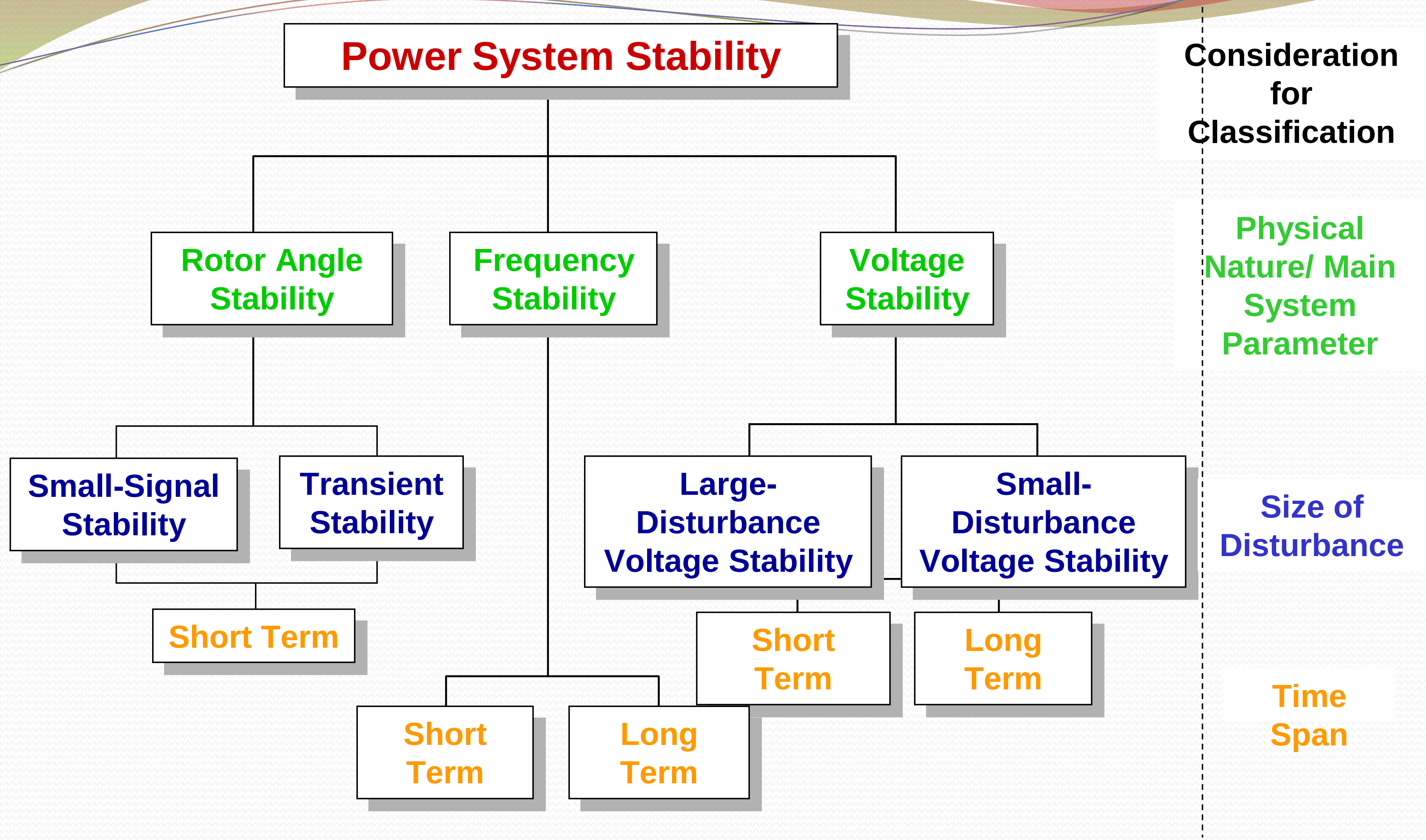
Wide Area Monitoring and Control

S.C. Srivastava, Professor
Departmentof Electrical Engineering
Indian Institute of Technology Kanpur
Email: scs@iitk.ac.in

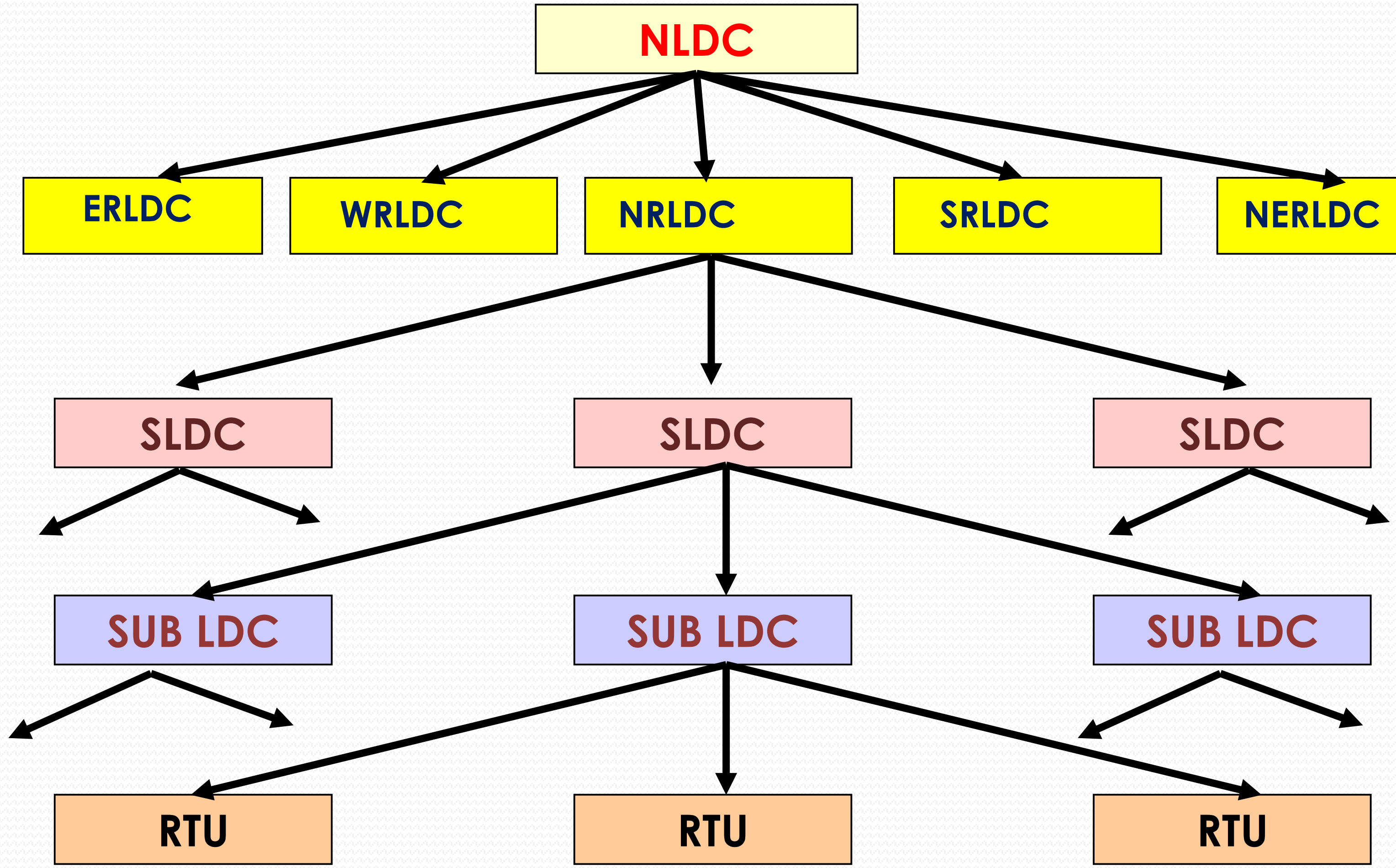
General Introduction

- **The size and complexity of the system has increased.**
  - **A.C. transmission systems at 1100/1200 kV.**
  - **Generating unit sizes have gone upto 800/1000 MW.**
  - **HVDC links (+/- 500/800 kV) are in operation for back to back and long distance power transfer.**
- **Concerns to its operators:**
  - **Maintaining security, reliability, quality and stability of power system**
  - **Ensuring economic operation. (→ Monopoly-Market based operation)**
  - **Leading to use of large number of sensors, DSP, PE devices, communication networks and IT enabled services (→ Large CPS)**
- **Computer aided monitoring & dispatching**
  - **SCADA (Supervisory Control and Data Acquisition) based Energy Management System (EMS)and Distribution Automation System (DMS).**
  - **Wide Area Monitoring and Control Systems (WAMCS) using synchrophasors.**



P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. V. Cutsem, and V. Vittal, "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1387-1401, Aug. 2004.

SCADA EMS System+
(Typical Architecture in India)



+ Wide area monitoring system since 1960s

Components of SCADA EMS

- ***Remote Terminal Units*** – Intelligent units to collect data from field, convert these to suitable form (through A/D or D/A converters, Transducers etc.), communicate the data to Control Center.
- ***Communication Networks or Data Transmission Networks*** – PLCC, Microwave Telemetry Link, Dialup Network, **Fiber Optics** etc.
- ***Computer Systems & Man Machine Interface-*** at Control Center
- ***Software:***
  1. Operating system software for Data base management & MMI
  2. Communication Software
  3. Application Software (to perform advance functions of EMS)

Problems with SCADA based WAMS:

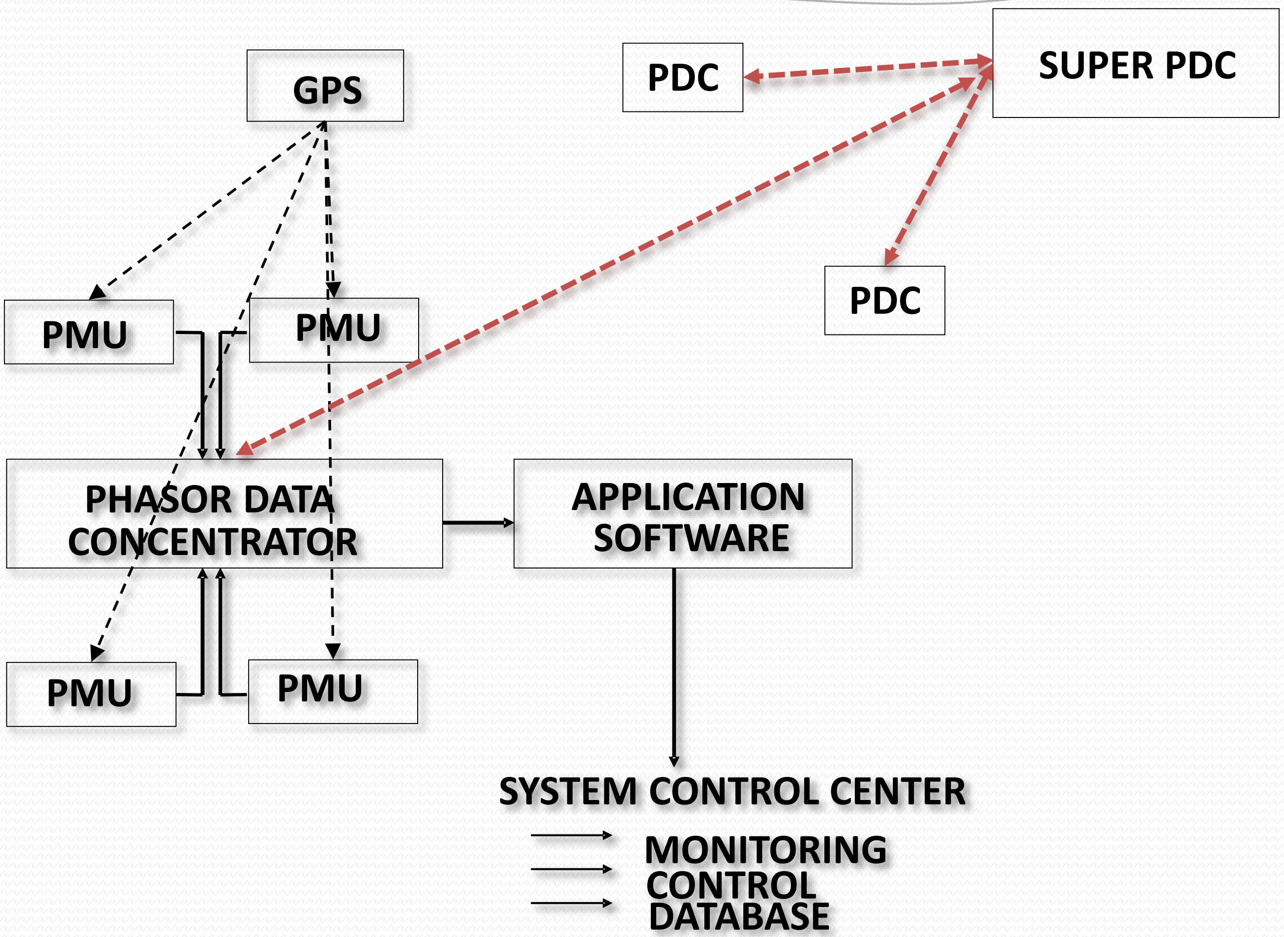
- Data time skewed. Data scan rate upto 10 sec.
- Only magnitude measurements and phasors through state estimation-time extensive.

Advance Functions of Energy Management System

- Supervisory Control & Data Acquisition (SCADA) functions
- System Monitoring and Alarm Functions
- State Estimation
- On line Load Flow
- Economic Load Dispatch
- Optimal Power Flow (including Optimal Reactive Power Dispatch)
- Security Monitoring and Control
- Automatic Generation Control
- Unit Commitment
- Load Forecasting
- Log Report Generation (Periodic & Event logs), etc.

A program scheduler may invoke various Application programs at fixed intervals.

