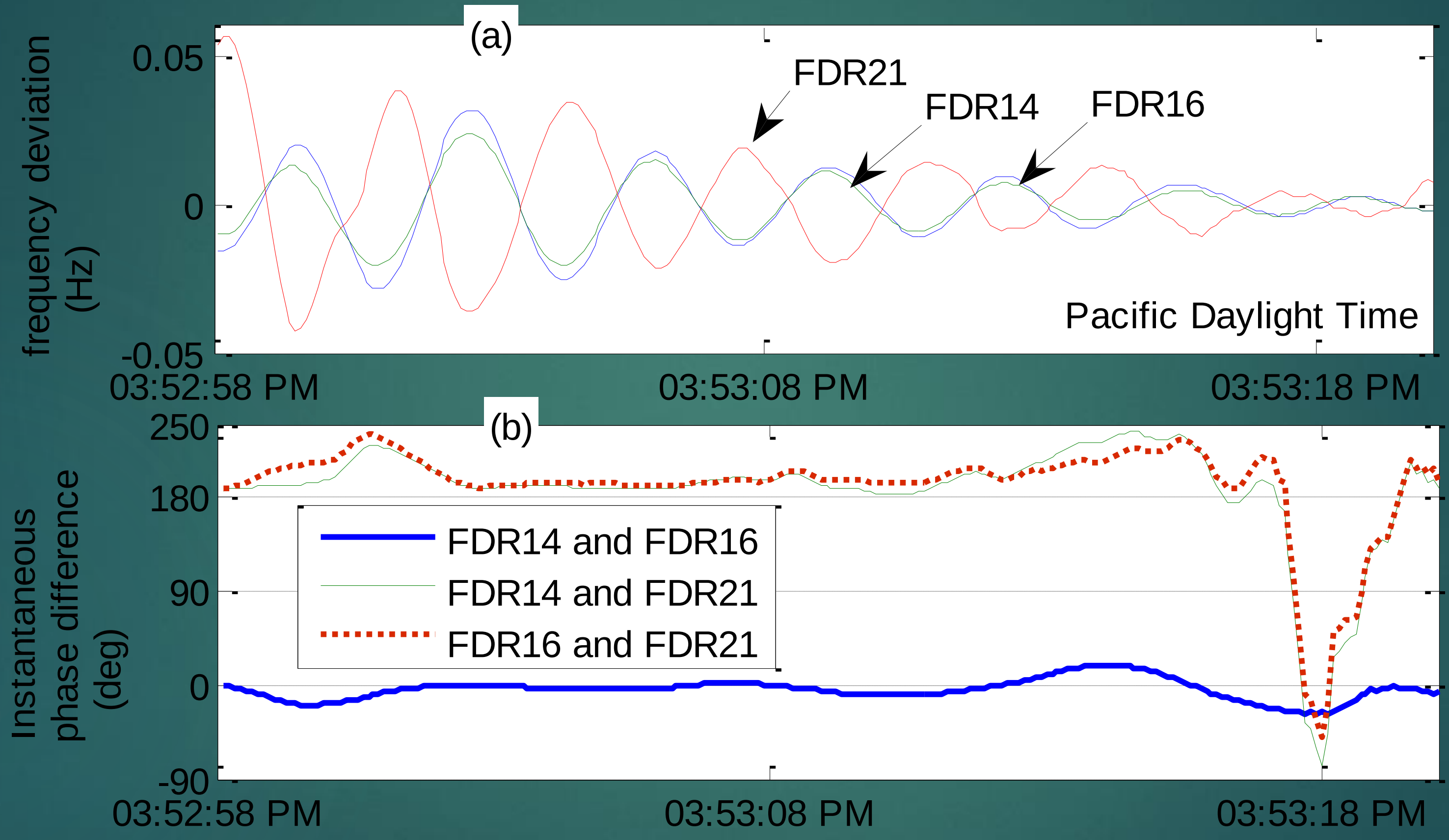


WAMS data – WSCC network



Source: N. Senroy, "Generator Coherency Using the Hilbert-Huang Transform," *IEEE Trans. Power. Sys.*, vol. 23, No. 4, pp. 1701-1708, June. 2008.

