Real-Life Observations of Power System Dynamic Phenomena

Some Interesting Aspects

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and

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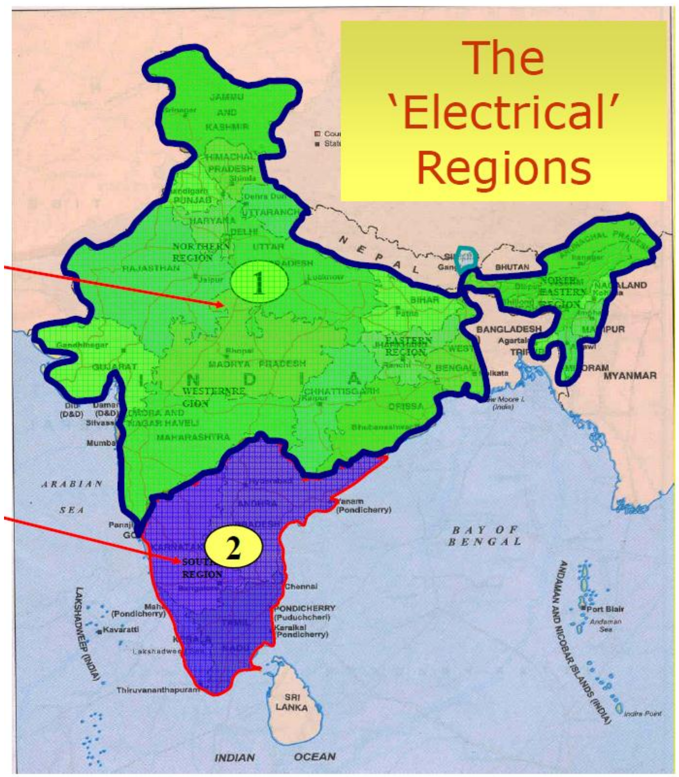
The Indian Grid

NEW grid

South grid



~2014 one synchronous grid

Installed Capacity: ~ 180 GW

By 2027: ~575 GW

Thermal	65%
Hydro	21 %
Nuclear	3 %
Renewable	11 %

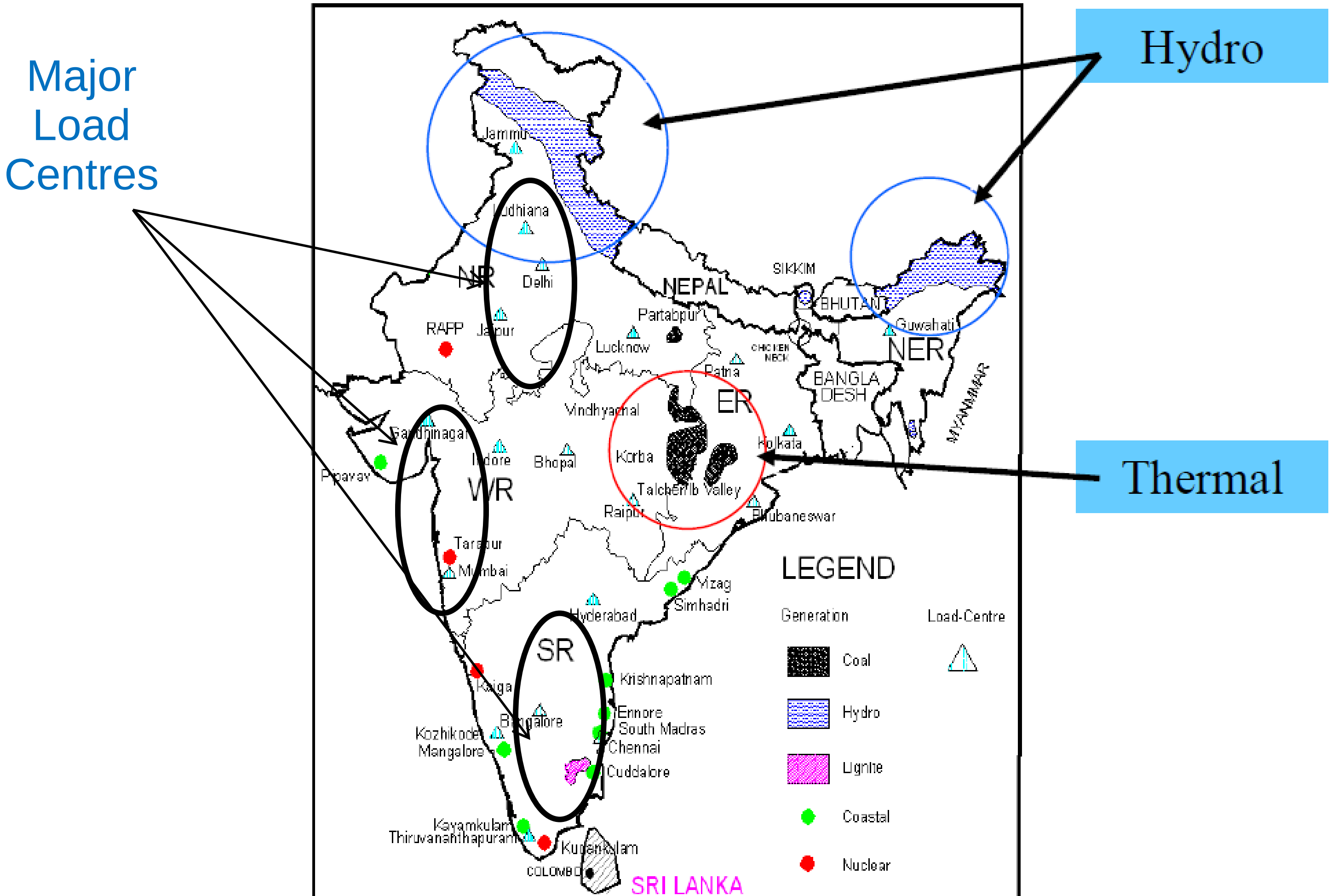
Renewables: Wind, Small Hydro, Biomass etc

Wind Energy: 14 GW (Fifth Largest)

Courtesy: Power Grid Corporation of India Ltd. / Ministry of Power

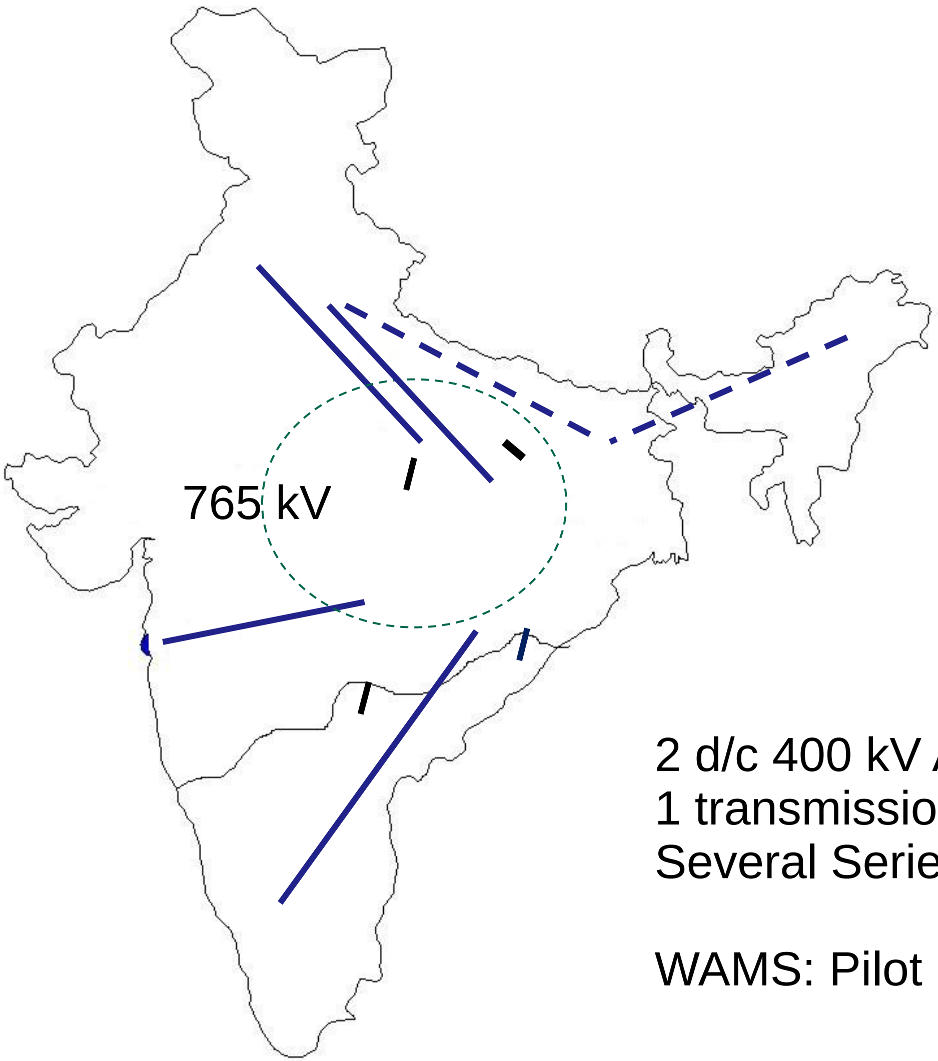
The Indian Grid

Energy Resources



Courtesy: Power Grid Corporation of India Ltd. / Ministry of Power

The Indian Grid: HVDC/FACTS

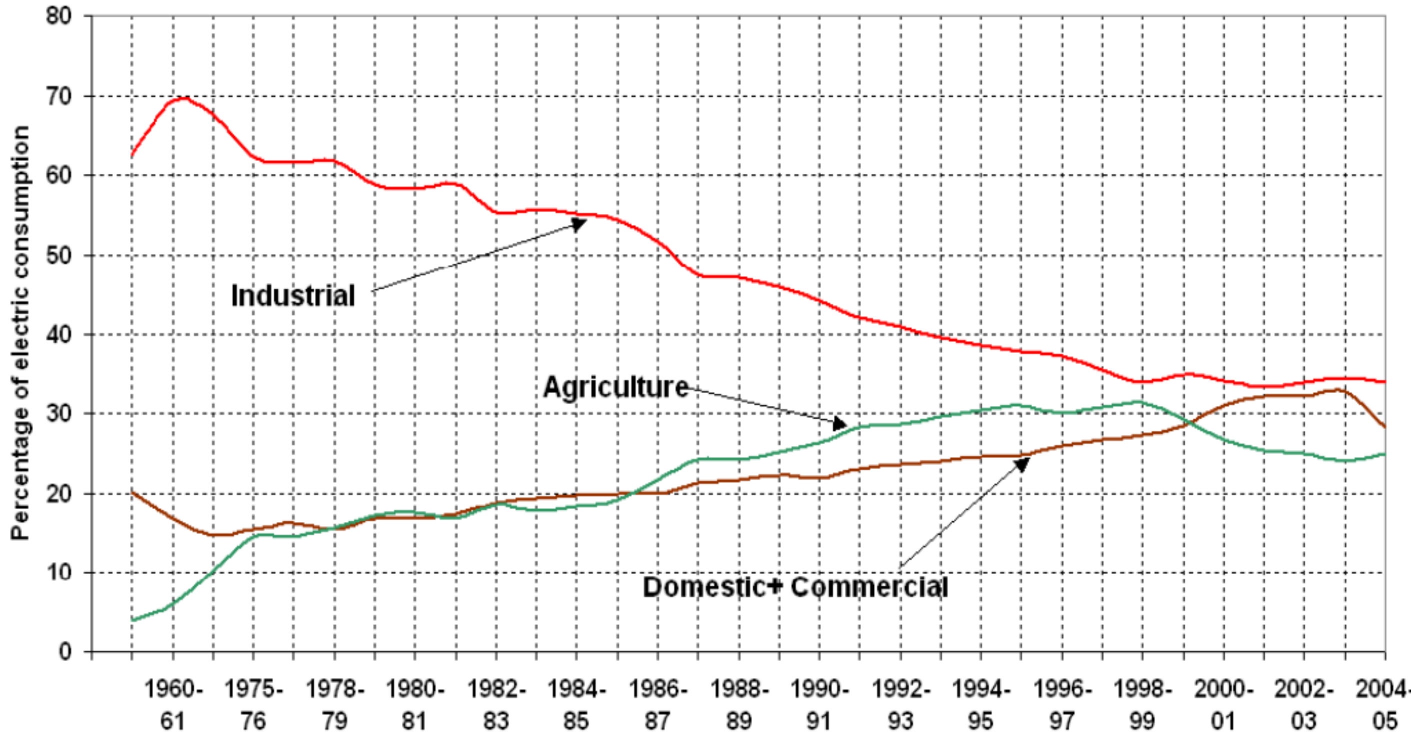


2 d/c 400 kV AC lines with TCSCs
1 transmission line SVC
Several Series Compensated lines

WAMS: Pilot project

Changing Load Characteristics

Source: CEA General Review 2006



Silicon Loads

Future Load Curve?