A Typical Synchrophasor based WAMCS Architecture



Recommended PMU reporting rates (frames/sec): as per IEEE std. 37.118

System frequency 50 Hz : 10 25 50
System frequency 60 Hz : 10 12 15 20 30 60

(New standard also encourages fps of 100, 120 or less than 10, if required for a specific application)

Few Major Black-out Events across the World

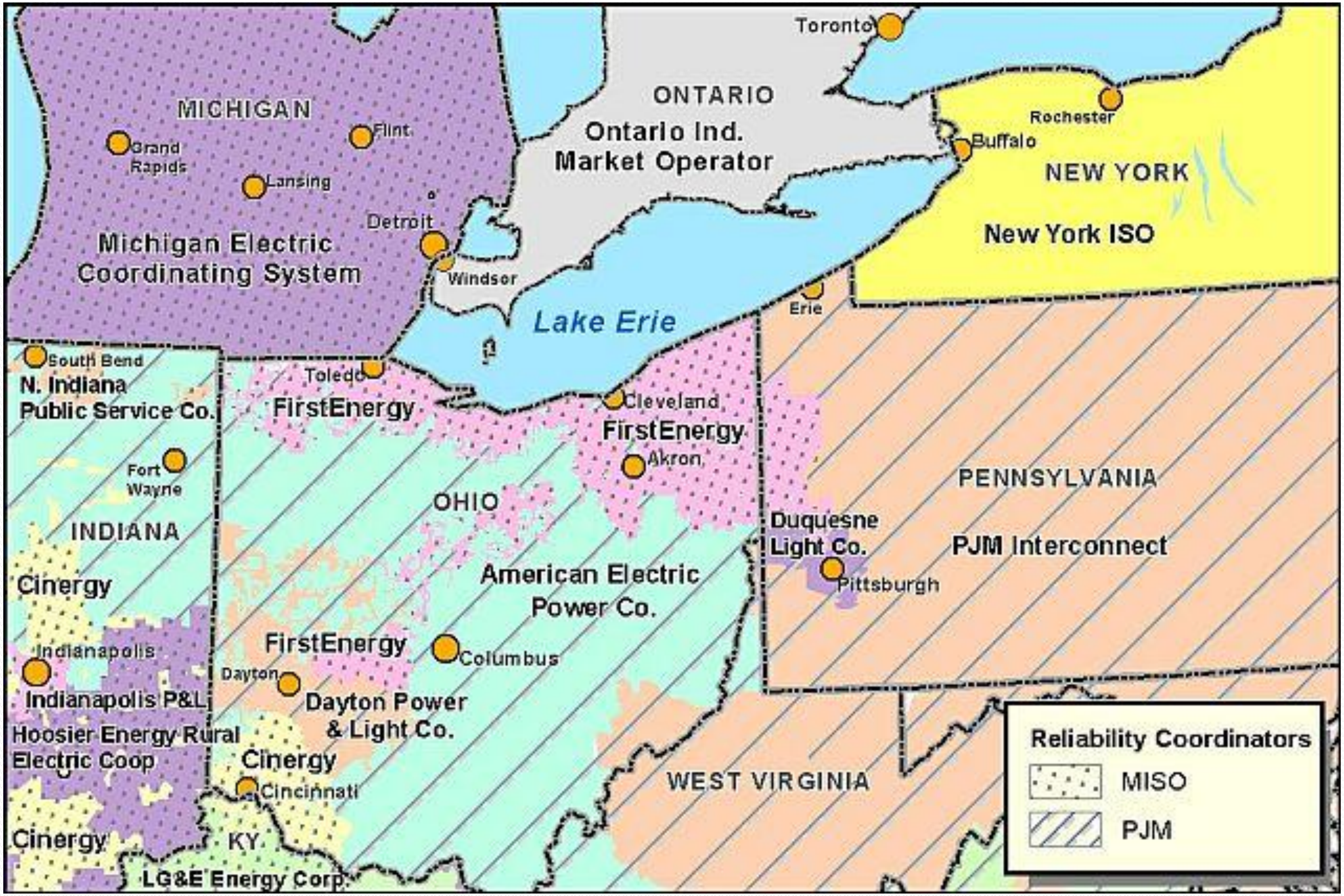
(Ref. http://en.wikipedia.org/wiki/List_of_power_outages)

Event	Millions of people affected	Location	Date
July 2012 India blackout	620	India	30–31 July 2012
2014 Bangladesh blackout	150	Bangladesh	1 Nov 2014
2005 Java-Bali blackout	100	Indonesia	18 Aug 2005
1999 Southern Brazil blackout	97	Brazil	11 March 1999
2009 Brazil and Paraguay blackout	87	Brazil, Paraguay	10–11 Nov 2009
Northeast blackout of 2003	55	United States, Canada	14–15 Aug 2003
2003 Italy blackout	55	Italy, Switzerland, Austria, Slovenia, Croatia	28 Sep 2003
Northeast blackout of 1965	30	United States, Canada	9 Nov 1965

August 14, 2003 North-East Blackout in US, Canada

RTO/ISO in USA

Reliability Coordinators in Midwest



2003 US Blackout: Few Events

https://en.wikipedia.org/wiki/Northeast_blackout_of_2003

- 12:15 p.m. Incorrect telemetry data renders inoperative the state estimator, operated by the Indiana-based MISO. An operator corrects the telemetry problem but forgets to restart the monitoring tool.
- 2:02 p.m. The first of several 345 kV overhead transmission lines in northeast Ohio fails due to contact with a tree in Walton Hills, Ohio
- 2:14 p.m. An alarm system fails at FirstEnergy's control room, not repaired.
- 3:05 p.m. A 345 kV transmission line known as the Chamberlin-Harding line sags into a tree and trips in Parma, south of Cleveland.
- 3:32 p.m. Power shifted onto another 345 kV line, the Hanna-Juniper interconnection, causes it to sag into a tree, bringing it offline as well. While MISO and FirstEnergy controllers concentrate on understanding the failures, they fail to inform system controllers in nearby states.
- 3:39 p.m. A FirstEnergy 138 kV line trips in northern Ohio.
- 4:05:57 p.m. The Sammis-Star 345 kV line trips due to undervoltage and overcurrent interpreted as a short circuit. Later analysis suggests that the blackout could have been averted prior to this failure by cutting 1.5 GW of load in the Cleveland–Akron area.

- 4:09:02 p.m. Voltage sags deeply as Ohio draws 2 GW of power from Michigan.
- 4:10:34 p.m. Many transmission lines trip out, first in Michigan and then in Ohio, blocking the eastward flow of power around the south shore through Erie, Pennsylvania and into the Buffalo, New York area.
- 4:10:38 p.m. Cleveland separates from the Pennsylvania grid after a series of line and generator trip.
- 4:10:40 p.m. Flow flips to 2 GW eastward from Michigan through Ontario (a net reversal of 5.7 GW of power), then reverses back westward again within a half second.
- 4:10:43 p.m. International connections between the United States and Canada start to fail.
- 4:10:45 p.m. Northwestern Ontario separates from the east The first Ontario power plants go offline
- 4:10:46 p.m. New York separates from the New England grid.
- 4:10:50 p.m. Ontario separates from the western New York grid, cascaded separation and tripping happens.
- 4:13 p.m. End of cascading failure. 256 power plants are off-line, 85% of which went offline after the grid separations occurred, most due to the action of automatic protective controls.

Blackout Root Cause : FE Situational Awareness & Vegetation Management

- **FE did not ensure a reliable system after contingencies occurred because it did not have an effective contingency analysis capability**
- **FE did not have effective procedures to ensure operators were aware of the status of critical monitoring tools**
- **FE did not have effective procedures to test monitoring tools after repairs**
- **FE did not have additional high level monitoring tools after alarm system failed**
- **FE did not adequately manage tree growth in its transmission rights of way**

Blackout Cause: Reliability Coordinator Diagnostics

- **MISO's state estimator failed due to a data error.**
- **MISO's flowgate monitoring tool didn't have real-time line information to detect growing overloads**
- **MISO operators couldn't easily link breaker status to line status to understand changing conditions.**
- **PJM and MISO ineffective procedures and wide grid visibility to coordinate problems affecting their common boundaries**