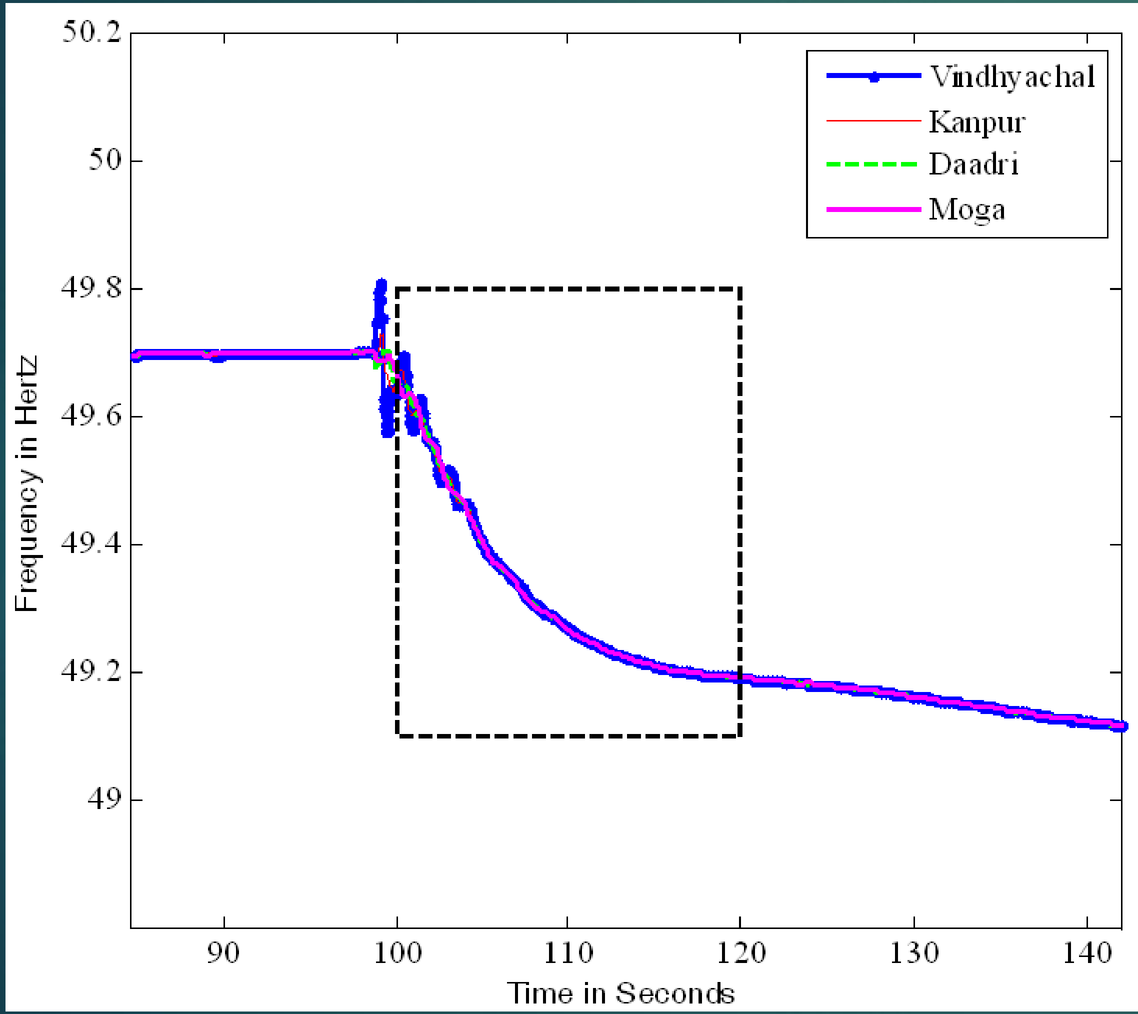
Instantaneous coherency

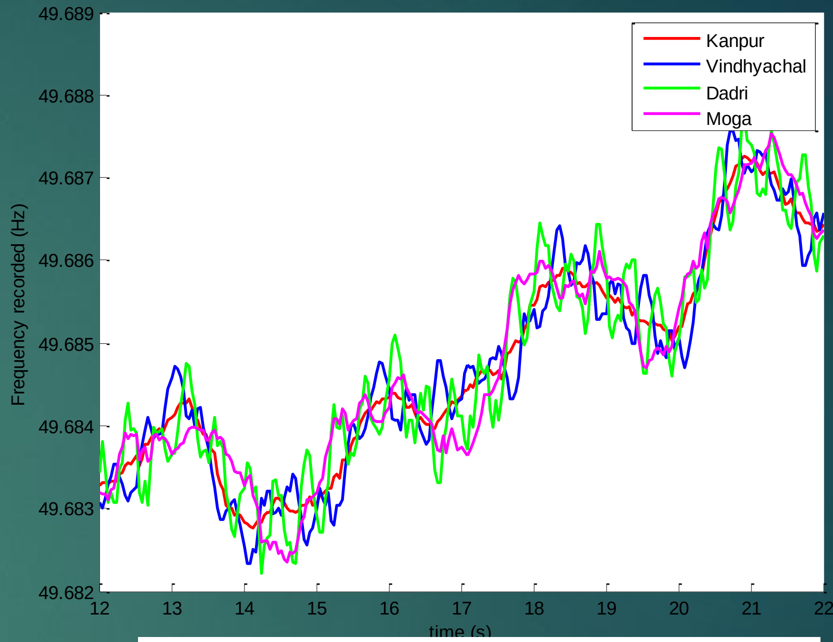


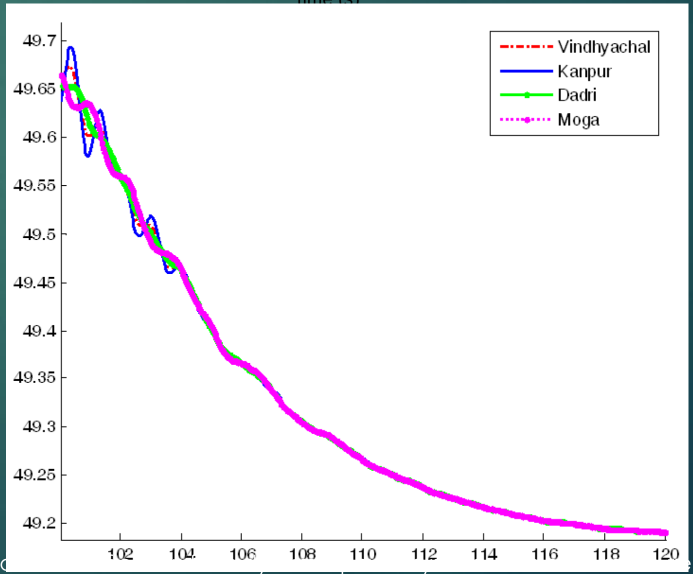
FDR14 (ASU) is coherent with FDR16 (Los Angeles).

Source: N. Senroy, "Generator Coherency Using the Hilbert-Huang Transform," *IEEE Trans. Power. Sys.*, vol. 23, No. 4, pp. 1701-1708, June. 2008.