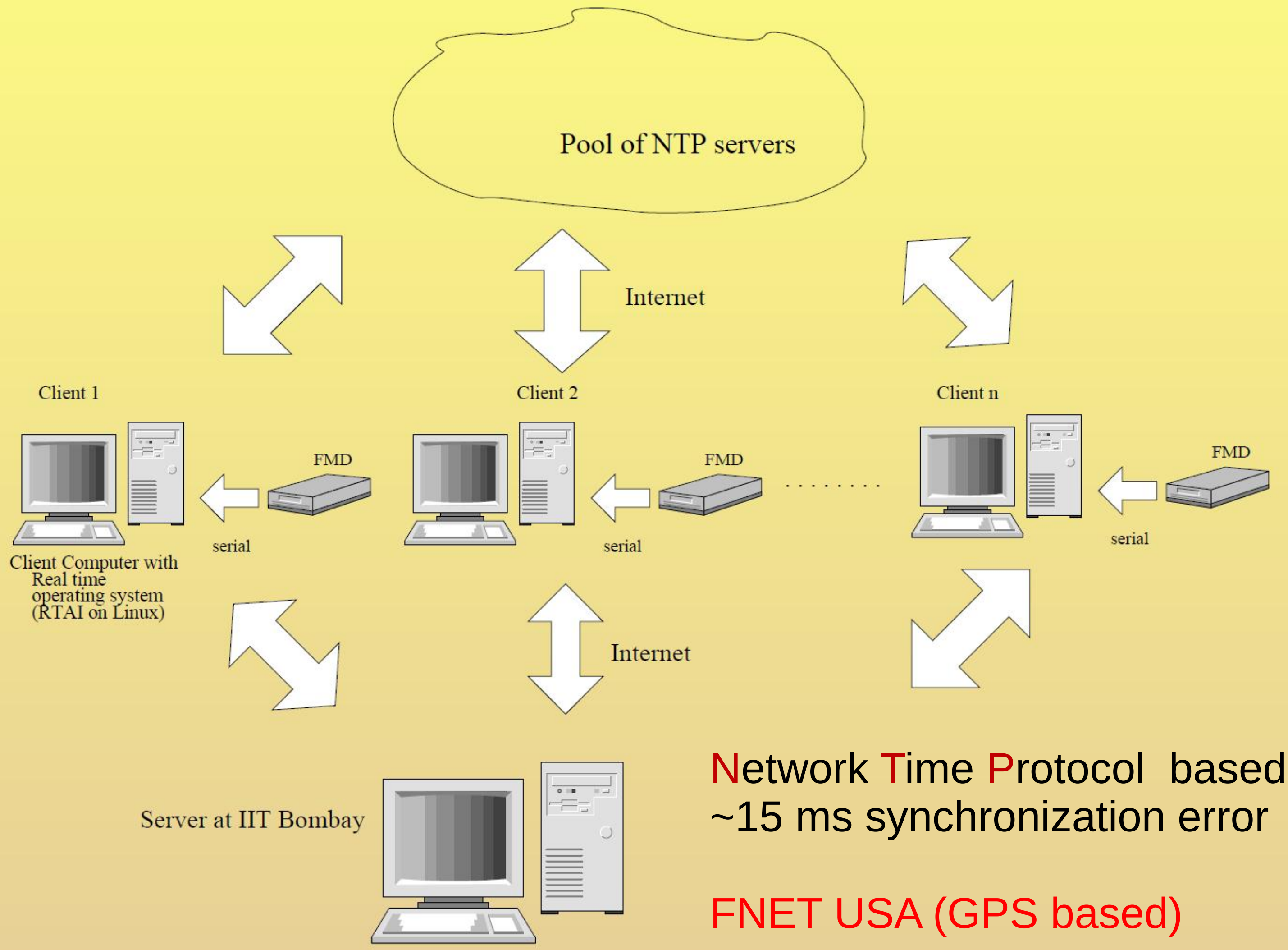
Overview

- Real-Life Observations in the Indian Grid
  - Small Signal Instabilities
  - Propagation Delay of Electro-Mechanical Transients
  - Generator Tripping Events: System Inertia

Sources of these Observations:

1. NTP-synchronized wide-area frequency measurement system (IITB)
2. PSS Tuning Exercise (IITB/WRPC/BHEL)
3. Disturbance Reports (WRPC/MSTECL)
4. Published Literature

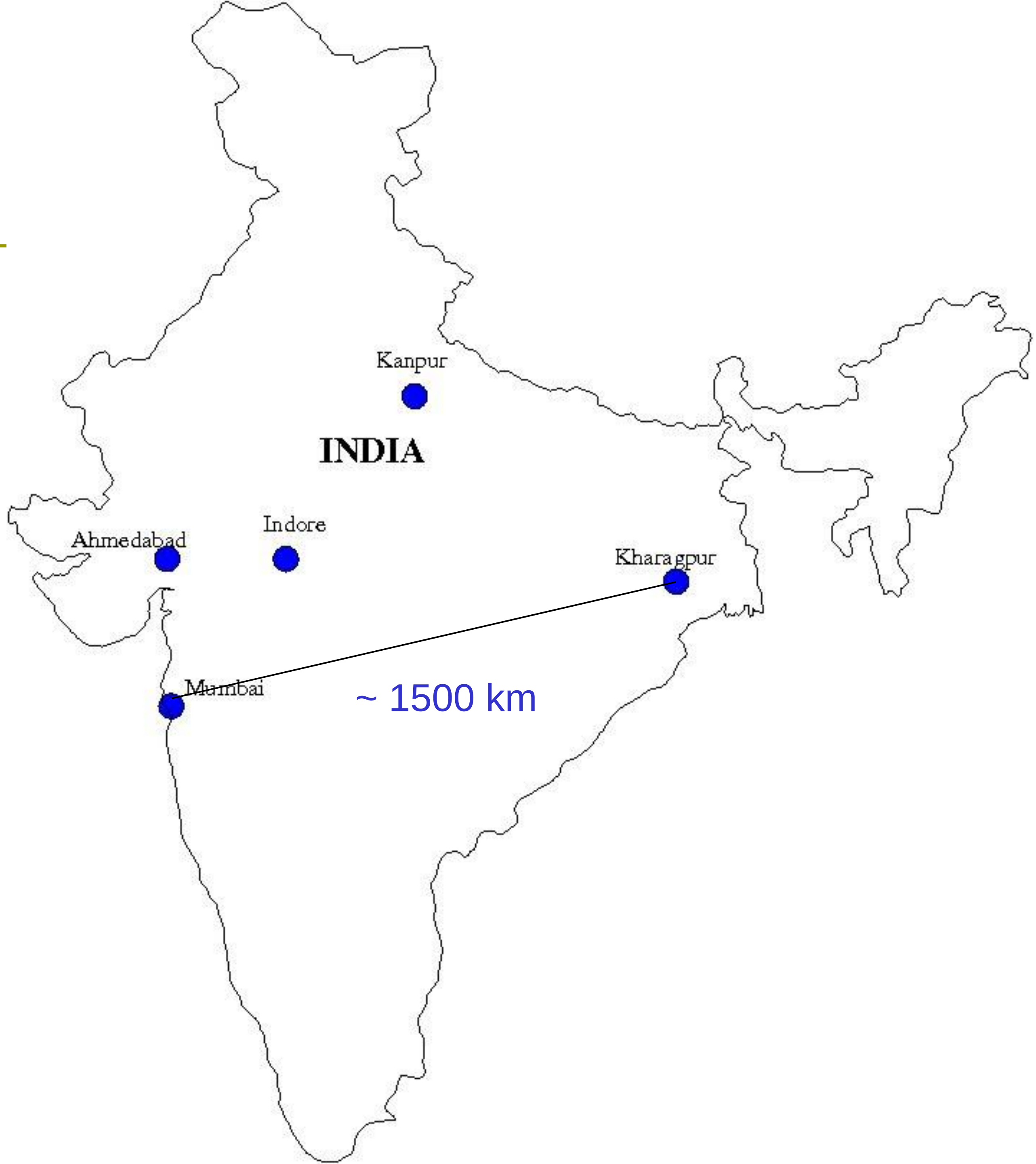
Wide Area Frequency Measurement



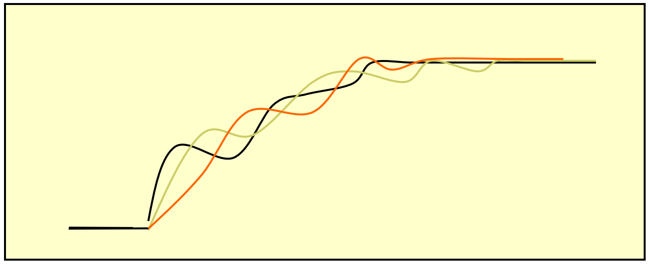
Network Time Protocol based
~15 ms synchronization error

FNET USA (GPS based)

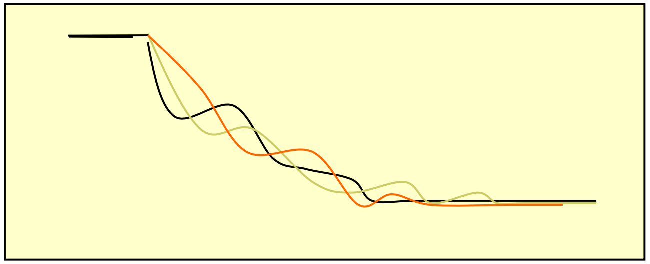
WAFM Locations



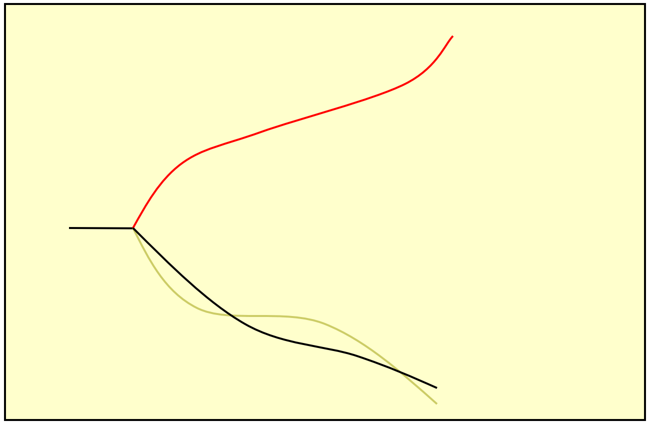
Wide Area, Electro-mechanical Phenomena



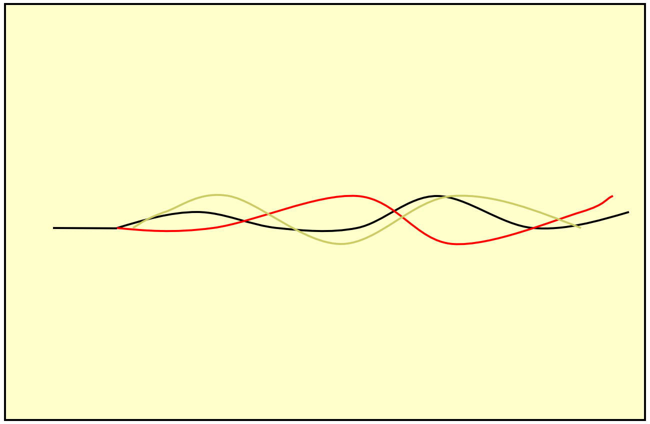
Sudden Load Throw Off
Stable Common and Relative Motion