Grid Disturbances in India on 30th & 31st July 2012

Enquiry Committee report

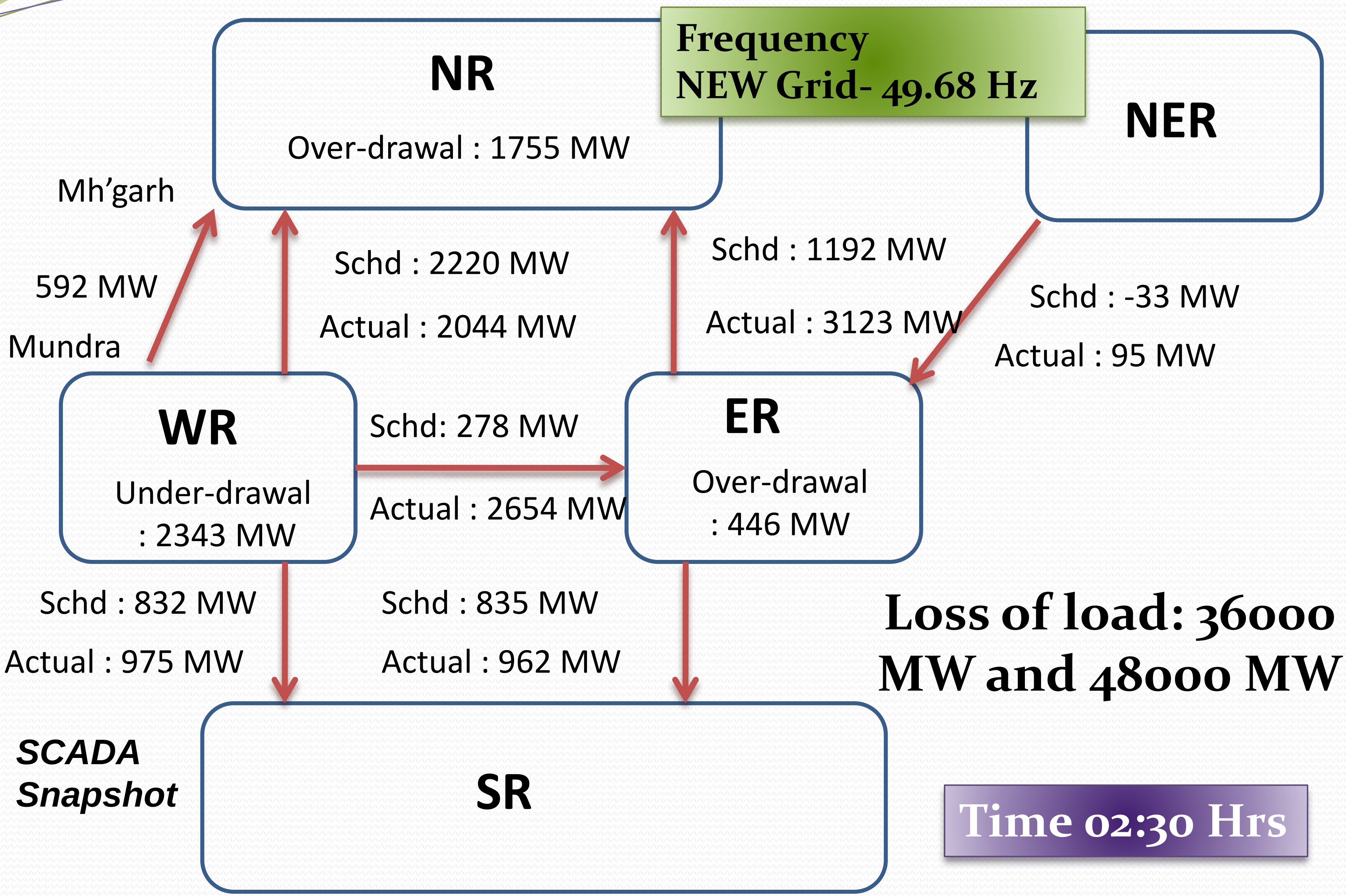
posted at

http://www.cercind.gov.in/2012/orders/

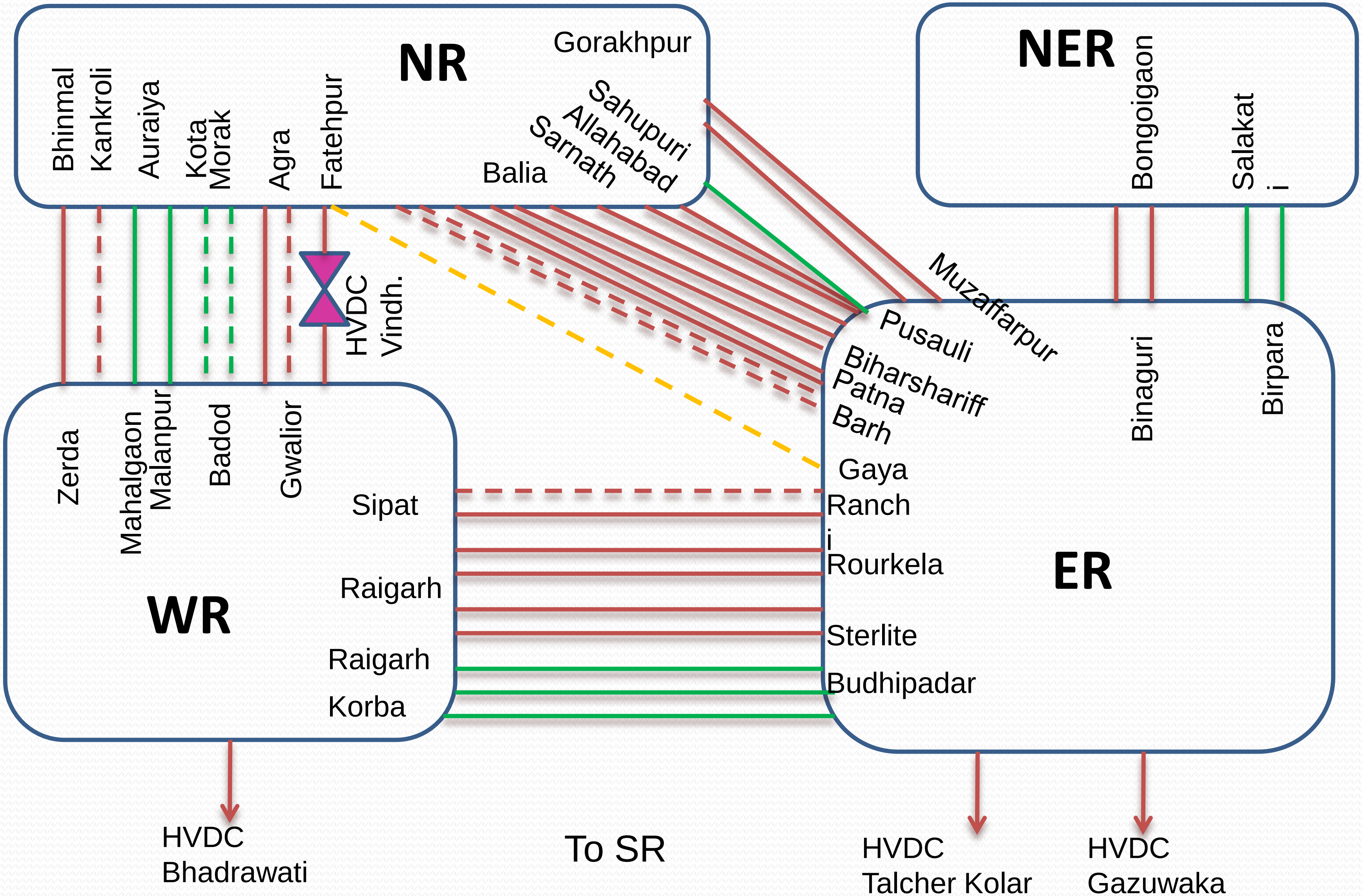
Final_Report_Grid_Disturbance.pdf

Loss of load: 36000 and 48000 MW

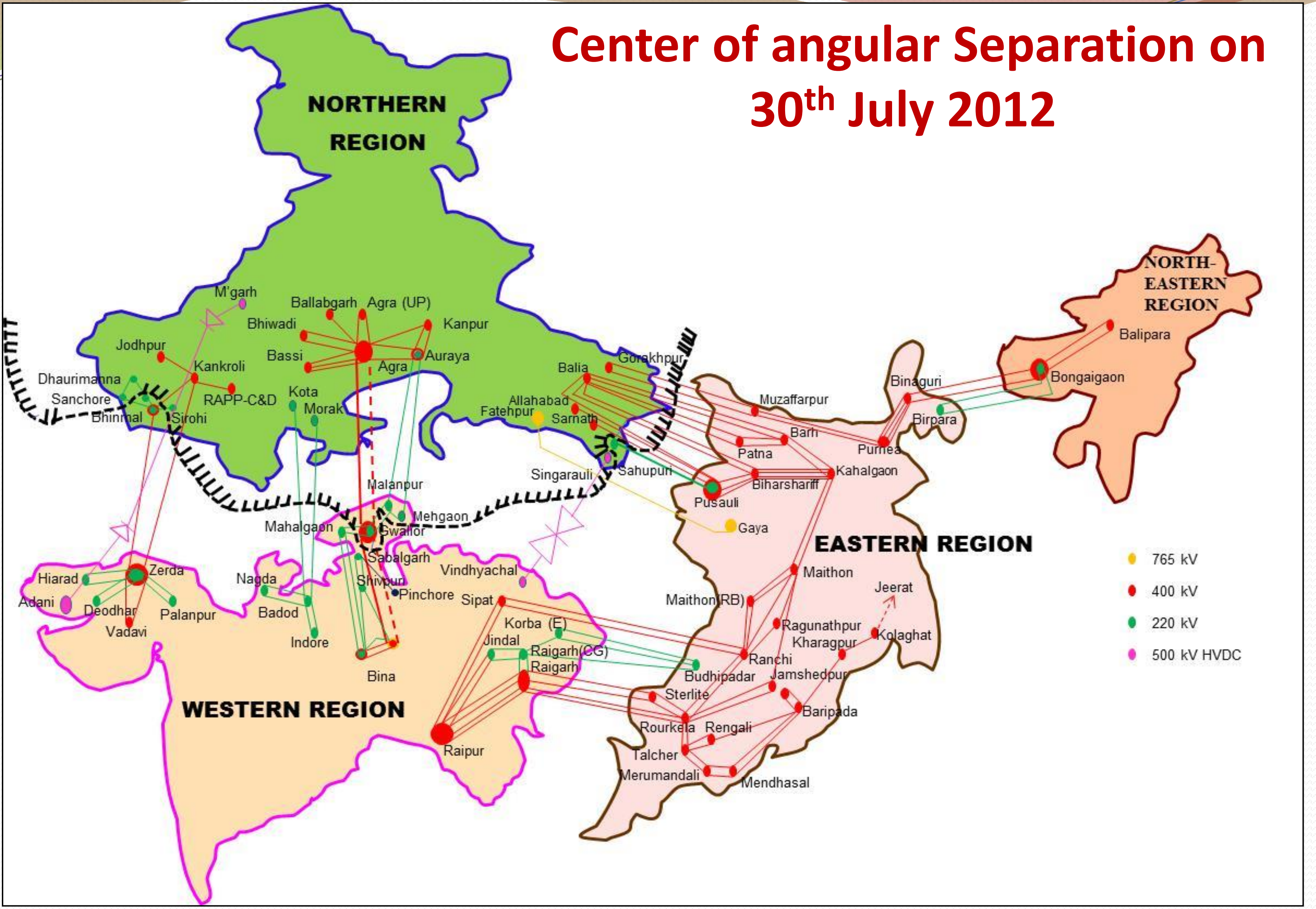
Antecedent Conditions on 30th July 2012



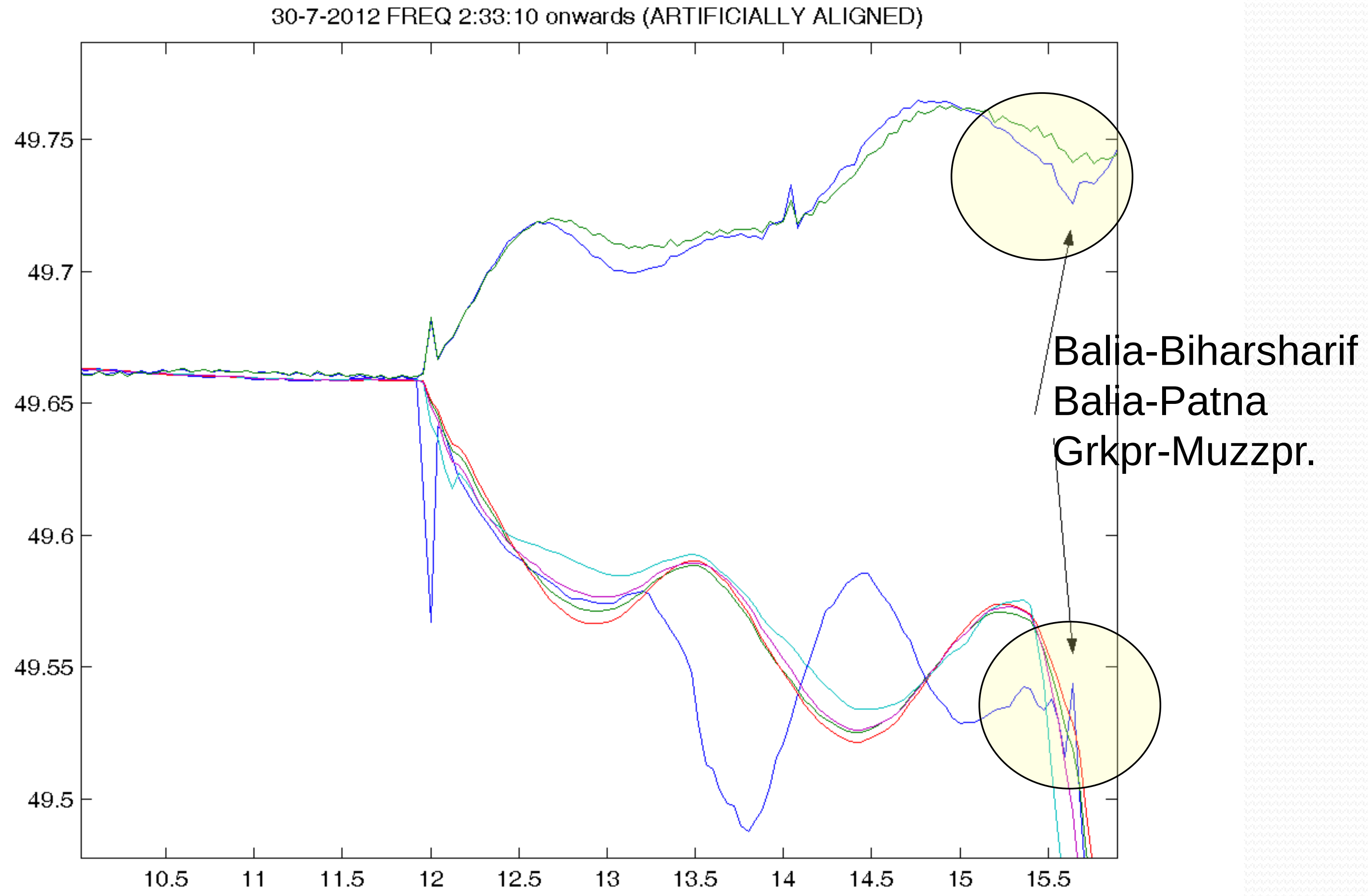
Inter-regional lines under outage on 30th July 2012



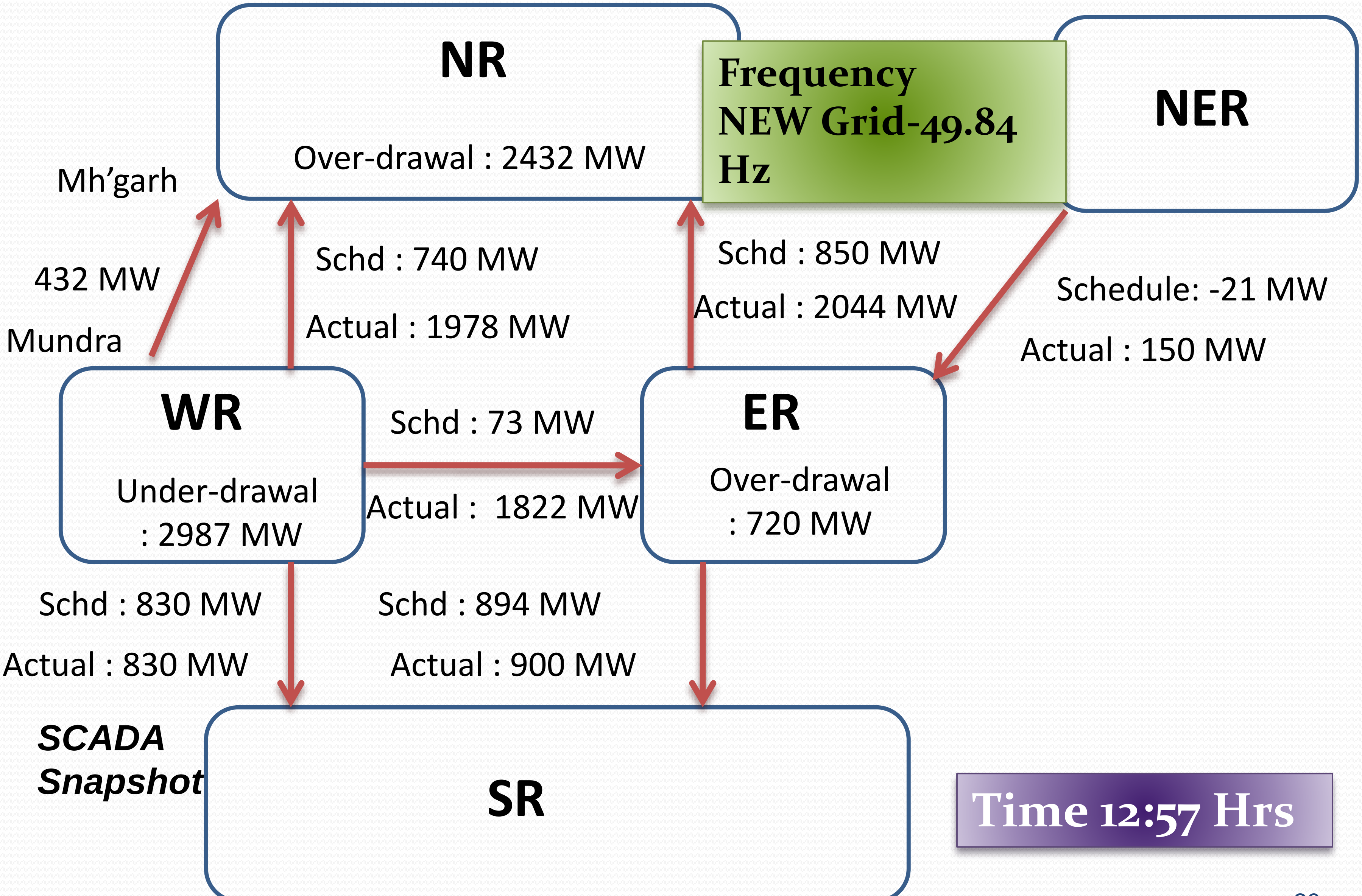
Center of angular Separation on 30th July 2012