Tripping of 2000 MW at Rihand STPS



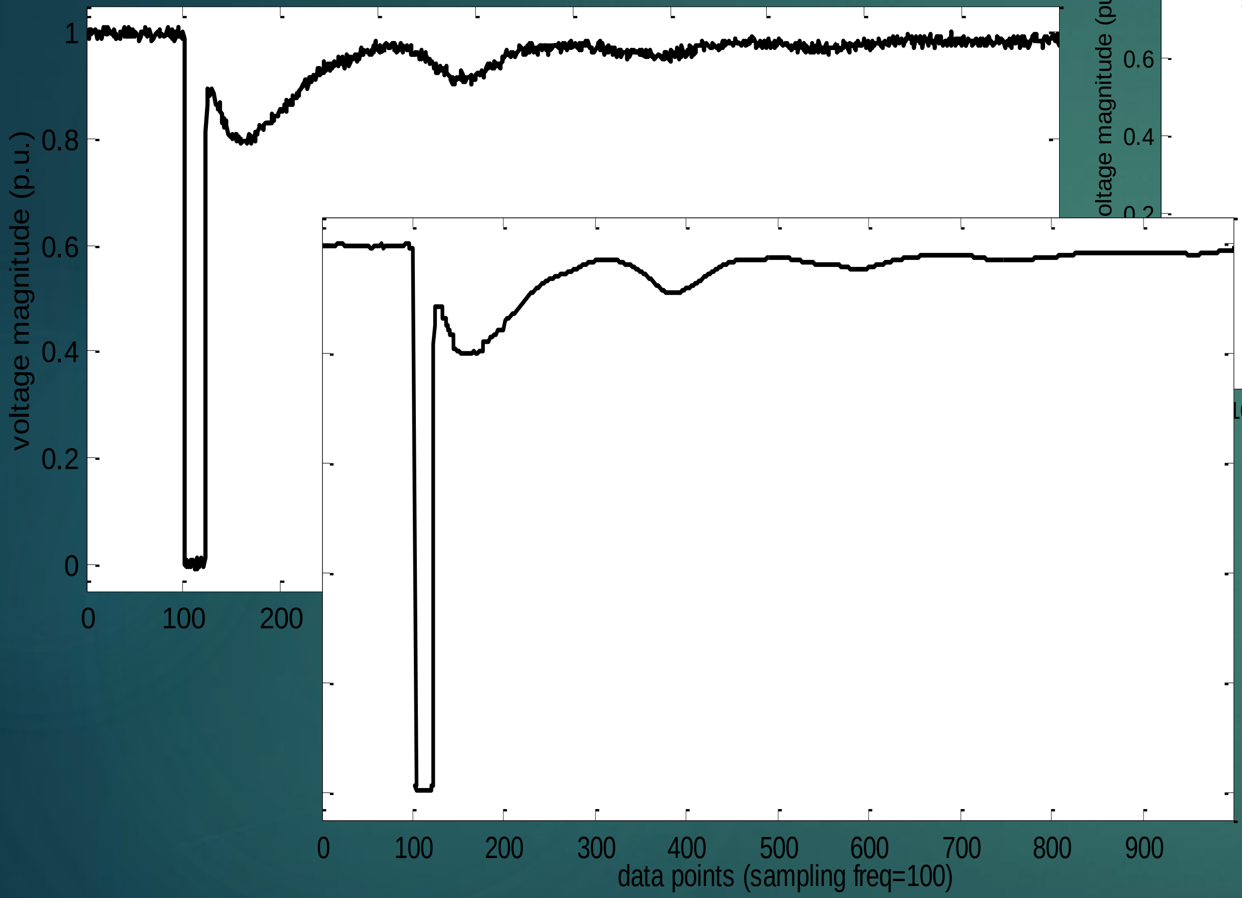


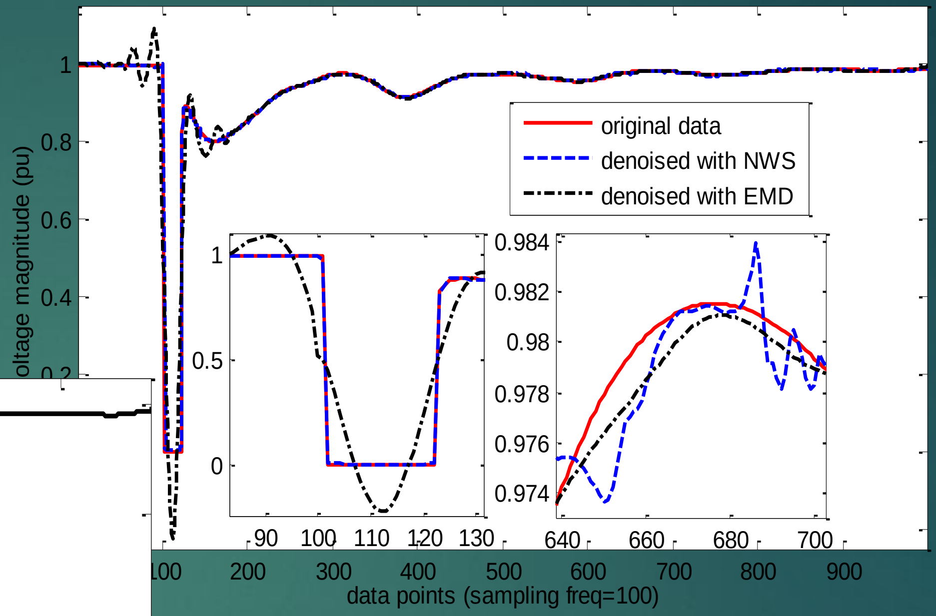


Source: A. Prince, N. Senroy, R. Balasubramanian, “Targeted approach to apply masking signal-based empirical mode decomposition for mo … ement signal data,” *IET Gen. Trans. Distr.*, vol. 5, No. 10, pp. 1025-1032, 2011.

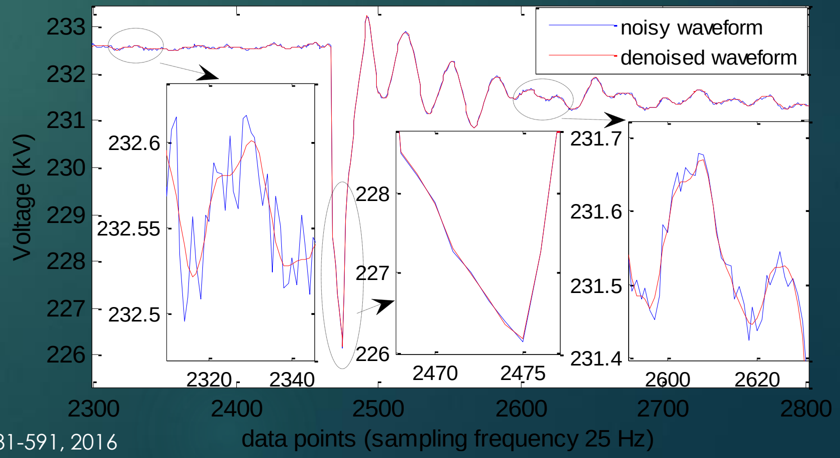
Denoising of PMU Data

- Sampling rate 100 Hz





- Sampling rate 25 Hz.



Source: P. Bhui and N. Senroy, “Application of Recurrence Quantification Analysis to Power System Dynamic Studies,” *IEEE Trans. Power Sys.*, vol. 31, No. 1, pp. 581-591, 2016

Online tripped line identification

- Proposed Method-
- Part 1: Probable Tripped Lines: The most probable tripped lines are ranked after a fault by comparing offline-stored and online-measured normalized kinetic energy gained by generators in 0.1s of the fault.
- Part 2: Exact Tripped Line- Consider a line as tripped and then calculate power output of generators, compare it with measured power. Repeat it for first few lines among the ranked ones to identify the exact tripped line.

$$\overline{KE} = [\overline{ke_1}\,\overline{ke_2}..\overline{ke_i}..\overline{ke_G}] = \frac{[ke_1 ke_2 \ldots ke_i \,..\, ke_G]}{\sum_{i=1}^{G} ke_i}$$

- Advantages of using normalized KE
  - Remains same for all types of faults, no need of identifying fault type.
  - Remains almost same for small variation in fault duration. Both stored and measured norm-KE are of duration 0.1 s. However, as norm-KE varies small with fault duration, it will reduce the impact of error in exact fault inception point.