Sudden Generation Trip
Stable Common and Relative Motion

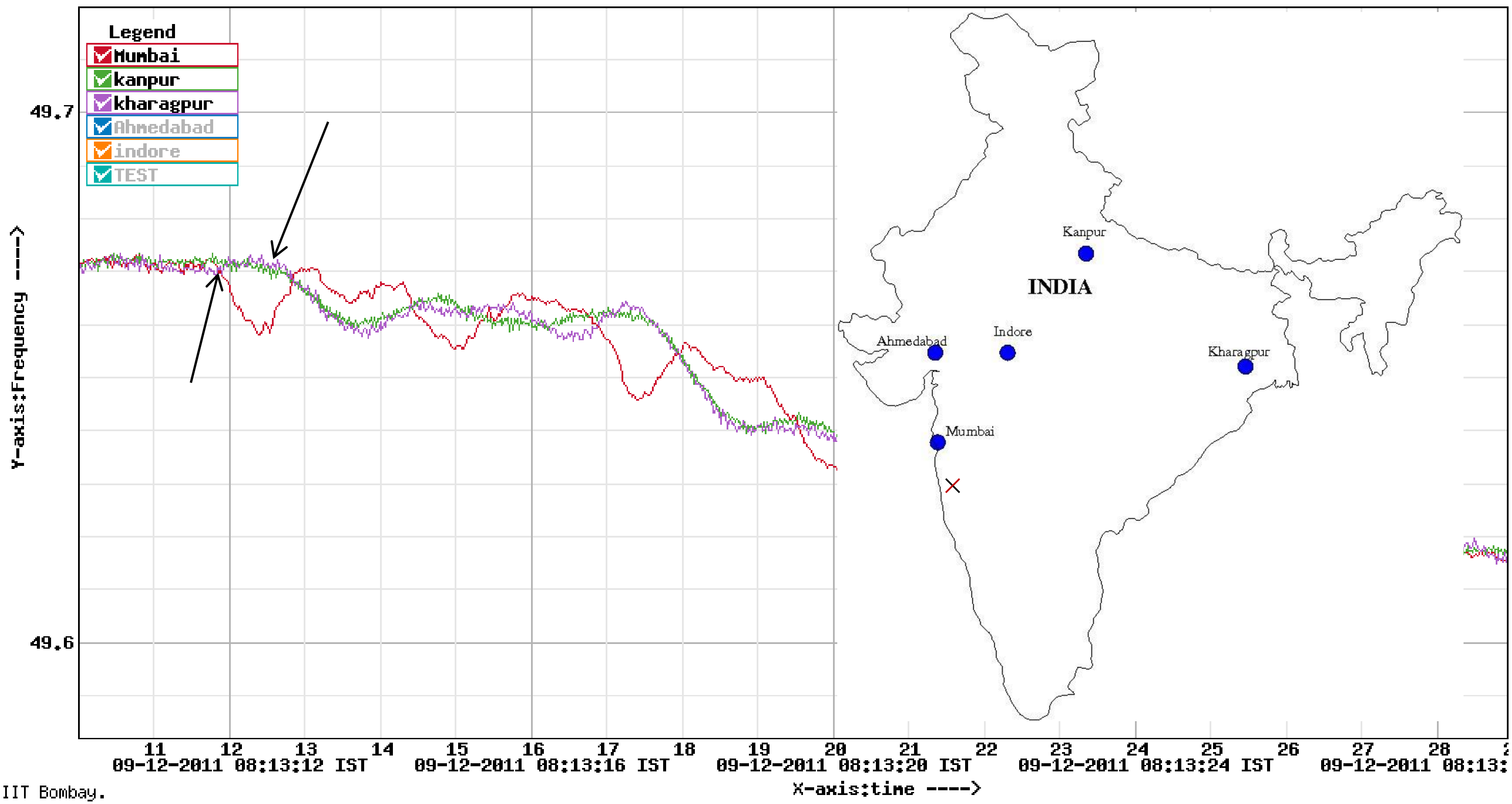


Large Disturbance Angular
Instability : Loss of Synchronism

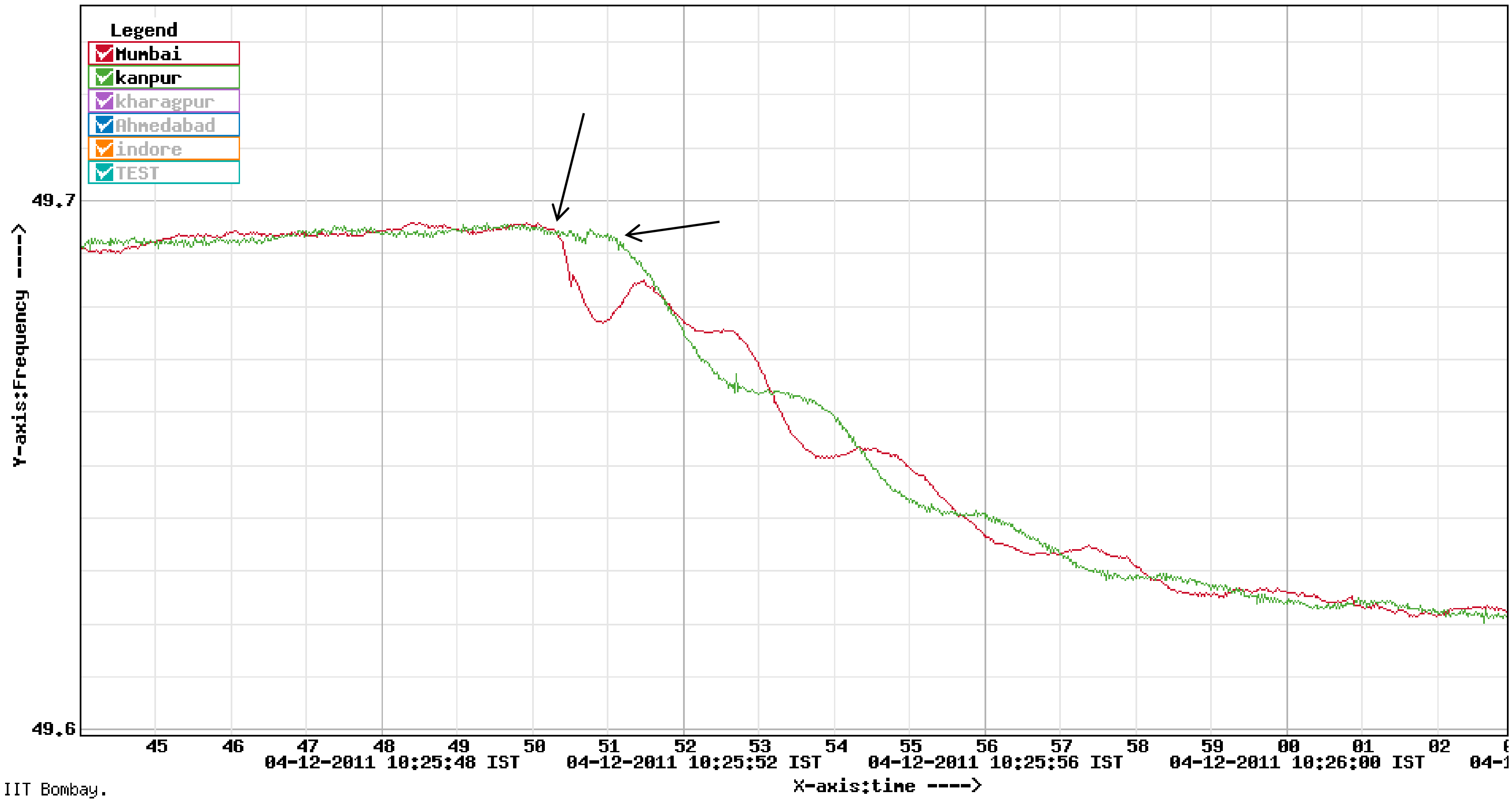


Small Disturbance Angular
Instability : Growing Oscillations
(triggered by *any* disturbance: big or small)