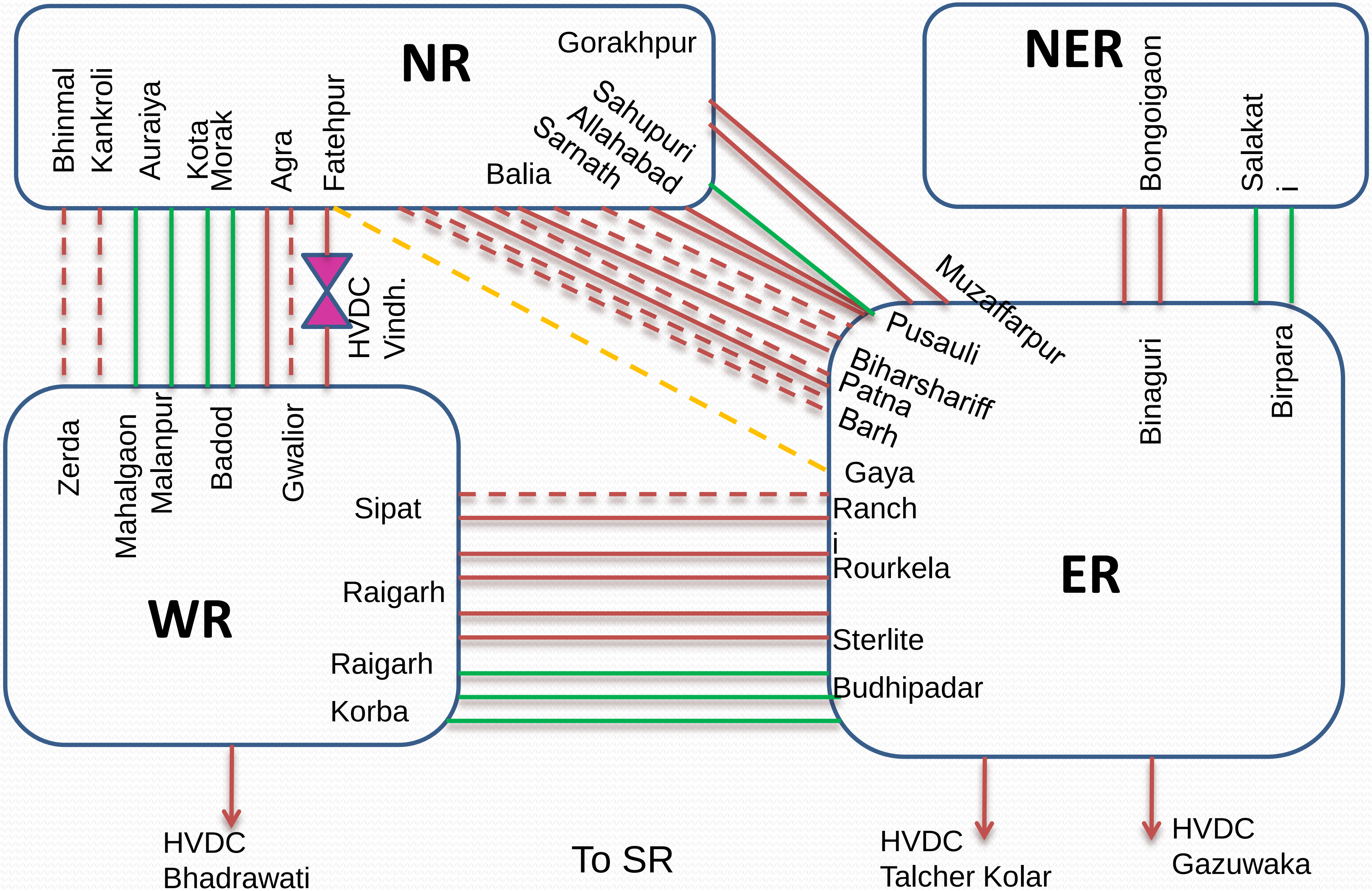
PMU plots on 30th July 2012. The trippings at ~2:33:15 due to large angular separation – correlates with DRs and WAFMS



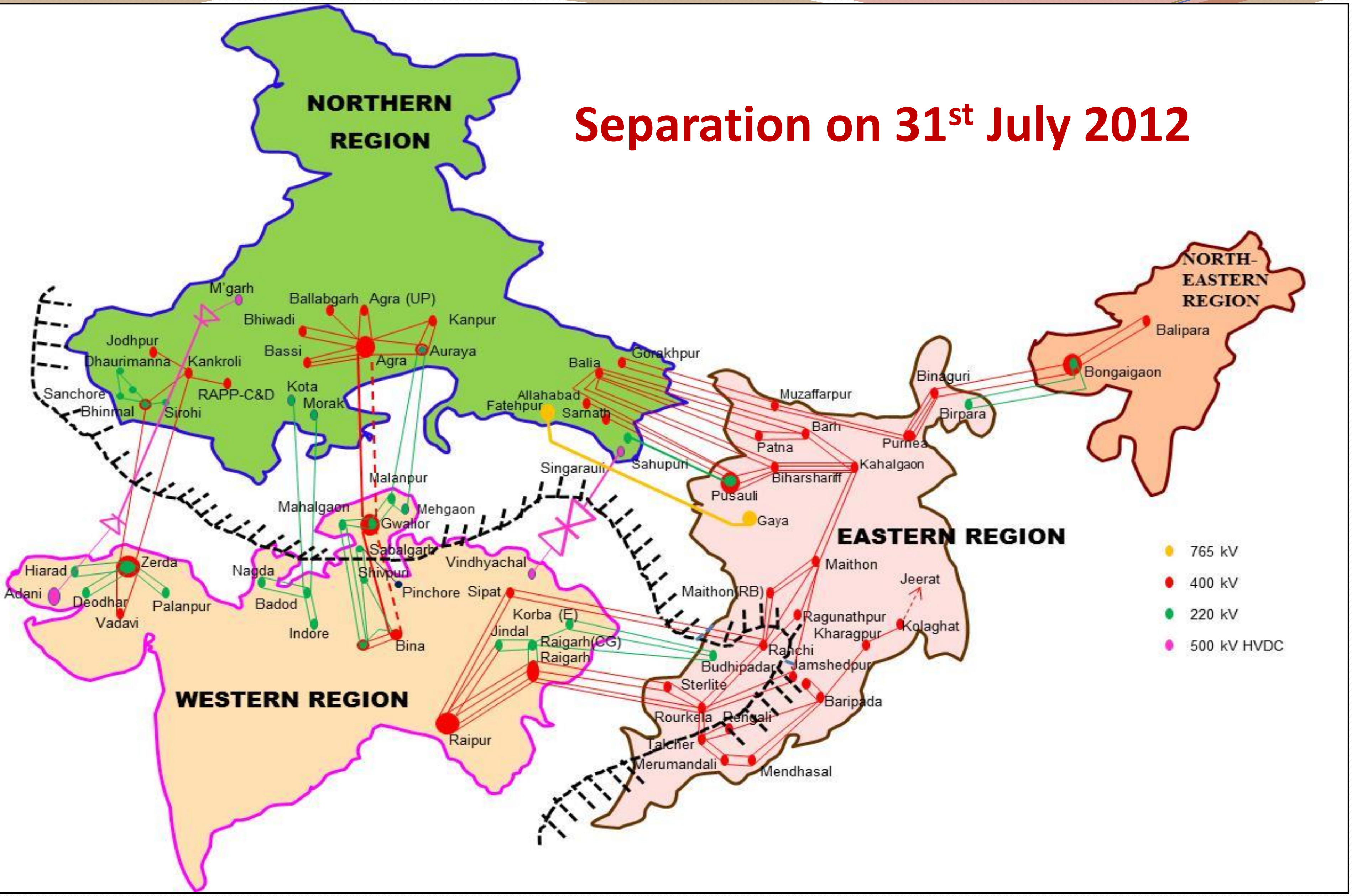
Antecedent Conditions on 31st July 2012



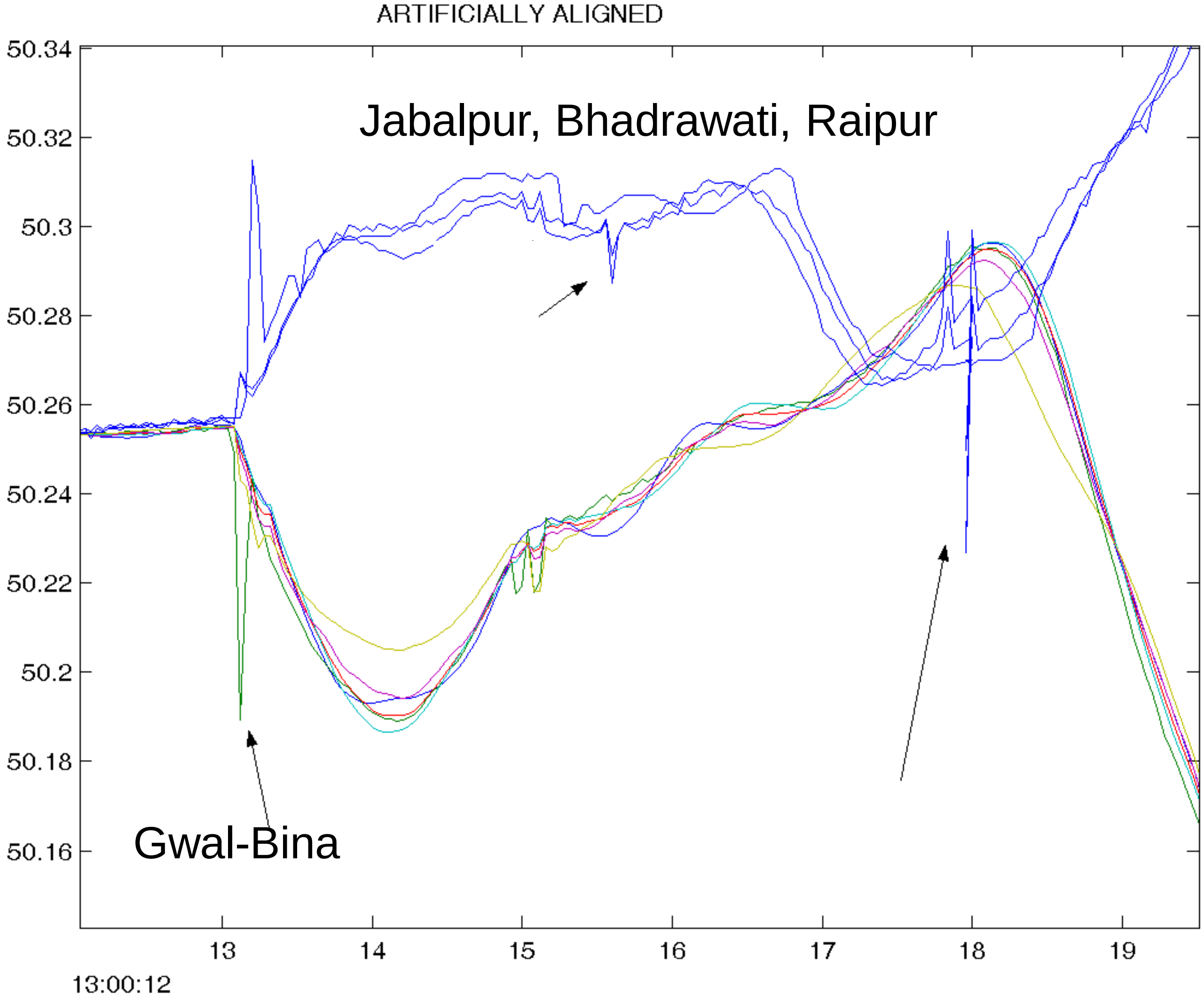
Inter-regional lines under outage on 31st July 2012



Separation on 31st July 2012



PMU Plots



ARTIFICIALLY ALIGNED
Jabalpur, Bhadrawati, Raipur
Gwal-Bina
50.34
50.32
50.3
50.28
50.26
50.24
50.22
50.2
50.18
50.16
13
14
15
16
17
18
19
13:00:12

Important Observations

Few Major Causes of the Grid Disturbances:

- Lack of Situational Awareness and real time monitoring tools
- Early security assessment/warning system.
- Unintended operation of Protection/ Improper coordination of Control Actions
- Lack of enough reactive compensation
- Human error & Grid Indiscipline

Few Remedial Measures:

- Wide area monitoring & control. PGCIL-URTDMS Project (http://www.cea.nic.in/reports/powersystems/sppa/scm/allindia/agenda_note/1st.pdf)
- Ensuring activation of all emergency controls and protection
- Smart grid - Proper automation, information flow and data management.
- Regulatory changes to strengthen system security and operation.

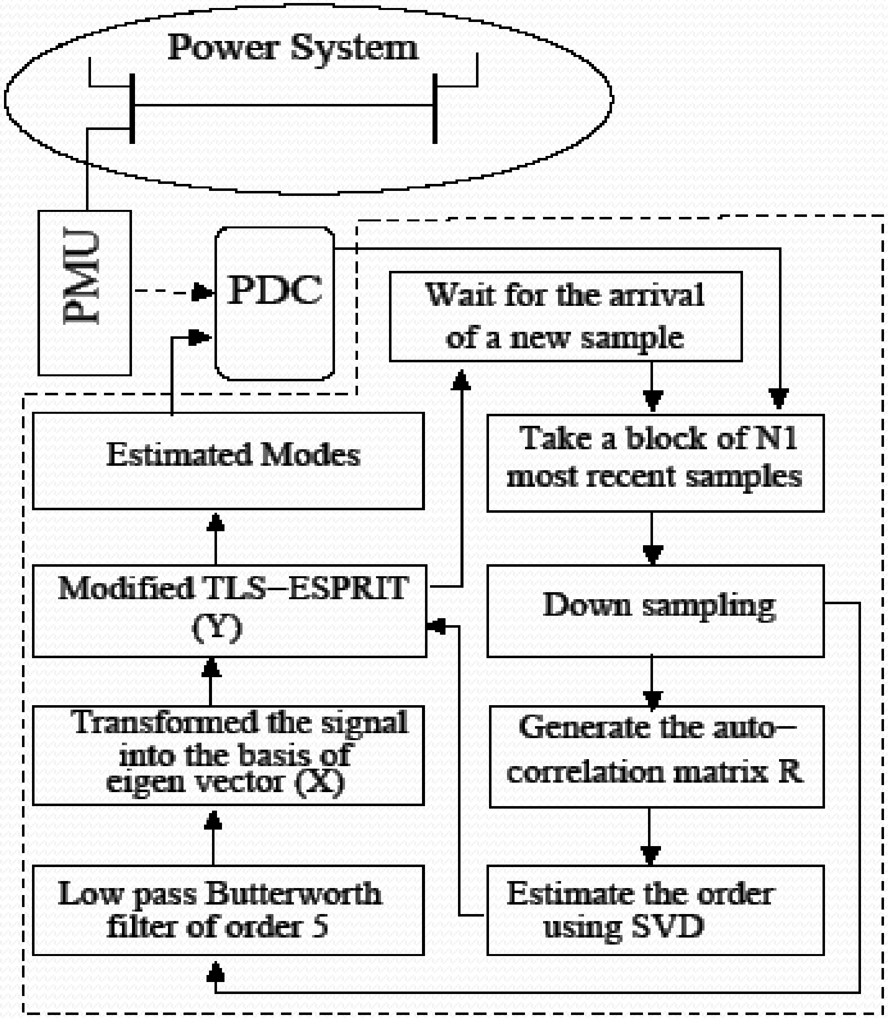
Roadmap of WAMCPS Deployment in India

- Pilot projects in all regions already in place.
- Integrate the pilot project PMUs with the National plan.
- Unified Real Time Dynamic Measurement System (URTDMS) being implemented.
- About 1700 PMUs are planned, to be placed at all the 400 kV and above voltage buses and major generating plant buses. Analytics being developed by IIT Bombay.
- Few analytics to be implemented in the first phase include; Line parameter estimation, Oscillation monitoring, Distance relays' vulnerability analysis, Linear/dynamic state estimation, CT/CVT calibration, Supervision of zone-3 distance protection.