Loading Condition Variation for Data Set Generation	Fault distance as % of line			
	50%		75%	
	Wrong identification	Average number of lines tested	Wrong identification	Average number of lines tested
0%	0/372	3.0403	0/372	3.0242
3% randomly	1/372	3.0645	1/372	3.0376
5% randomly	2/372	3.0914	2/372	3.1048
20% randomly	2/372	3.1720	2/372	3.1452
2.5% uniformly	1/372	3.0591	1/372	3.0323
5% uniformly	0/372	3.0699	0/372	3.0833
10% uniformly	1/372	3.1129	1/372	3.0887
20% uniformly	2/372	3.1989	2/372	3.1855

Impact of Load modelling

Percentage error between measured and calculated power of generators	Wrong identification
No error	0/34
0.5%	0/34
0.75%	0/34
1.1%	1/34
2.2%	2/34
2.5%	2/34

Source: P. Bhui and N. Senroy, "Online Identification of Tripped Line for Transient Stability Assessment," *IEEE Trans. Power Sys.*, vol. 31, No. 3, pp. 2214 - 2224, 2016

LQG based WADC:

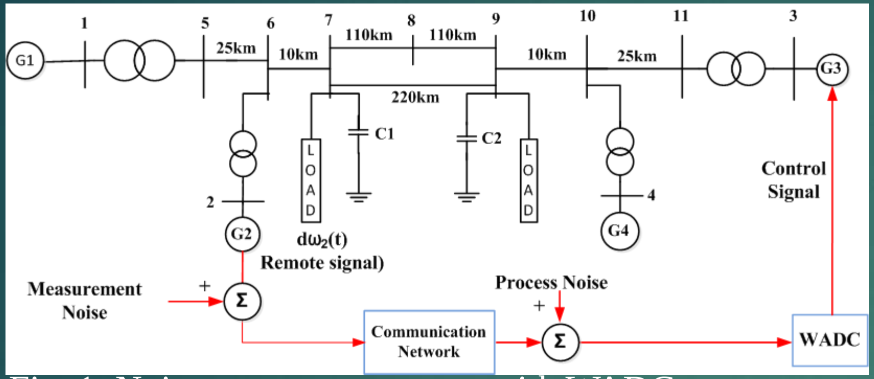


Fig. 1: Noisy test power system with WADC

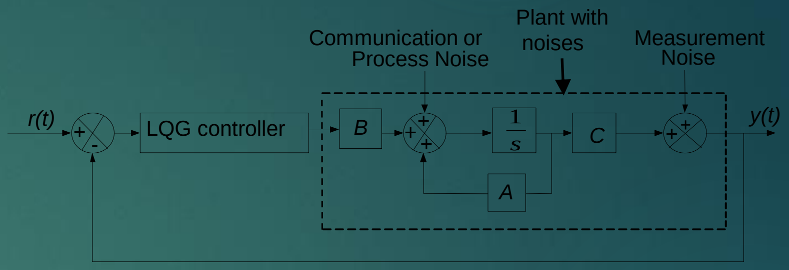