Observation I : Propagation Delay



Observation I : Propagation Delay



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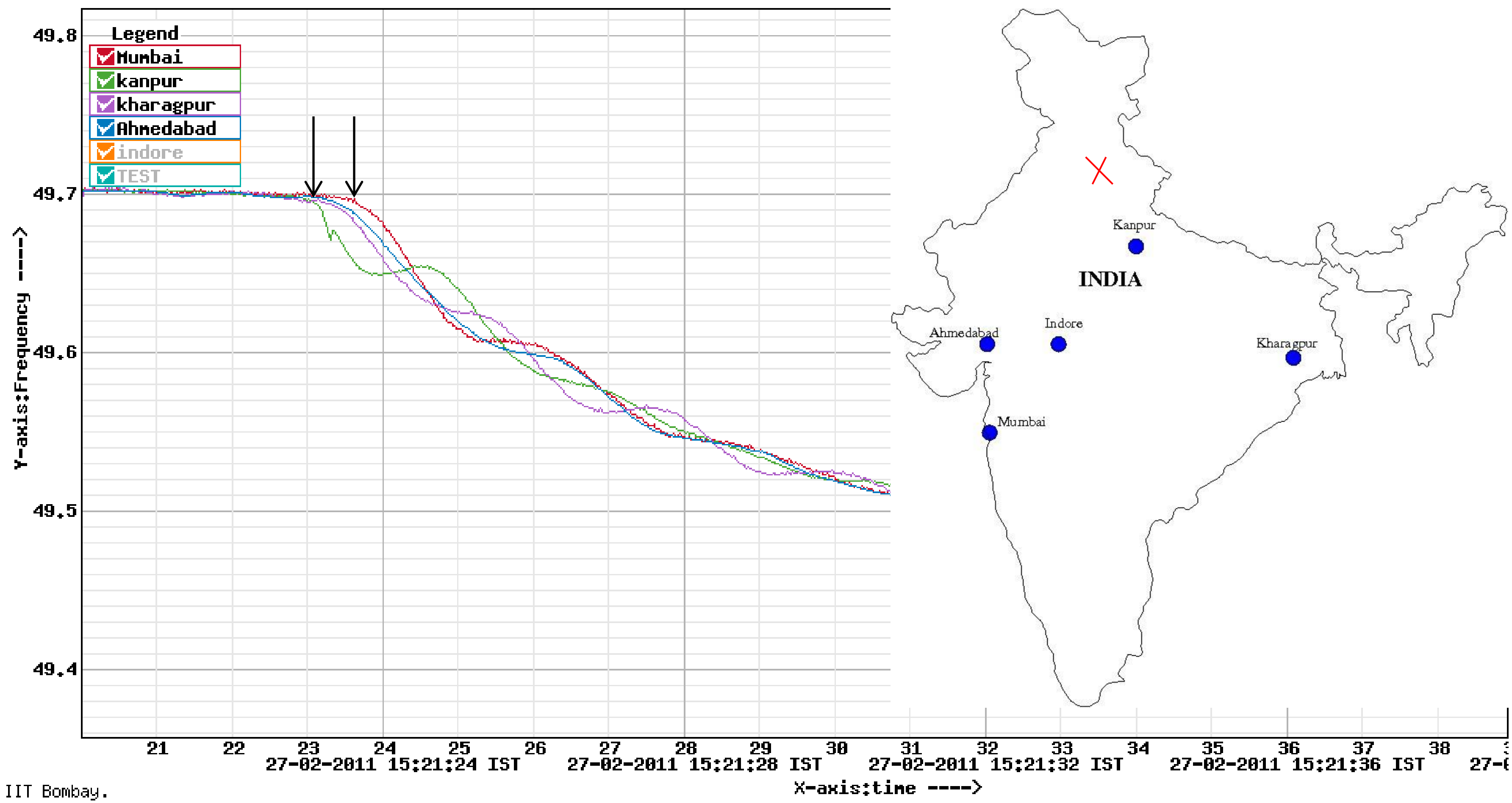
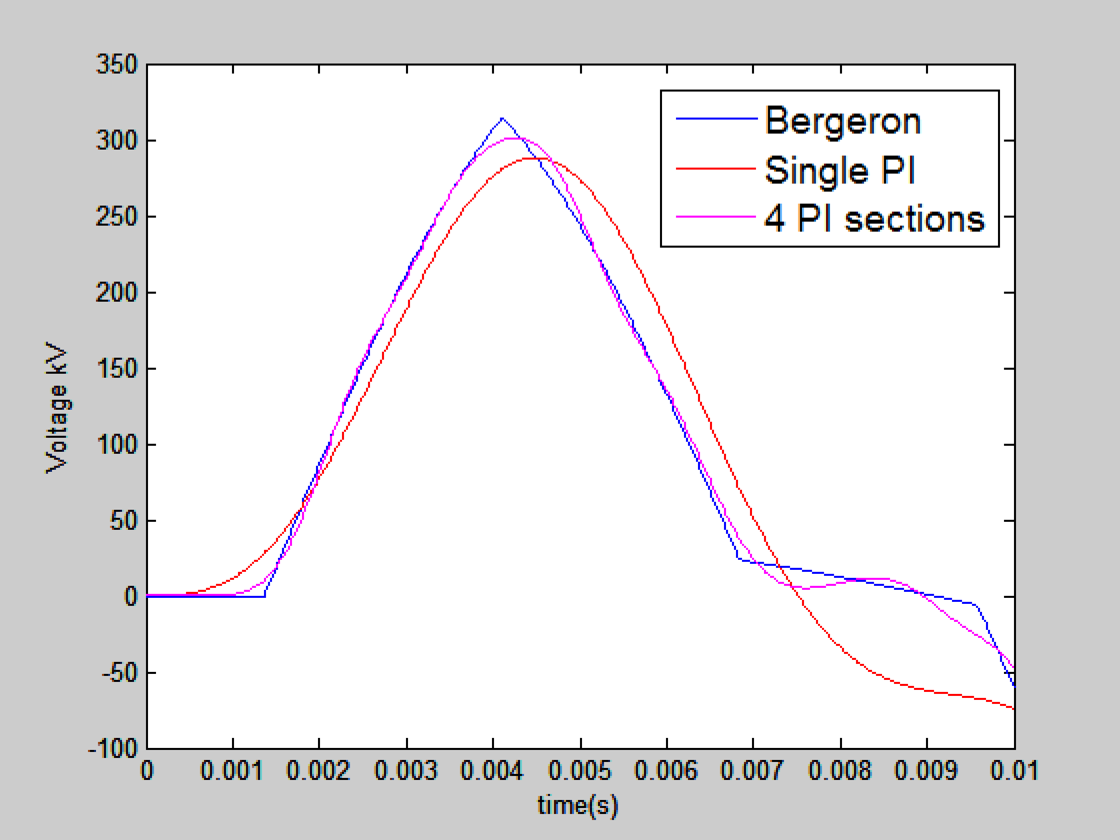
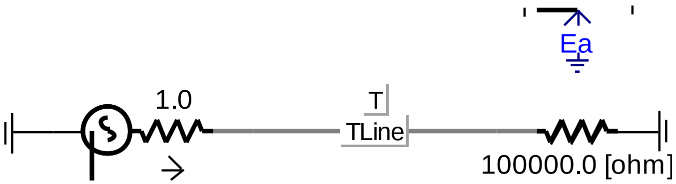
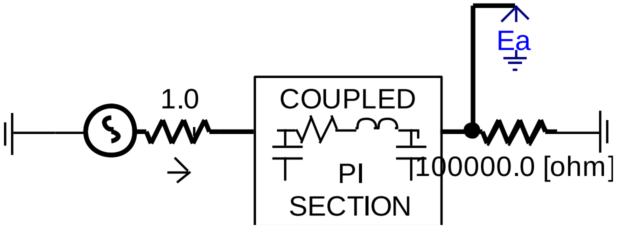
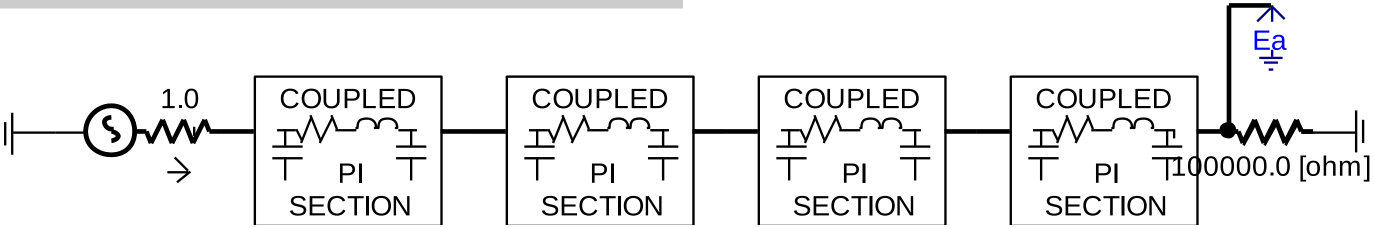


Lumped/Distributed Parameter Models – Electro-magnetic







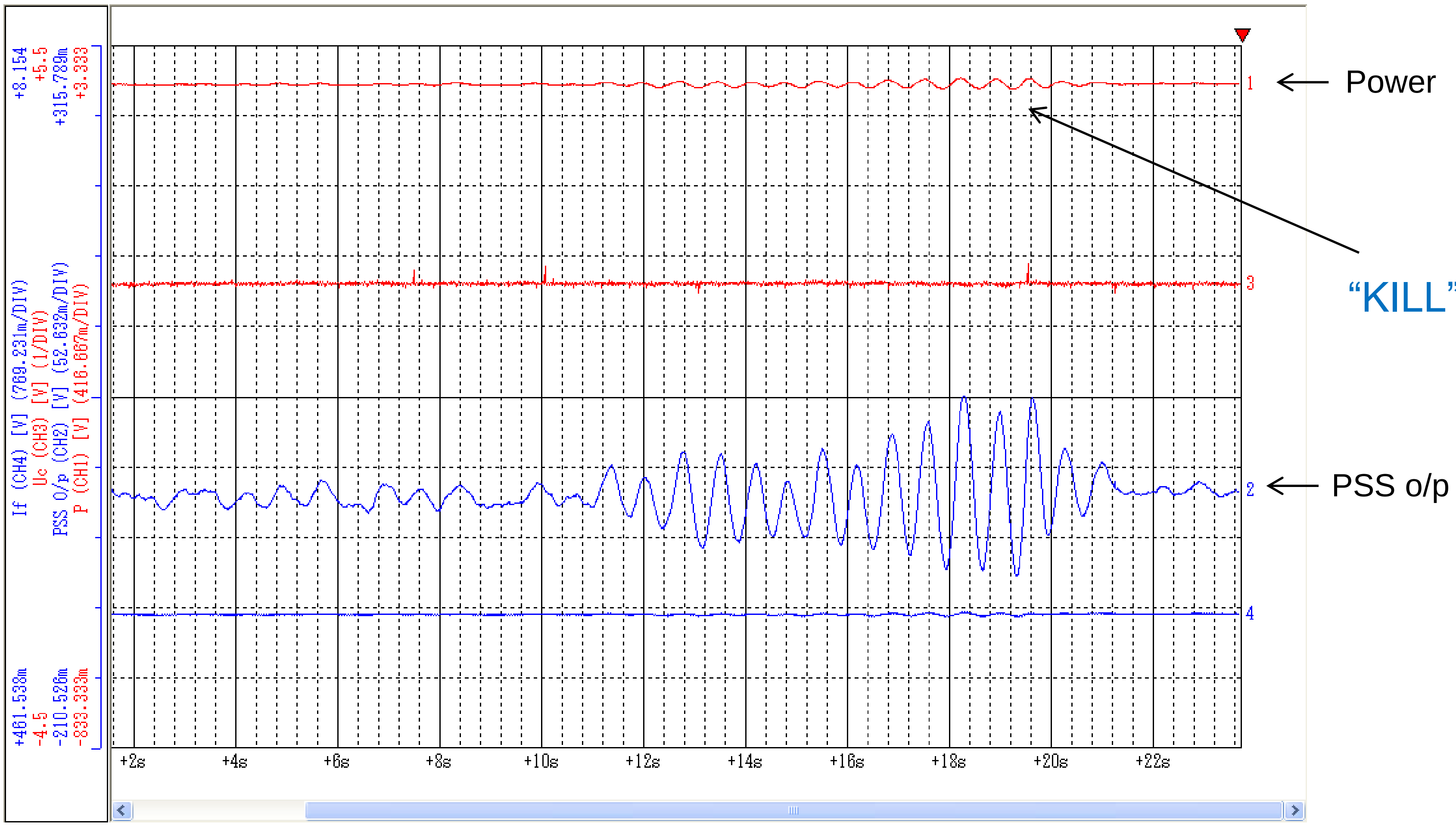


Lumped/Distributed Parameter Models – Electro-mechanical

- A.Semlyen "Analysis of disturbance propagation in power systems based on a homogeneous dynamic model", *IEEE Trans. Power App. Syst.*, 1974.
- Electromechanical Wave Propagation in Large Electric Power Systems, James S. Thorp, Charles E. Seyler, and Arun G. Phadke, IEEE 1998.
- Electro-mechanical Analogy: Mass-Spring System
- A large system with spread-out generators and lines ~ like a distributed parameter mass-spring system!