Some Research Work on Synchrophasor based WAMCPS carried out at IIT Kanpur

- **Phasor Assisted State Estimation**
- **Dynamic Phasor Estimation**
- **Machine Rotor Angle Estimation for Transient Stability**
- **Critical Mode Identification for Small Signal Stability**
- **Synchrophasor based Voltage Stability Assessment**
- **Wide Area Measurement based Adaptive Distance Protection**
- **Network based Wide Area Damping Control**
- **Optimal Frequency and Voltage stability based load shedding**
- **Load, Transmission Line and Generator Model Parameter Estimation.**
- **On Line Tuning of Power system Stabilizers**
- **Testing in WAMS Lab using RTDS**

Modified TLS-ESPRIT+ based Low Frequency Mode Identification*



+ Total Least Squares Estimation of Signal Parameters via Rotational Invariance Technique (TLS-ESPIRIT)

*P. Tripathy, S. C. Srivastava, and S. N. Singh, "A Modified TLS-ESPRIT-Based Method for Low-Frequency Mode Identification in Power Systems Utilizing Synchrophasor Measurements", *IEEE Transactions on Power Systems*, vol. 26, no. 2, May 2011, pp. 719-727.

Test Cases

- Test signals corresponding to inter-Area modes
  - The test signal, considered for simulations had a small signal oscillation* of 0.4 Hz, having attenuation factor -0.07, amplitude set to unity with an initial phase of 60 degree.
- Two area test system assuming the availability of power signals from PMUs (Ref: Kundur's book)
- Probing test data of the Western Electricity Coordination Council (WECC) system (obtained from BPA site)
- PMU data obtained on Northern Grid system (source: POSOCO)

Test Signal corresponding to Inter- Area Oscillations with SNR 30 dB

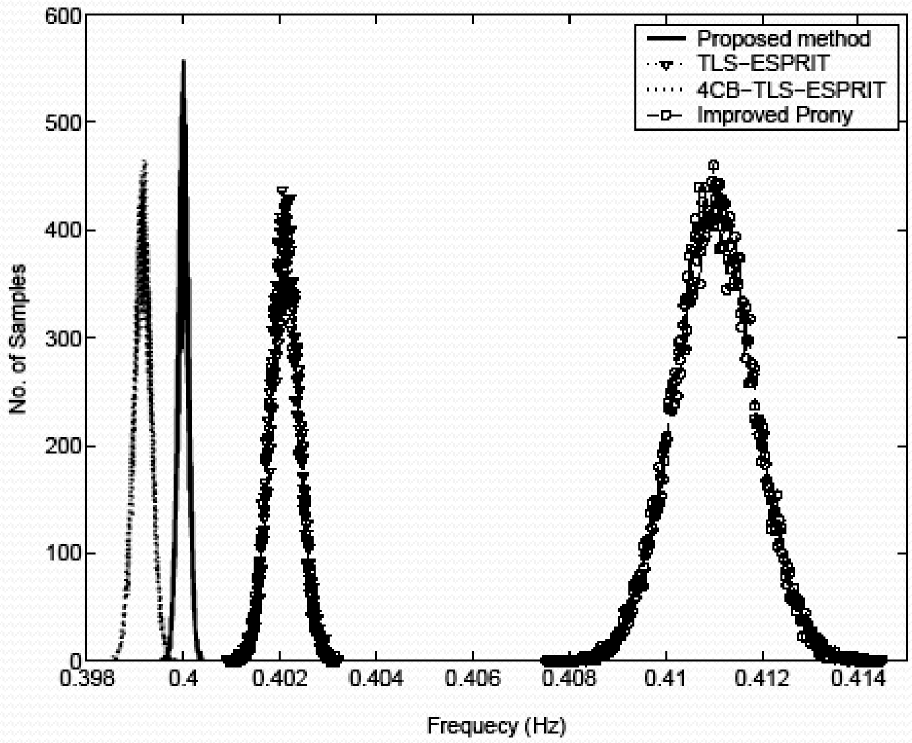


Figure: Distribution of the estimated frequency

- Standard deviation of proposed method is 62% as compared with 4CB-TLS-ESPRIT
- Bias in mean for proposed method=3.9999×10^{-1}, and 4CB-TLS-ESPRIT=3.9915×10^{-1}
- Bias in mean for Proposed method=2.79×10^{-6}, and 4CB-TLS-ESPRIT=8.45×10^{-4}

Test Signal corresponding to Inter- Area Oscillations with SNR 30 dB

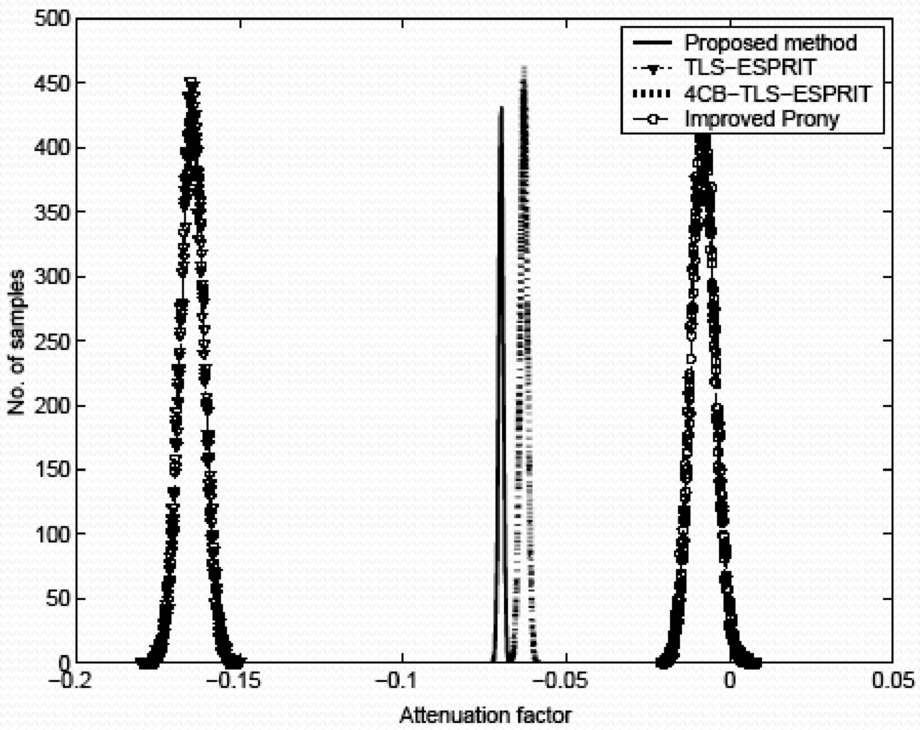


Figure: Distribution of the estimated attenuation factor

- Standard deviation of proposed method is 61% as compared with 4CB-TLS-ESPRIT
- Bias in mean for proposed method=-6.99×10^{-2}, and 4CB-TLS-ESPRIT=-6.29×10^{-2}
- Bias in mean for proposed method=1.36×10^{-5}, and 4CB-TLS-ESPRIT=7.01×10^{-3}

Improved Voltage Instability Monitoring Index*

Improved Voltage Instability Monitoring Index (IVIMI) :

$$\mathrm{IVIMI}_i = w_1(i) \times \frac{VDR_i}{\mathrm{VDR}_{\max}} + w_2(i) \times \frac{CVD_i}{\mathrm{CVD}_{\max}}$$

VDR – Voltage Deviation from its Reference
CVD – Consecutive Voltage Deviation (Rate of Voltage Deviation)

$$ISVIMI_i = \max(IVIMI_i^{\,p}) \quad p \in all\ the\ load\ buses\ set$$

- $ISVIMI_i$ is system wide voltage instability index at instant-i.
- Based on voltage deviation and rate of voltage change.
- Rate of change of voltage reflects the dynamic variation.

* Sodhi, R., Srivastava, S.C., Singh, S.N., "A Simple Scheme for Wide Area Detection of Impending Voltage Instability," *IEEE Trans. on Smart Grid*, vol.3, no.2, pp.818-827, June 2012.

*Ch. V. V. S. Bhaskara Reddy, S. C. Srivastava and Saikat Chakrabarti, “An improved Static Voltage Stability Index using Synchrophasor Measurements for Early Detection of Impending Voltage Instability,” National Power Systems Conference (NPSC), IIT (BHU), Varanasi, India, December 12-14, 2012.

Voltage Stability Risk Index (VSRI)#

1. Calculate the Moving Average $$v_j = \frac{1}{N}\sum_{i=1}^{N} v_i$$

2. Calculate the % diversity of the *i*th measurement $$d_i = \frac{v_i - v_j}{v_j} \times 100$$

3. Calculate the Risk Index $$z_j = \frac{1}{N}\left[\frac{\sum_{i=1}^{N}(d_i + d_{(i-1)})\Delta t}{2}\right]$$

where, V_i= voltage measurement at *i*th interval
V_j=moving average of *j*th window,
N=length of the moving window,
d_j=diversity of th *i*th measurement for the *j*th window
Z_j = VSRI of the *j*th window.

Kim, *et al.*, "System an method for calculating real-time voltage stability risk index in power system using time series data," Patent No. US007236898B2, Dt. Jun. 26,2007.

Simulation Results

NRPG 246 bus Indian test system

i. Slow increase of load

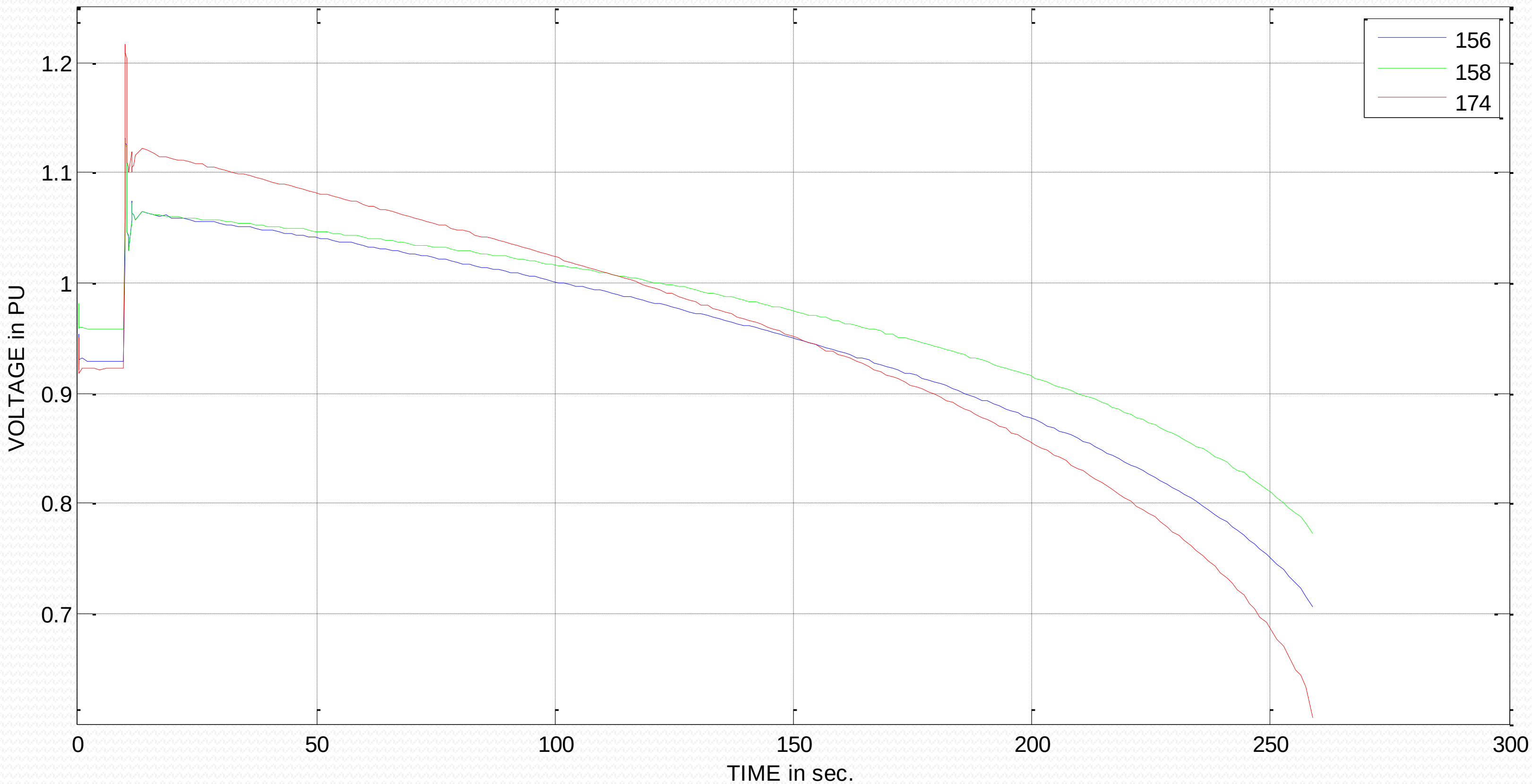


Fig: Critical bus voltages for load increase.