Fig. 2: LQG controller with Plant details

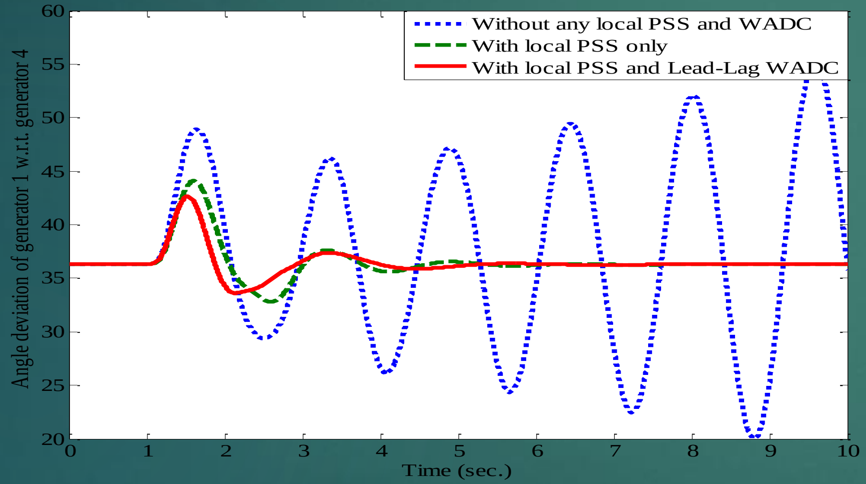


Fig.3: With and without lead-lag WADC, perfect medium

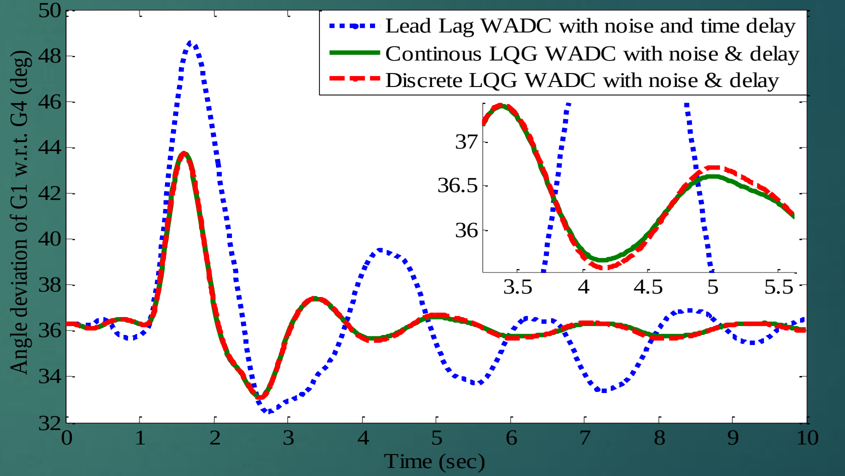


Fig. 4: With and without LQG controller, having time delay of 0.25 s and noise in remote signal

TABLE 1:

MODAL ANALYSIS OF SYSTEM(having perfect medium), WITH AND WITHOUT LEAD-LAG WADC

Mode	Without any PSS		With local PSS only		With local PSS & WADC	
	Freq. (Hz)	**Damp. factor**	Freq. (Hz)	**Damp. factor**	Freq. (Hz)	**Damp. factor**
Local 1	1.12	**0.09**	1.55	**0.29**	0.97	**0.46**
Local 2	1.15	**0.09**	1.63	**0.28**	1.67	**0.42**
Inter-area	0.64	**-0.03**	0.63	**0.23**	0.57	**0.34**

TABLE 2:

MODAL ANALYSIS OF SYSTEM(having noise and delay), WITH LQG CONTROLLER AS WADC

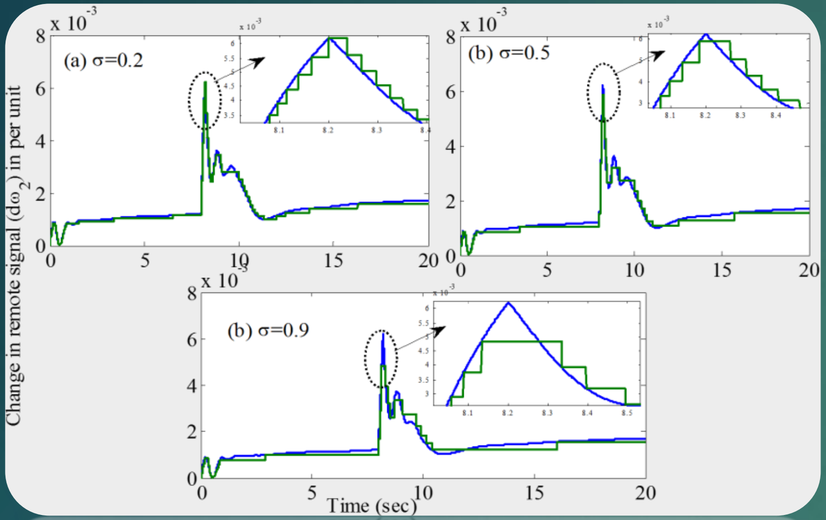
Mode	Continuous LQG		Discrete LQG	
	Freq.(Hz)	**Damping factor**	Freq.(Hz)	**Damping factor**
Local 1	1.56	**0.29**	1.56	**0.29**
Local 2	1.60	**0.30**	1.61	**0.30**
Inter-area	0.63	**0.25**	0.63	**0.25**