~ 1500 km/s

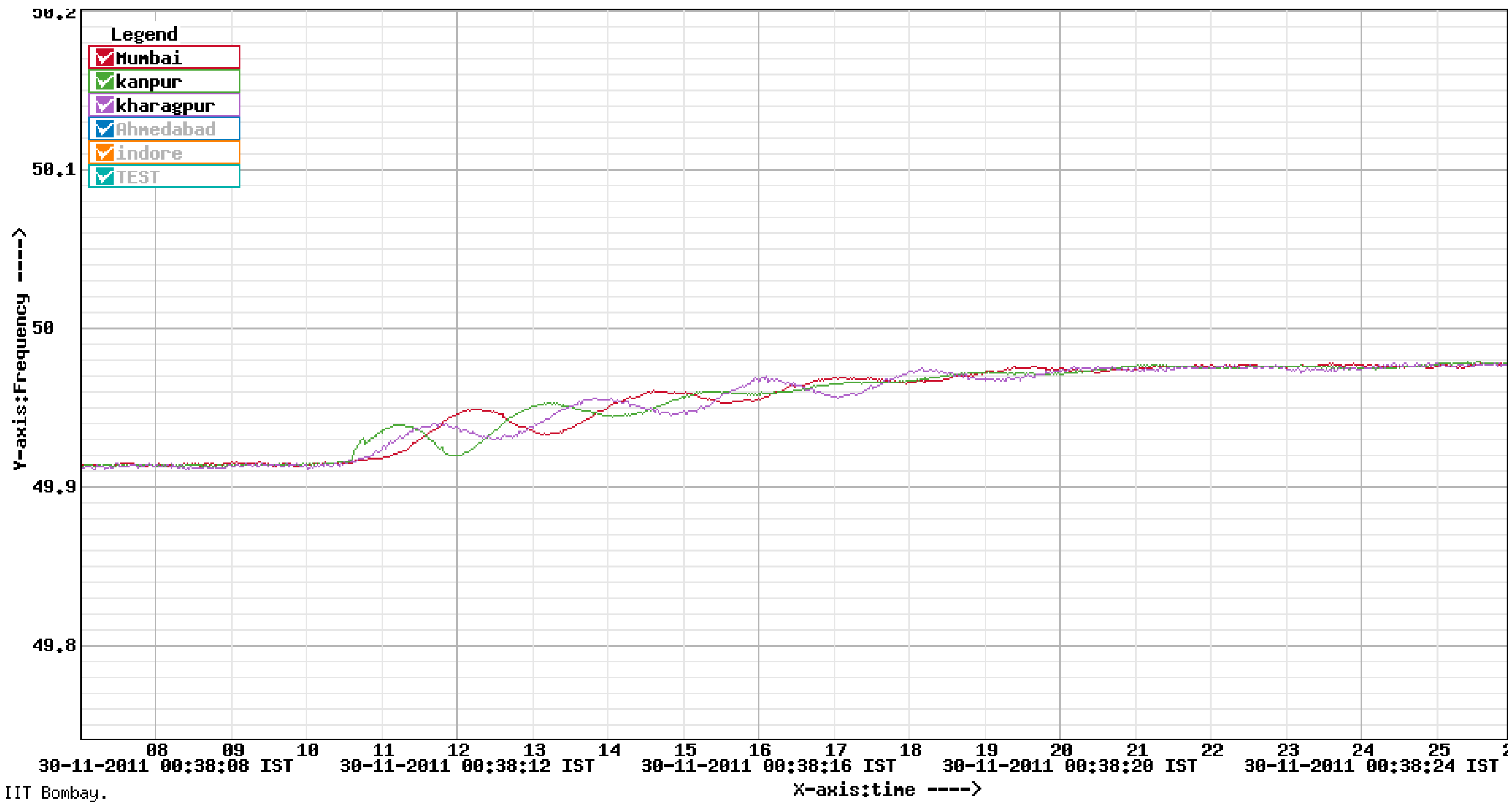
Unstable Intra-Plant Swings



PSS Tuning at 210 MW Satpura (India) – PSS polarity incorrect

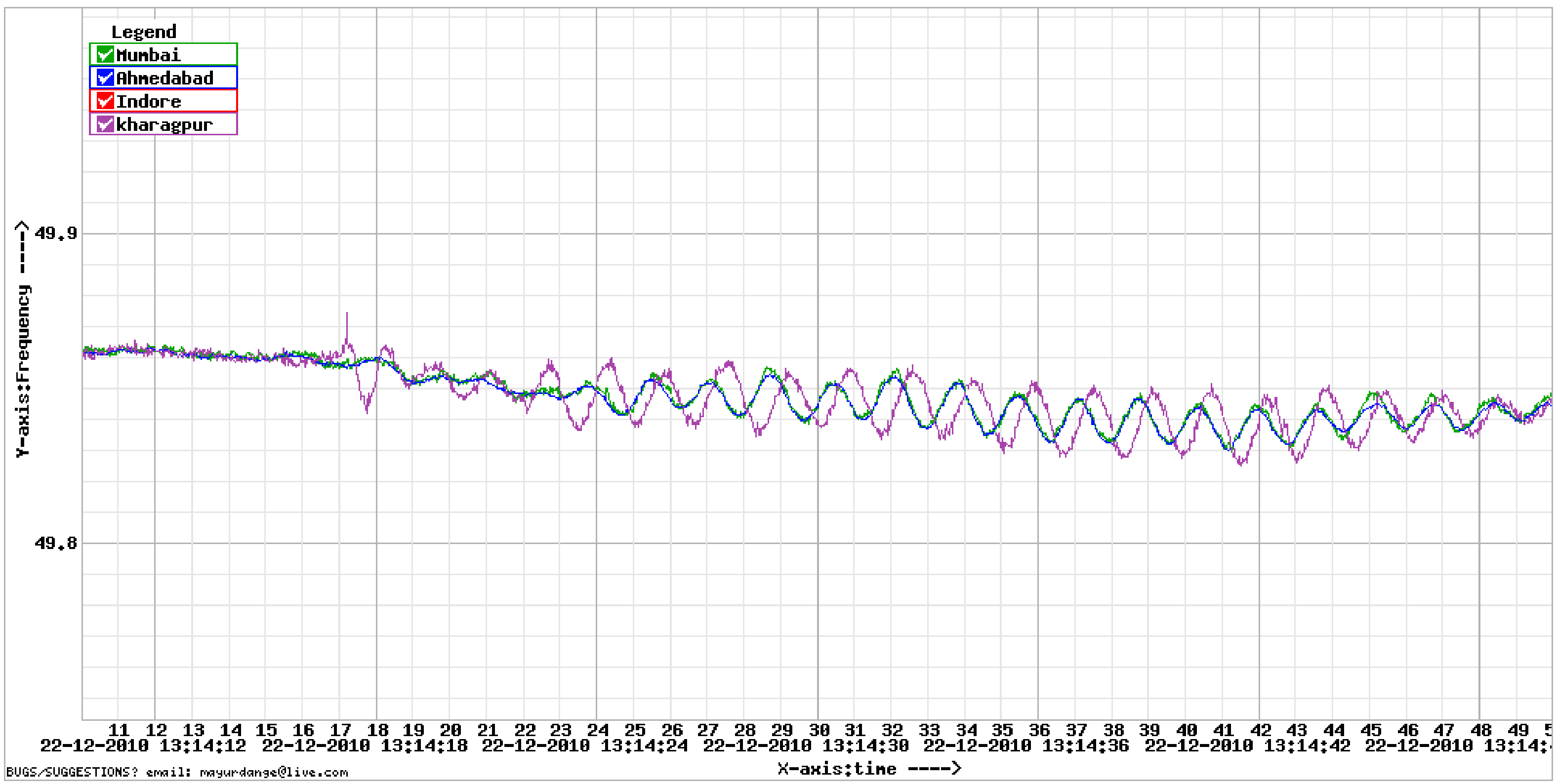
Local and Inter-area Swings

- A Stable Swing

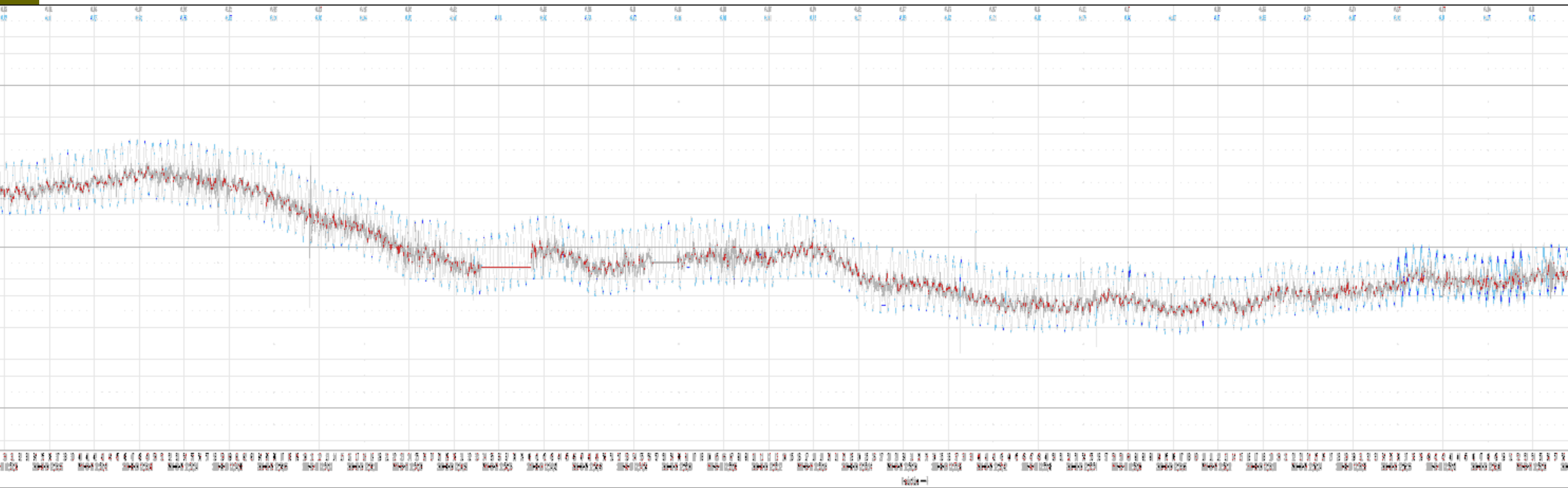


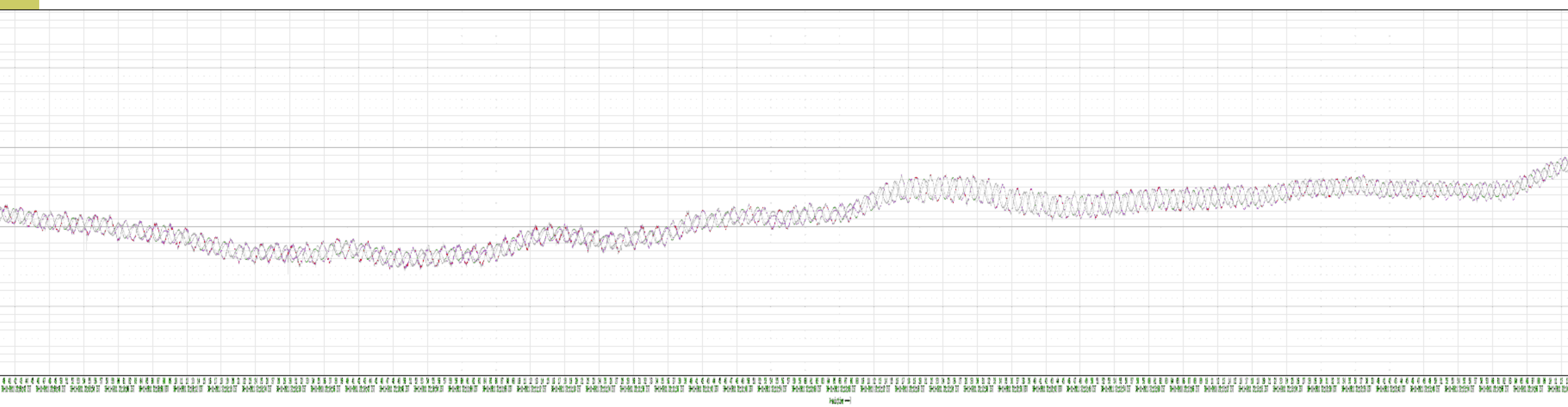
Local and Inter-area Swings

- Sustained Swing

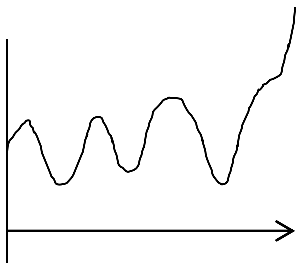


Two Sustained Local and Inter-area Swings (Limit Cycle ?)