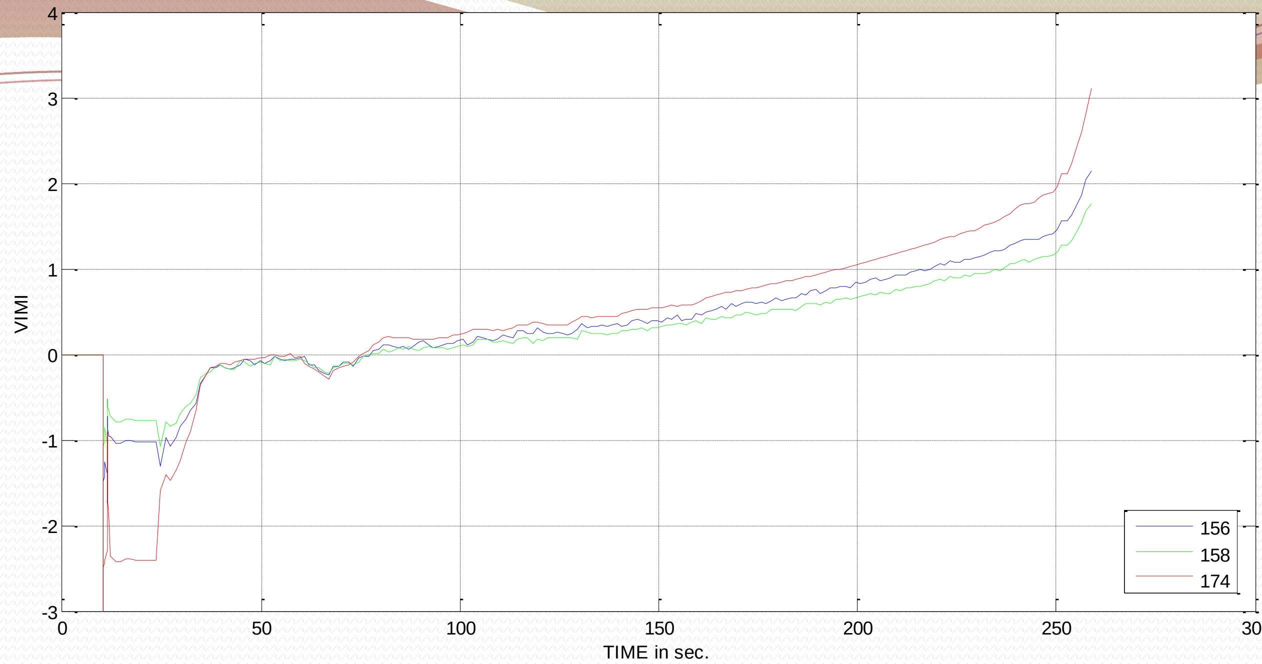


Fig: IVIMI plot for load increase. (195 s early prediction)

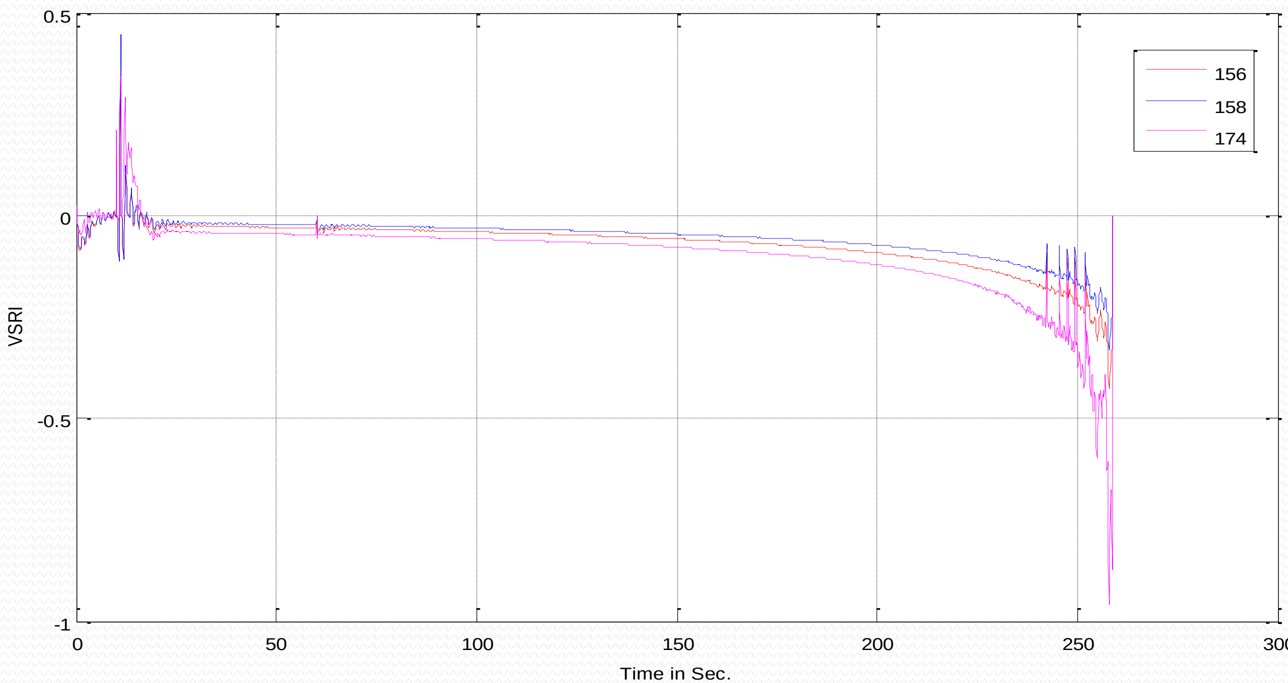


Fig.: VSRI plot for load increase.

ii. A line outage and simultaneous load increase

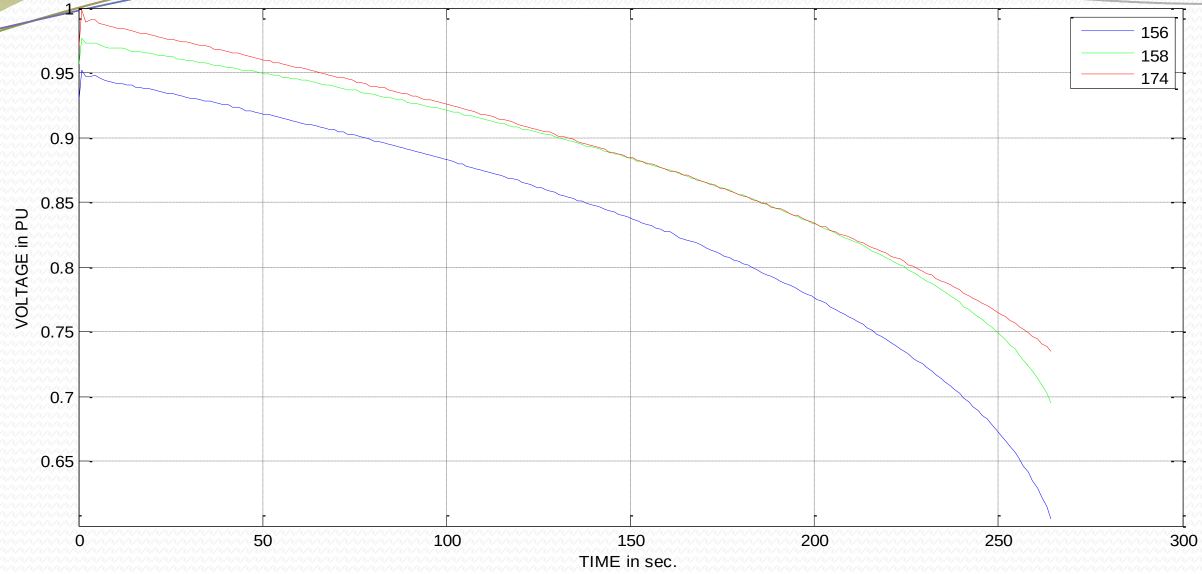


Fig: Critical bus voltages for line outage

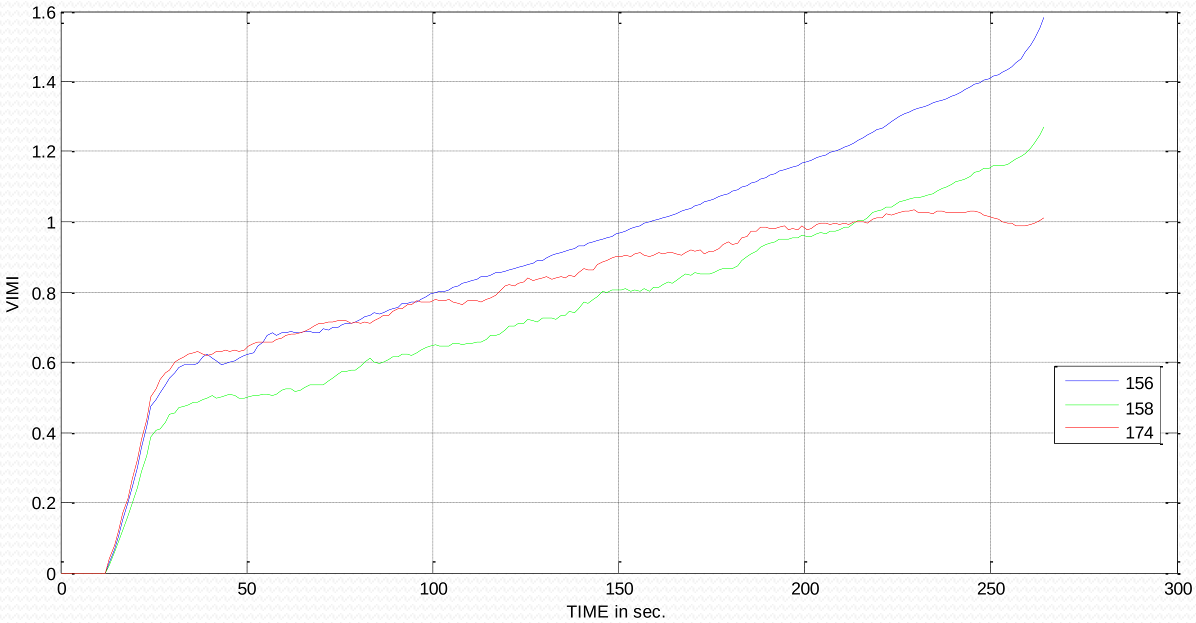
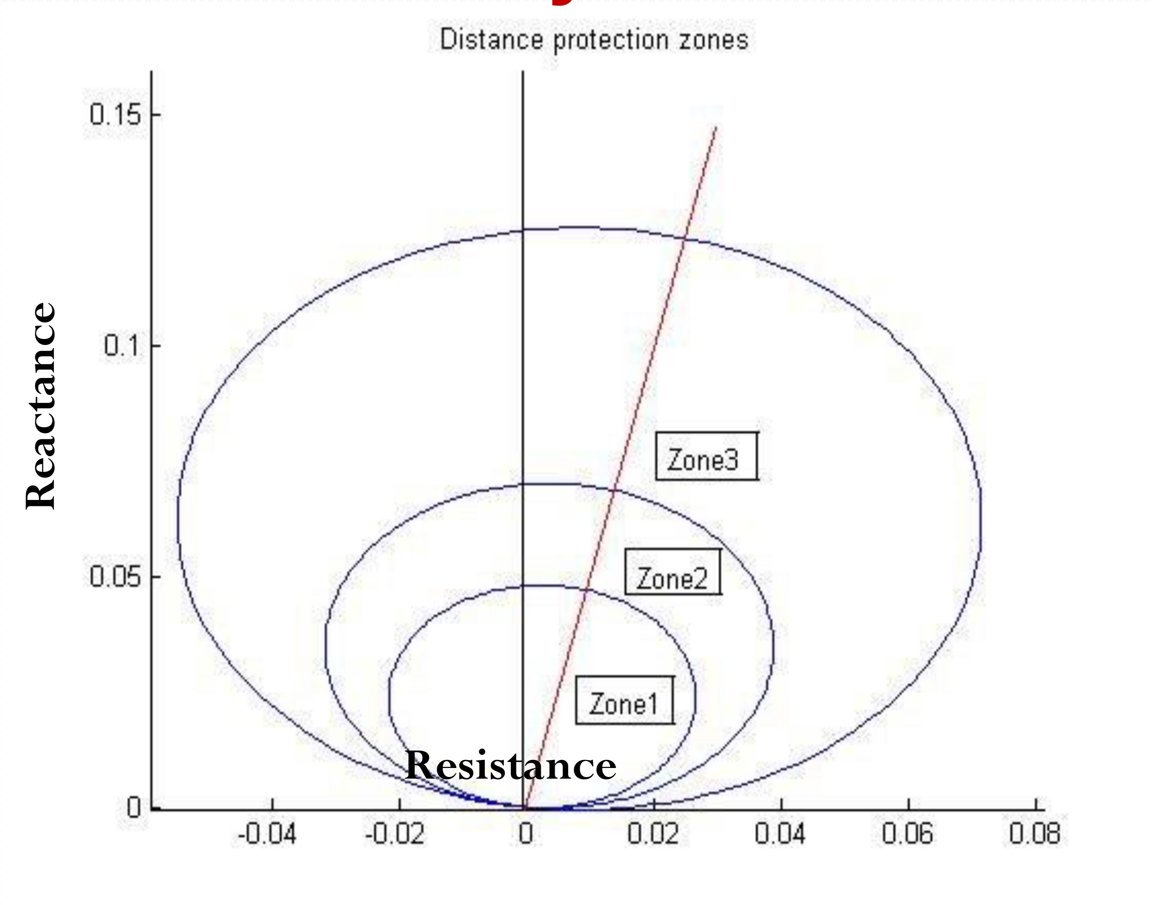


Fig: IVIMI plot for load increase. (170 s early prediction)

Distance Relay Protection



- Power system events that cause the impedance trajectories to enter into tripping zones, under no-fault situations, cause system security concerns.

Unintended Operation of Distance Relays

- Due to impedance trajectory encroachment into relay tripping zone.
- System events which, sometimes, lead to distance relay operation
  - Dynamic
    - Power Swings - Blinders and Timer blocking scheme
    - Voltage Instability
  - Static
    - Load encroachment
- Operation under Zone-3 has been observed to result in cascading failures of power systems.

A Method* using SVM to avoid Unintended Operation of Distance Relays

- **Relay Ranking Index**
  - Ratio of normalized apparent impedance of the relay to branch loss sensitivity used to rank the relays in terms of its vulnerability to Power Swings and Voltage Instability.

- **Fault and Disturbance Classifiers**
  - Two support vector machines used, SVM-1 for distinguishing between fault and no fault condition, and SVM-2 for classifying the no fault disturbance in 'Voltage Instability' or 'Power Swing.

*Seethalekshmi K., S.N. Singh and S.C. Srivastava, "A Classification Approach Using Support Vector Machines to Prevent Distance Relay Mal-operation under Power Swing and Voltage Instability", IEEE Transactions on Power Delivery, Vol. 27, No. 3, July 2012, pp. 1124-1133.