Source: M. Bhadu, N. Senroy, … ower System Damping Controller," *IET Gen. Trans. Dist.*, vol. 10, No. 6, pp. 1470 - 1478, 2016

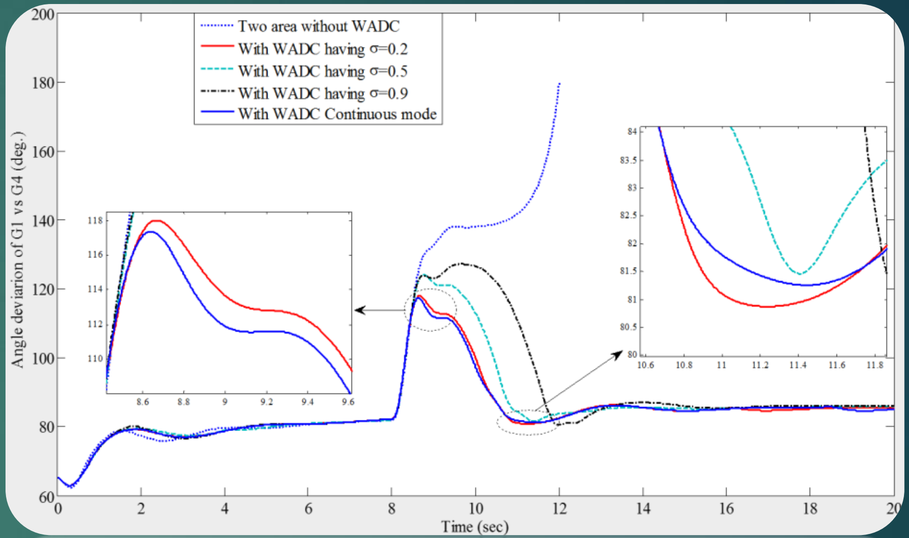
Delay Calculations

- Fixed delay
  - Delay due to processing, DFT, multiplexing and data concentration
  - Independent of communication medium used
  - Estimated to be around 75 ms
- Propagation delay
  - Function of the communication link and physical separation
  - Ranges from 25 ms in case of fiber-optic cables to 200 ms in case of low earth orbiting (LEO) satellites

Event triggered communication



Comparison of remote signal in continuous and discrete mode for different sigma's



Comparison of time domain response with various values of tuning parameter sigma

TABLE 1:

Comparison of the number of data samples communicated in the ET-WADC and continuous time WADC for different σ

σ	0.2	0.5	0.9
Continuous-time WADC	2000	2000	2000
ET-WADC	329	263	206

Source: M. Bhadu, N. S. Tripathy, I. N. Kar, and N. Senroy, "Event-triggered Wide-area Damping Controller for Inter-area Oscillations: A Limited Output Feedback Based Approach," *IET Gen. Trans. Dist.*, vol. 10, No. 6, pp. 4094 - 4104, 2016

Big data in smart grids

- Equipment reliability, asset management
- Forecasting
- Demand side management
- State estimation
- Online DSA
- Distribution metering
- Electric vehicles, distributed energy storage, roof top solar

Decision making framework

- Corrective: e.g. fault location, anomaly detection
- Predictive: load/resource forecasting, management of reserves
- Distributed: distributed monitoring and control infrastructure
- Adaptive: online DSA, power quality monitoring, load signatures
- Economic: power market operations, pricing

Challenges in developing big data analytics

- Data is noisy, latency issues
- Heterogeneous data
  - Flexible system architectures to handle such data
- Privacy and information security issues
- Sophisticated mathematical algorithms to handle high dimensionality, distributed data
  - Machine learning, clustering, classification
  - Linear/nonlinear optimization
  - Feature extraction
  - Outlier detection and handling
  - Dimensionality and model order reduction
- Electricity sector in India is over-regulated!
- Lack of skilled manpower

Thank you…

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