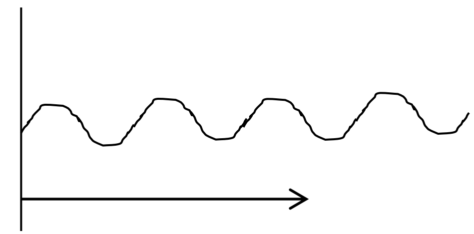


Non-linear behaviour

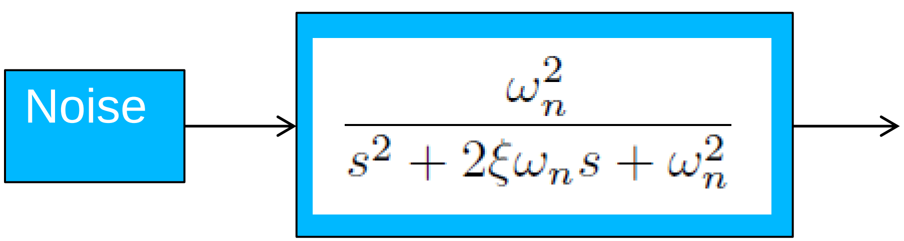


Out of step

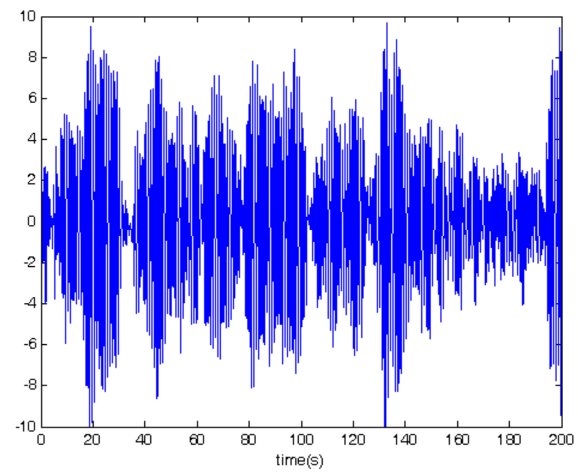
← Small Signal Unstable →



Sustained oscillation
(stable limit cycle)

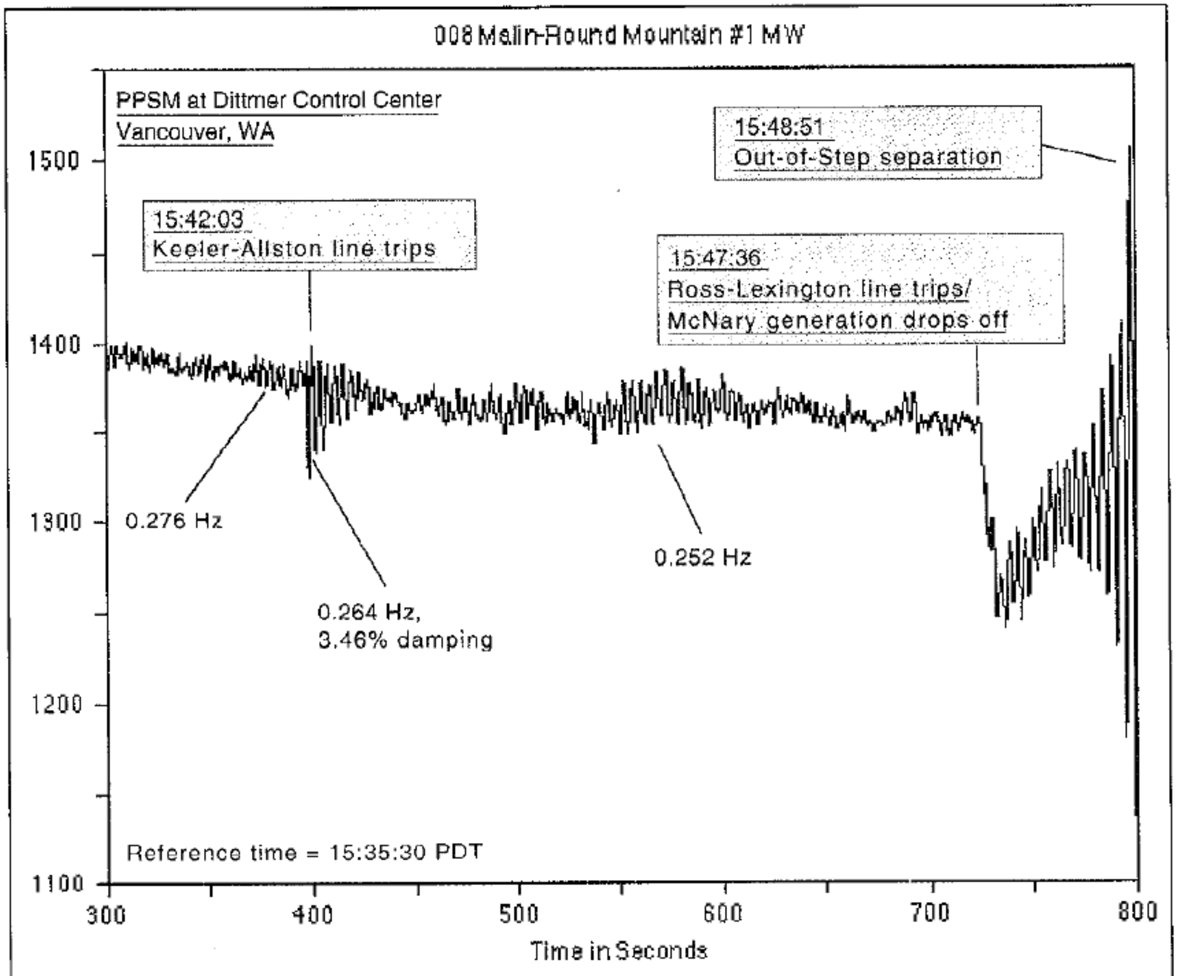


$$\omega_n = 2 \times \pi \times 1 \ \text{rad/s}, \quad \xi = 0.01$$



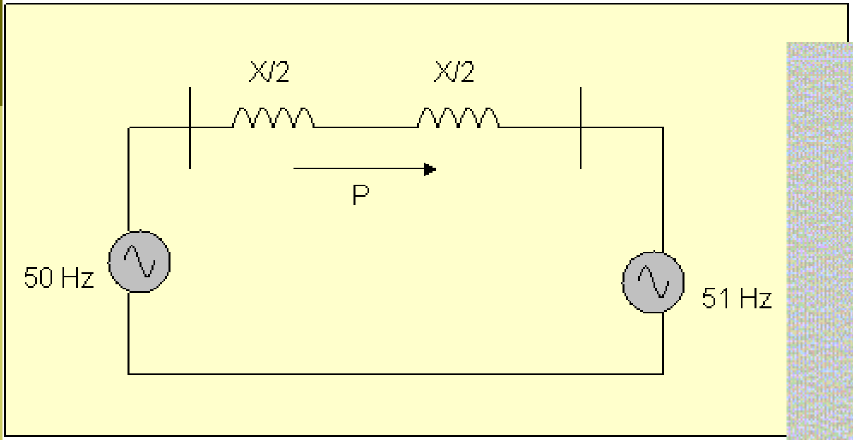
Small Signal **Stable** (poorly damped) excited by noise

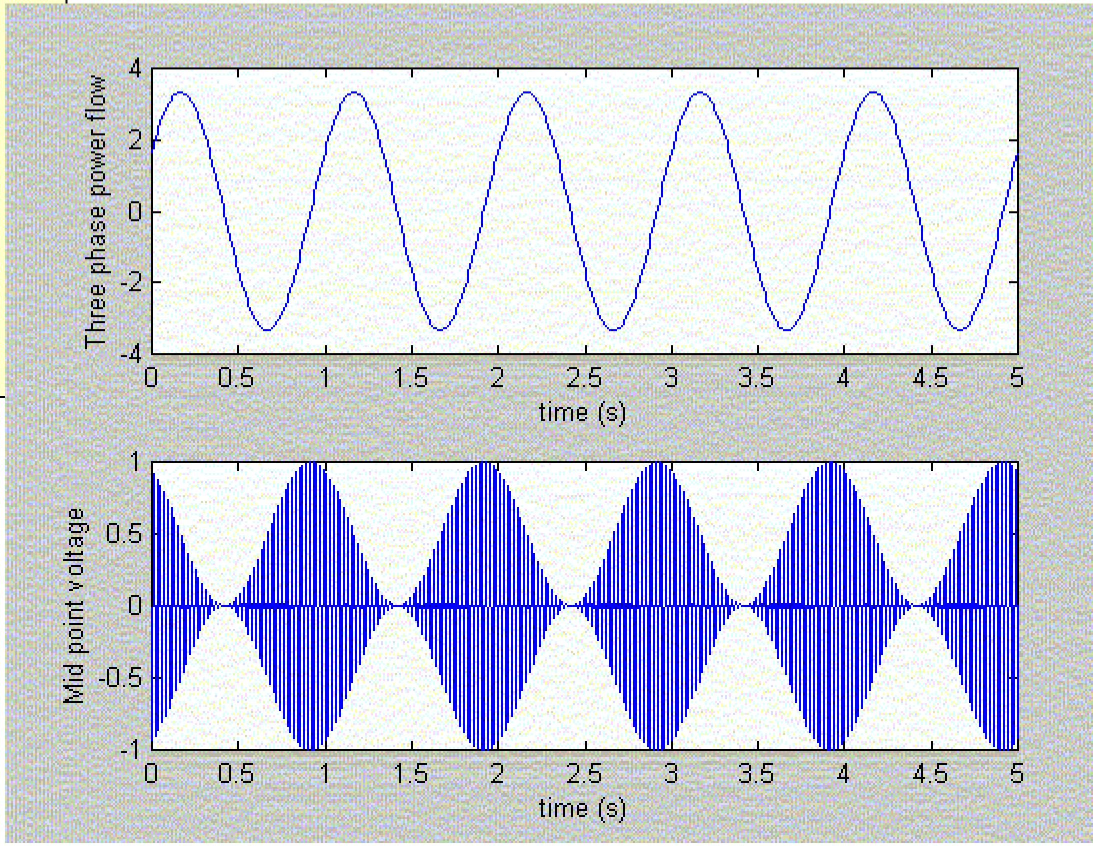
Oscillations in the WSCC System, August 1996



John Hauer, Dan Trudnowski, Graham Rogers, Bill Mittelstadt Wayne Litzenberger, Jeff Johnson, *Keeping an Eye on Power System Dynamics*, **IEEE Computer Applications in Power**, Oct 1997