Critical Relays' Identification

- Normalized Apparent Impedance for a relay, *Rij* in line i-j

$$Z_{r_{ij}} = \left| \frac{\overline{V}_i}{\left(\overline{V}_i - \overline{V}_j\right) / \overline{Z}_{r3ij}} \times \overline{Z}_{line} \right|$$

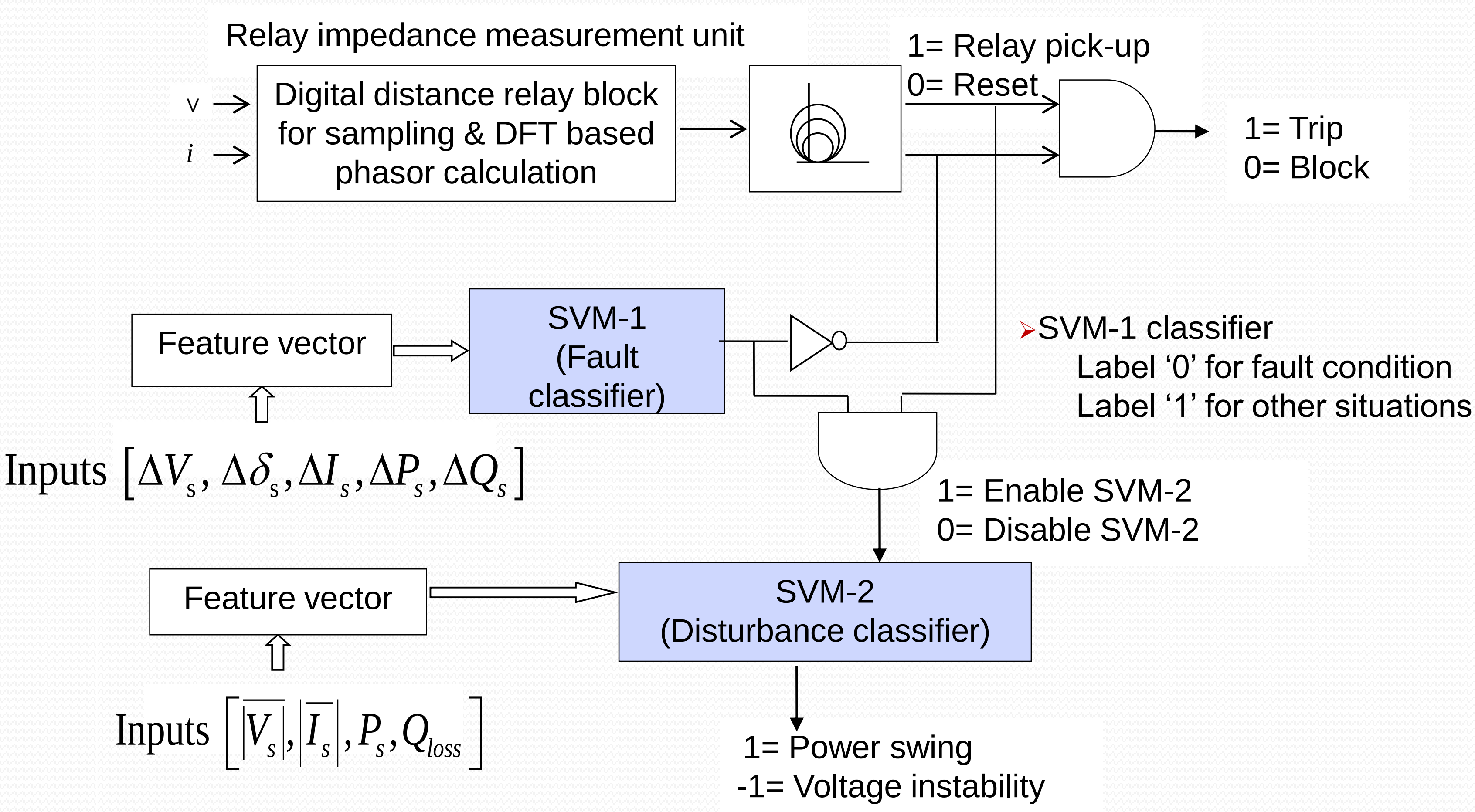
where, $\overline{V}_i$ and $\overline{V}_j$ are the sending and receiving end voltages of the line *i-j* and $\overline{Z}_{r3ij}$ is the impedance corresponding to third zone setting of the relay. $\overline{Z}_{line}$ is the impedance of the line.

- Branch loss sensitivity: $$S_{ij} = \sqrt{S_{ij}^{V_i^2} + S_{ij}^{V_j^2} + S_{ij}^{\delta_i^2} + S_{ij}^{\delta_j^2}}$$

where, $S_{ij}^{V_i} = \frac{\partial h}{\partial V_i},\ S_{ij}^{\delta_i} = \frac{\partial h}{\partial \delta_i},\ and \quad h = P_{loss} + jQ_{loss} in\ line\ i - j$

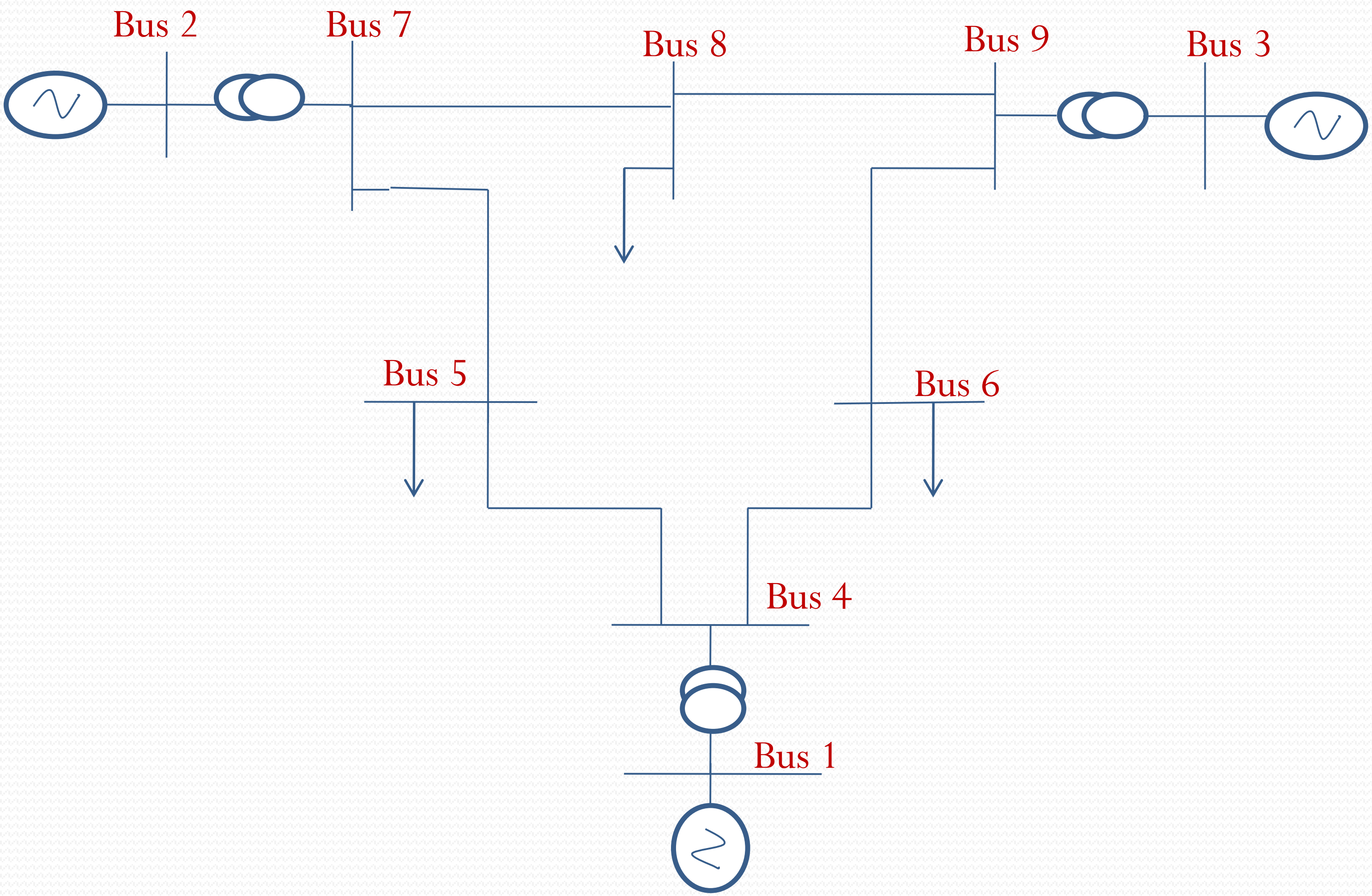
- **Relay Ranking Index** $$RRI_{ij} = \frac{\left|Zr_{ij}\right|}{S_{ij}}$$

Proposed Classification Strategy



Simulation Studies

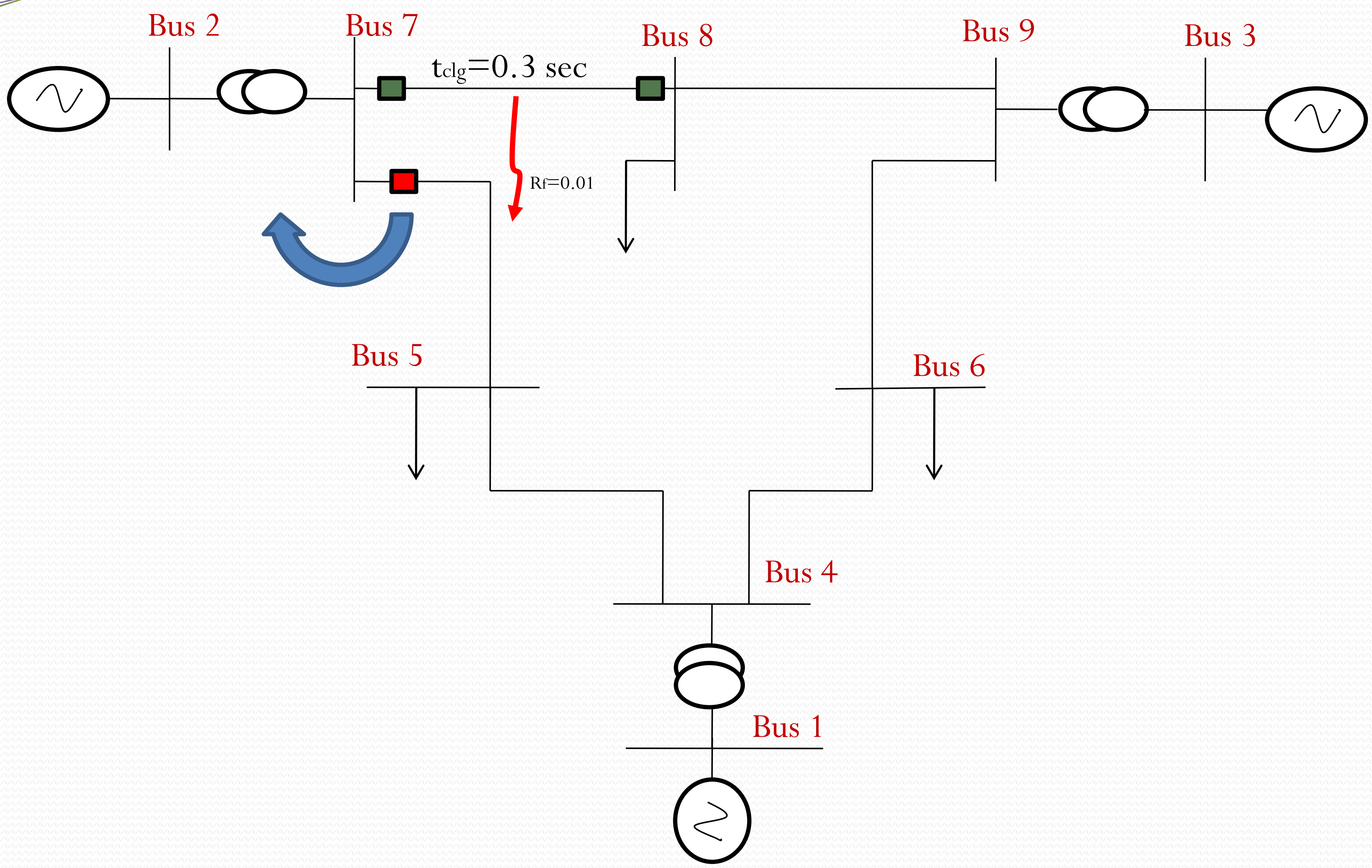
WSCC 9-bus System



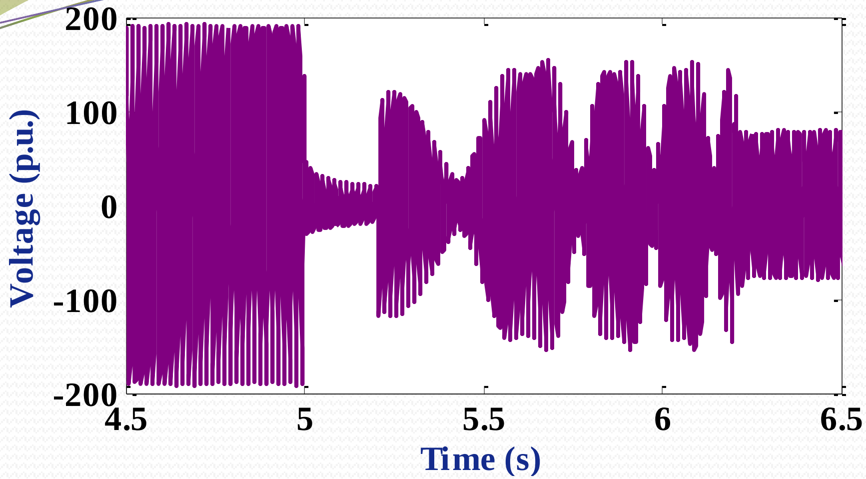
Step-1: Identification of Critical Relays