Loss of Synchronism / Out of Step Operation – Idealized Scenario

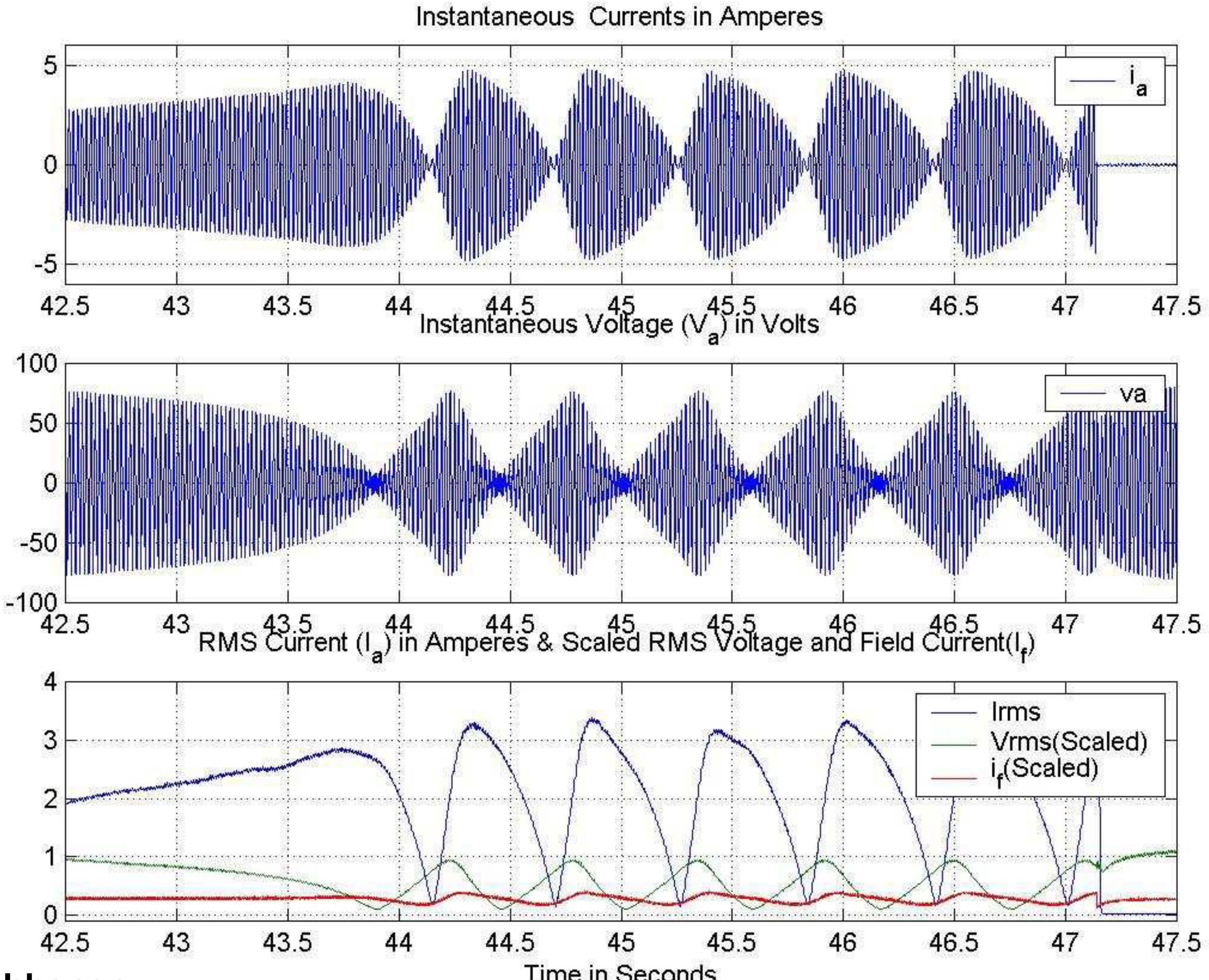




Not Acceptable !
Distance Relays trip

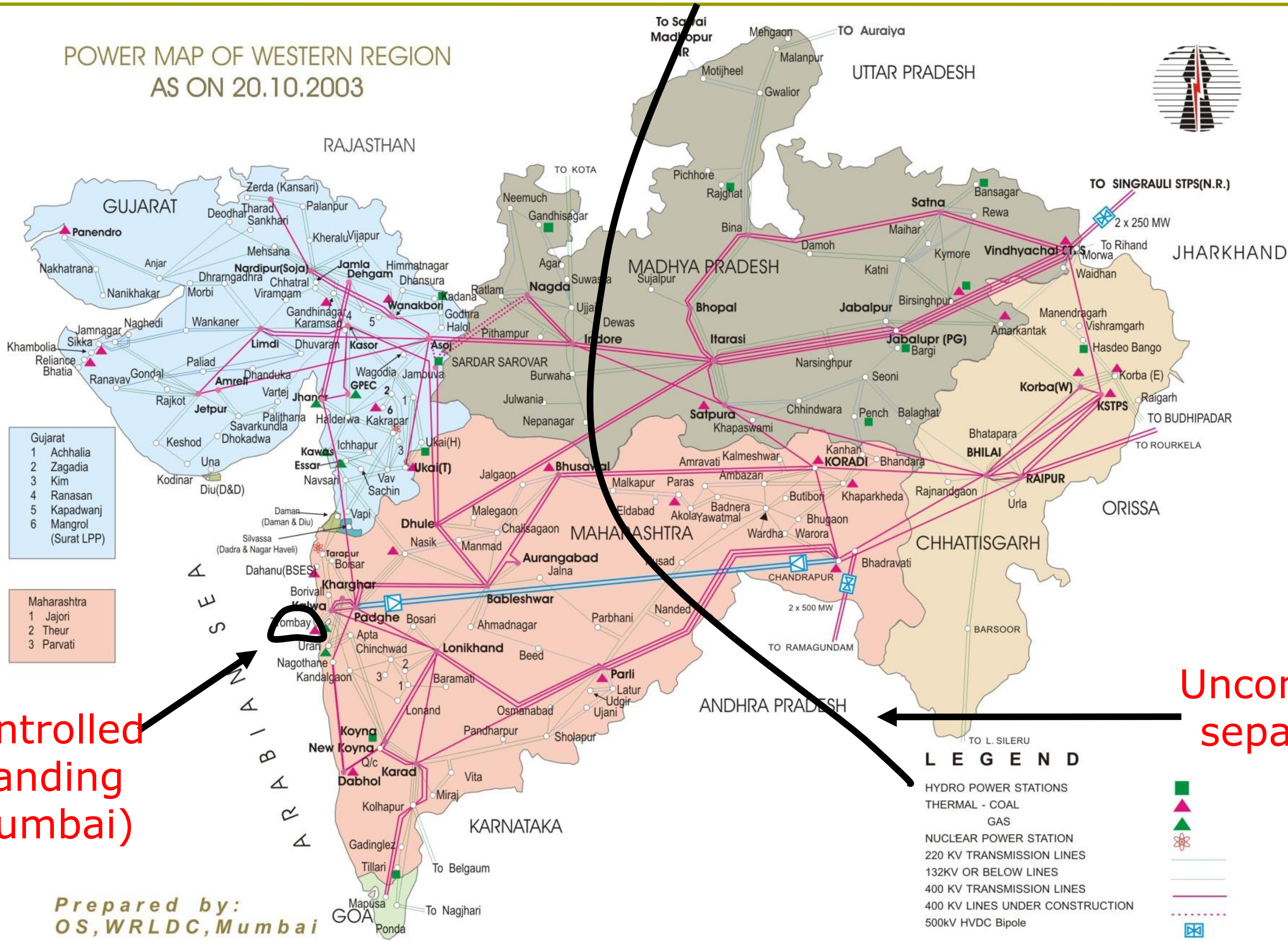
Uncontrolled
System Separation

Laboratory Observation



Courtesy:
Dr K.N. Shubhanga

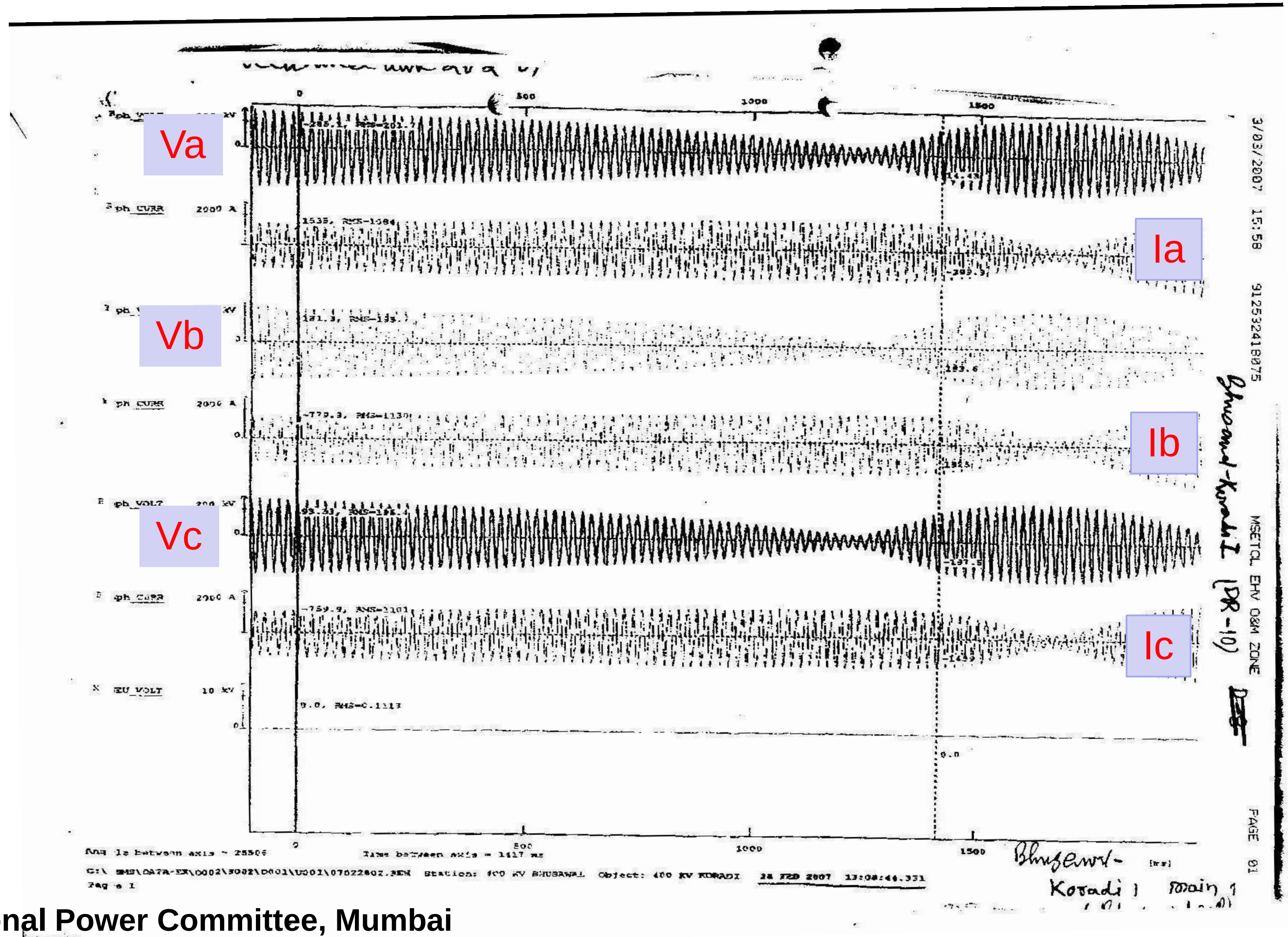
System Separation: Typical Cut Set



Controlled Islanding (Mumbai)

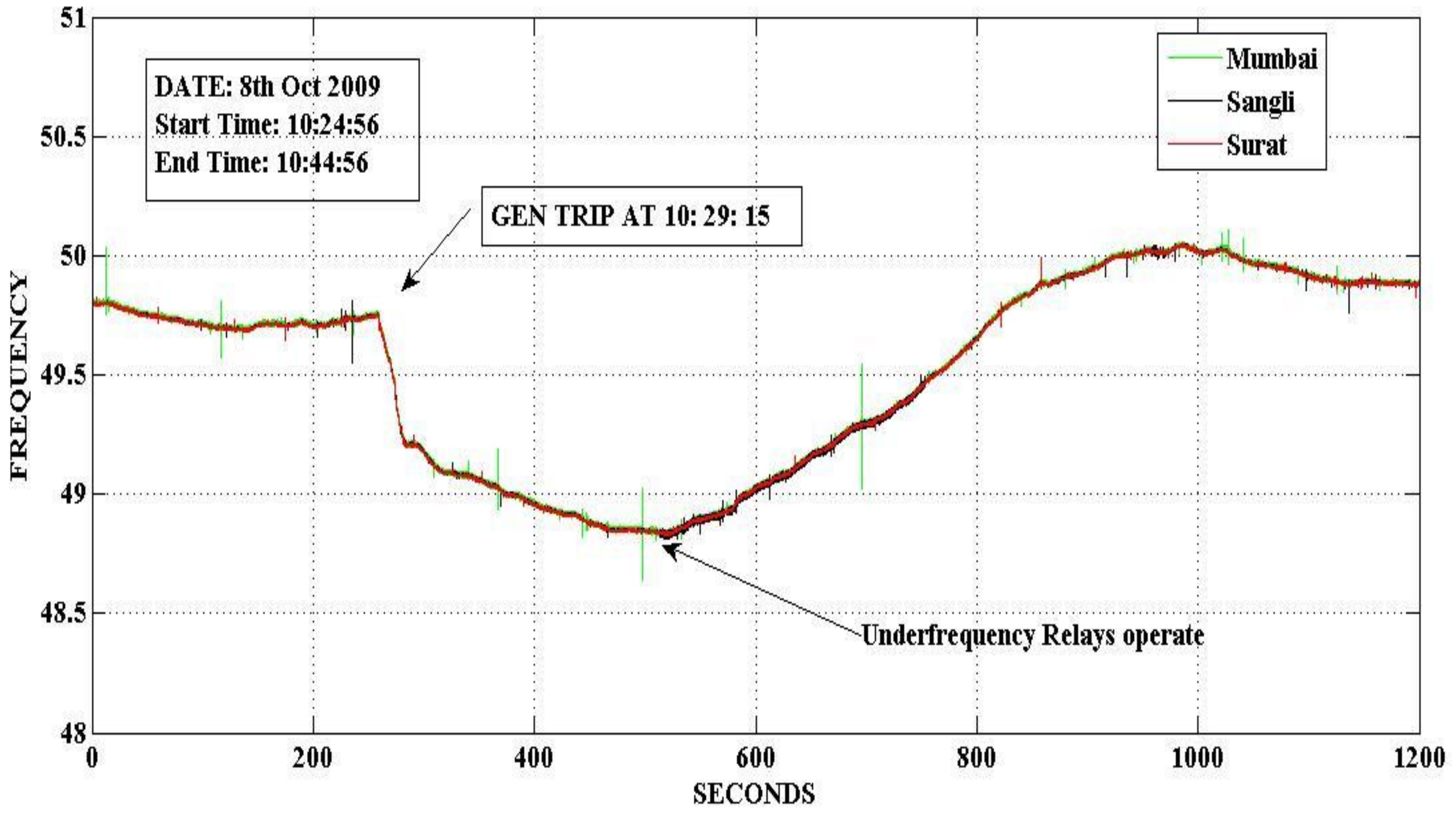
Uncontrolled separation

Large Power Swing / Loss of Synchronism

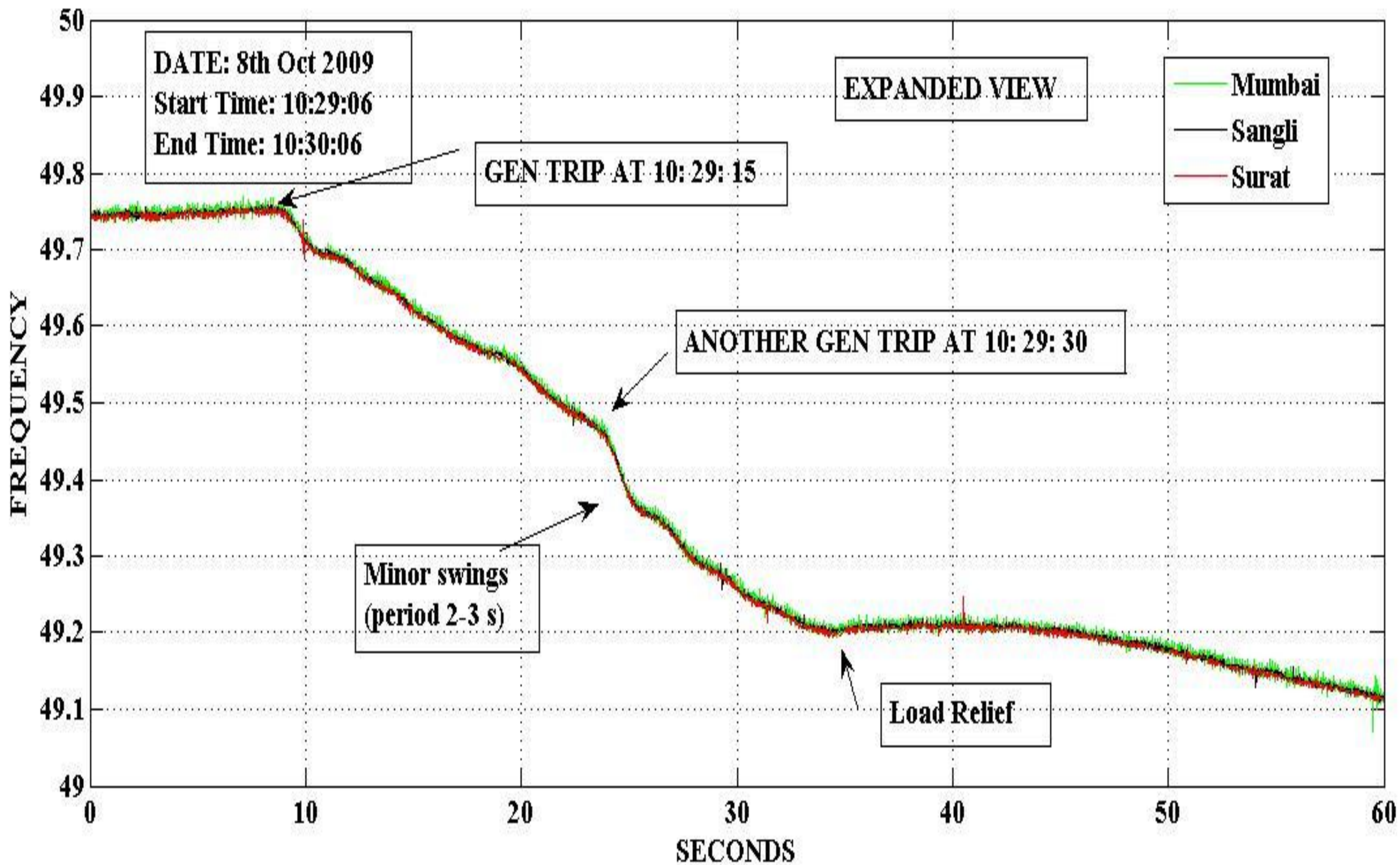


Courtesy:
Western Regional Power Committee, Mumbai

~1800 MW Generator Tripping



(Expanded)



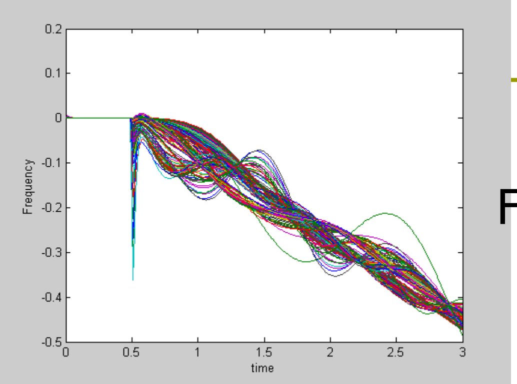
DATE: 8th Oct 2009
Start Time: 10:29:06
End Time: 10:30:06
EXPANDED VIEW
Mumbai
Sangli
Surat
GEN TRIP AT 10: 29: 15
ANOTHER GEN TRIP AT 10: 29: 30
Minor swings
(period 2-3 s)
Load Relief
FREQUENCY
SECONDS
50
49.9
49.8
49.7
49.6
49.5
49.4
49.3
49.2
49.1
49
0
10
20
30
40
50
60

How can WAMS help ?

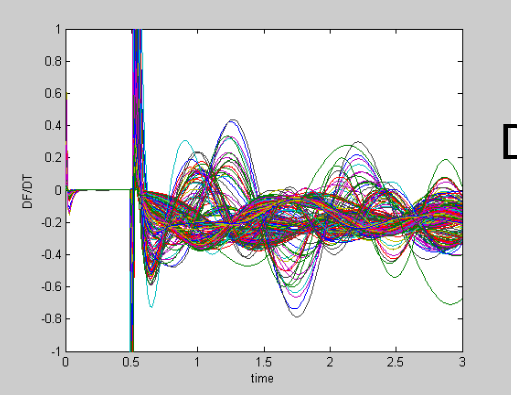
- **Frequency Control:**
  Under Frequency Relaying:
  Local frequency contaminated due to swings (1-2 Hz).
  df/dt should not trigger on swings but on “common” motion.

  Solution: filter, but filtering will involve delay.

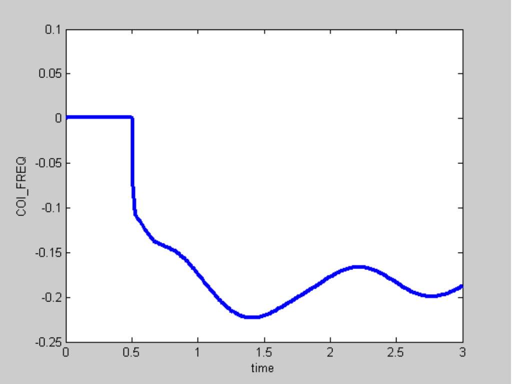
  - Rate of Change of Center of Inertia Speed (NOT LOCAL)
  - Reflects actual power deficiency. **Need to know total inertia** (will need to know whether islanded or not, which generators in island)



FREQ



DF/DT



d/dt of COI FREQ

Inertia Estimates

$$\frac{2H}{\omega_B}\frac{d\omega_{COI}}{dt} \approx \Sigma P_m - \Sigma P_L - losses$$

$$H = \Sigma H_i \qquad \omega_{COI} = \frac{\Sigma H_i \omega_i}{\Sigma H_i}$$

Generation Loss

MVA of generators on bar

Effective System Inertia “H”

Expected (adding up H of individual generators): between 3.5 - 4 MJ/MVA

What we generally get: 5-10 MJ/MVA !

Main Sources of Error? Load Dependence on Voltage, Load Inertia

Chassin, Z. Huang, M. K. Donnelly, C. Hassler, E. Ramirez,
and C. Ray, **Estimation of WECC System Inertia Using Observed Frequency Transients,** IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 2, MAY 2005

To conclude …

- The excitement of observing system-wide dynamic phenomena.

- Observations not inconsistent with theory – but some subtleties.