Relay No.	*Normalized Apparent Impedance*	*Branch Loss Sensitivity*	*Relay Ranking Index*	*Relay Ranking*
$R_{5\text{-}7}$	**0.0994**	**2.5031**	**0.0339**	**1**
$R_{7\text{-}5}$	**0.1025**	**2.4308**	**0.0360**	**2**
$R_{6\text{-}9}$	0.1201	1.6859	0.0608	3
$R_{9\text{-}6}$	0.1226	1.6534	0.0632	4
$R_{8\text{-}7}$	0.5456	2.1443	0.2171	5
$R_{7\text{-}8}$	0.5513	2.1232	0.2215	6
$R_{5\text{-}4}$	0.5643	1.4612	0.3294	7
$R_{4\text{-}5}$	0.5804	1.4376	0.3444	8
$R_{8\text{-}9}$	0.7929	0.7515	0.9001	9
$R_{9\text{-}8}$	0.8056	0.7440	0.9237	10
$R_{6\text{-}4}$	0.9881	0.8614	0.9786	11
$R_{4\text{-}6}$	1.0000	0.8531	1.0000	12

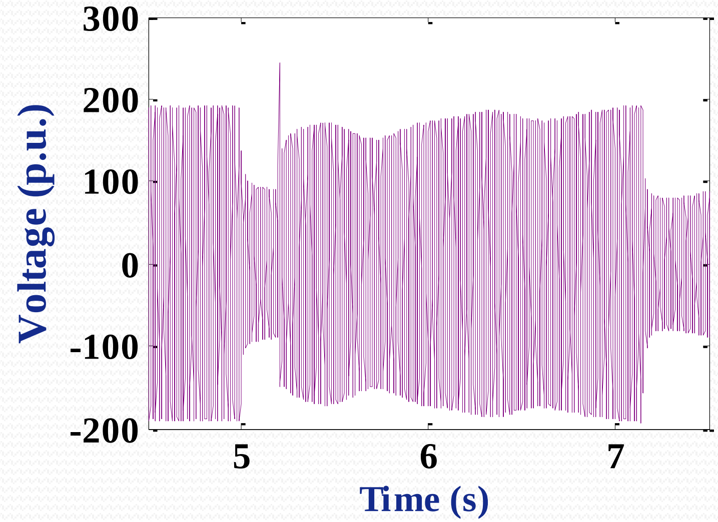
Simulation of Power Swing Scenario



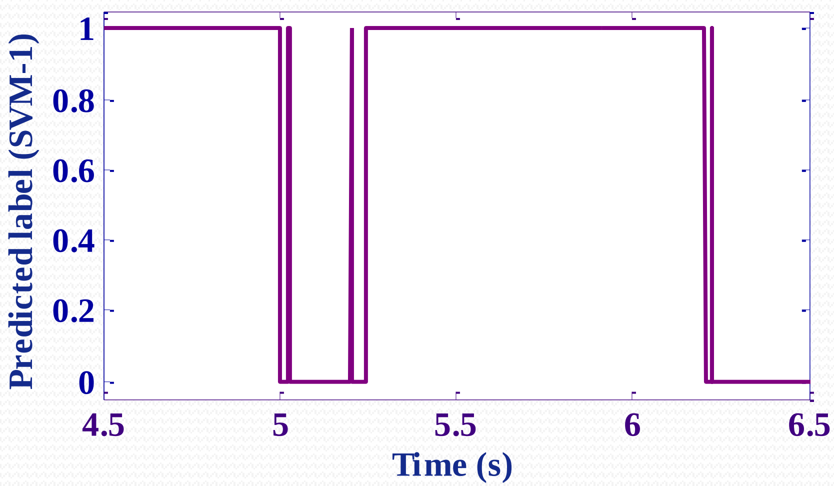
Classification by SVM-1



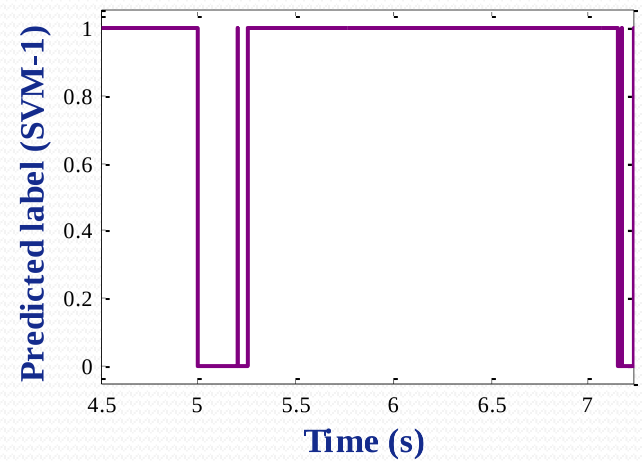
Fast Swing



Slow Swing

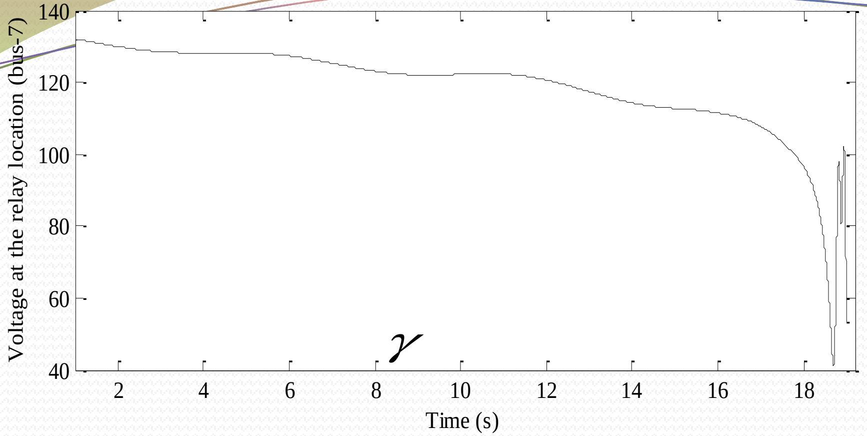


Classification label by SVM-1

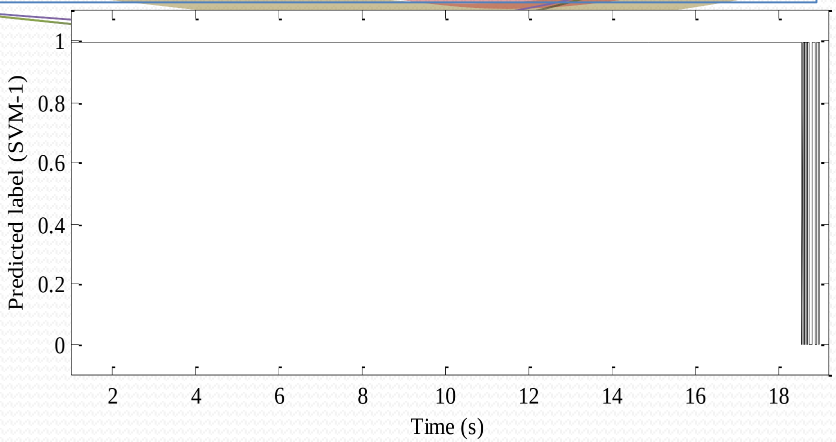


Classification label by SVM-1

Performance of SVM-1 (Fault Classifier)



Voltage unstable case



Classifier output

SVM-1 Comparison with ANFIS* Scheme

Scheme	Classification accuracy (%)	Testing accuracy (%)
ANFIS based classifier	80.02	75.83
SVM based proposed classifier	98.85	96.18

Accuracy of SVM-2 classifier in WSCC 9-bus system

Cases	Training accuracy (%)	Testing accuracy (%)
32	100	96.71

* H. K. Zadeh and Z. Li, "A novel power swing blocking scheme using adaptive neuro-fuzzy inference system, "Electric Power Systems Research, vol. 78, pp 1138-1146, 2008.

Avoiding Relay Unintended Operation Using Phasor Derivatives

Proposed Methodology:

- Logarithm of the singular values of the Hankel matrix formed from the Measurement data used for model order estimation.
- Second order Taylor series extended TLS-ESPRIT used for accurate dynamic phasor estimation*.
- Taylor's second order approximation used to estimate first and second derivatives of the phasor amplitude and phase derivatives.
- Deviation in the derivative values used to distinguish between fault and no fault conditions**.

* P. Banerjee and S. C. Srivastava, "An Effective Dynamic Current Phasor Estimator for Synchrophasor Measurements," *IEEE Transactions on Instrumentation and Measurements*, vol.64, no.3, Mar. 2015, pp. 625-637.

** Paramarshi Banerjee, *Improved Estimation of Dynamic Phasors, and their Applications in Distance Protection & Stability Assessment*, Ph.D. Thesis, IIT Kanpur, January 2015.

Proposed Approach for Relay Blocking

- The predicted and the accurate phasor at the present time

$$\hat{P}_k = \hat{X}_{b,k}^{(0)} e^{j\hat{\phi}_{b,k}^{(0)}}, \; P_k = X_{b,k}^{(0)} e^{j\phi_{b,k}^{(0)}}$$

- The vector deviation of the predicted phasor as a percentage of the amplitude at the fifth previous data window is given by

$$\% E = \frac{\sqrt{(\mathrm{Re}(\hat{P}_k) - \mathrm{Re}(P_k))^2 + (\mathrm{Im}(\hat{P}_k) - \mathrm{Im}(P_k))^2}}{X_{b,k-5\tau}^{(0)}} \times 100$$

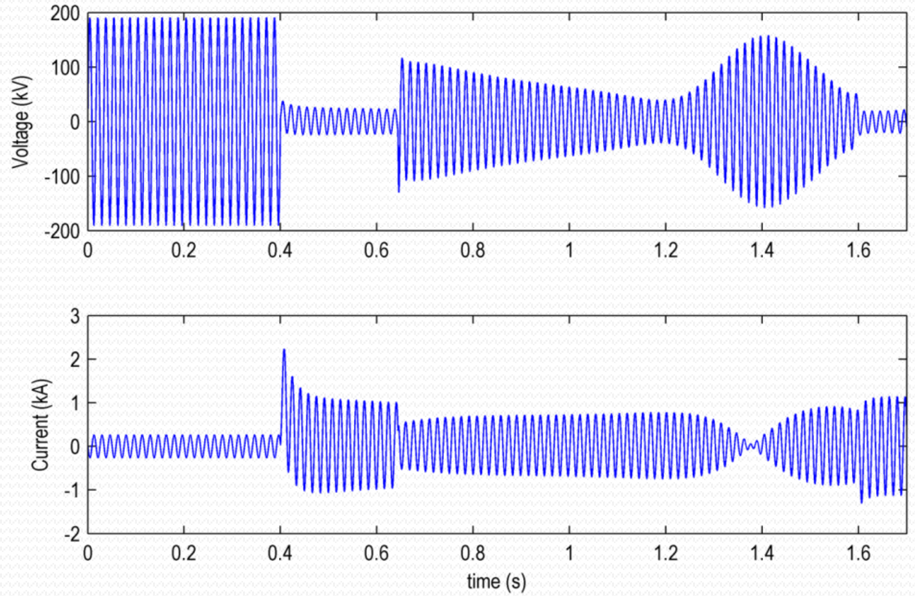
- Corresponding values for the voltage and the current phasors are denoted as E_V and E_I, respectively.

- The Relay Blocking (RB) signal is high and releases the relay for operation when E_V and E_I are simultaneously greater than 15% (experimentally established).

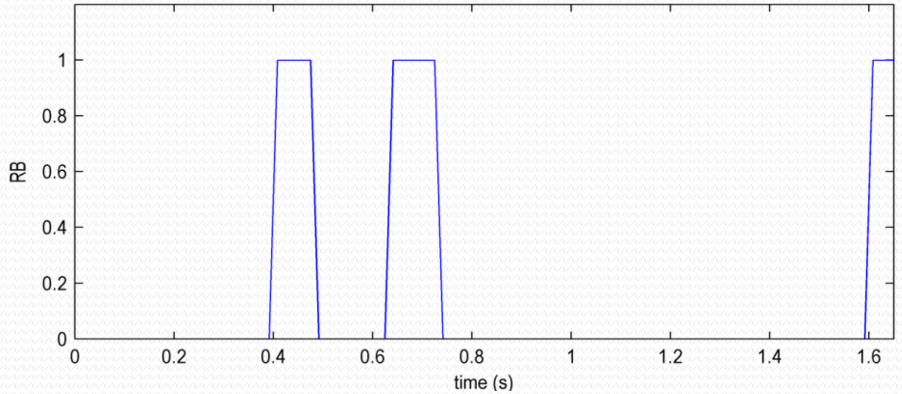
Performance Evaluation

- The proposed algorithm for generating RB signal should remain low for power swings and voltage instability but high for faults .
- The test cases considered in WSCC 9 bus system are
  - A:Unstable swing;
  - B:Fault during unstable swing;
  - C:Fault during stable swing;
  - D:Voltage Instability;
  - E:Fault during voltage instability;
- The test cases considered in NE-39 bus system are
  - F:Unstable swing;
  - G:2 cases of fault during unstable swing;
  - H:Stable swing;
  - I:Fault during stable swing;
  - J:Voltage Instability;
  - K:Fault during voltage instability;

Case B: Fault during unstable swing in WSCC 9 bus system

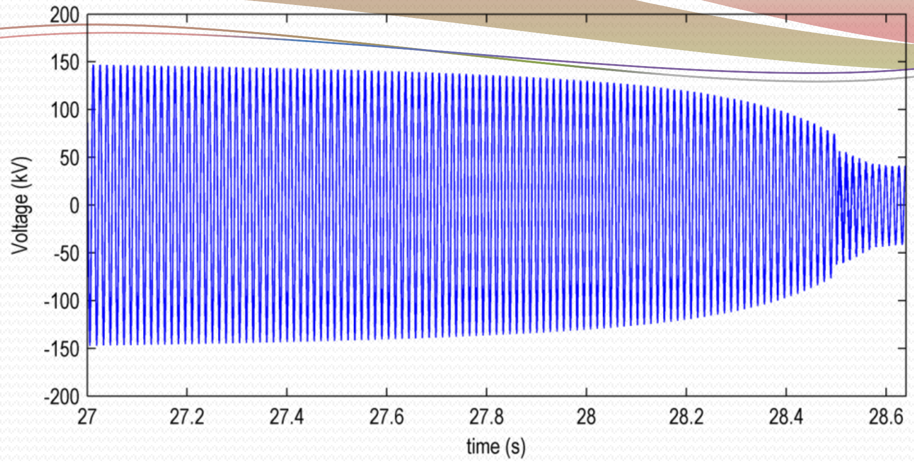


Voltage and current at bus 8 in WSCC 9 bus system for fault during unstable power swing.

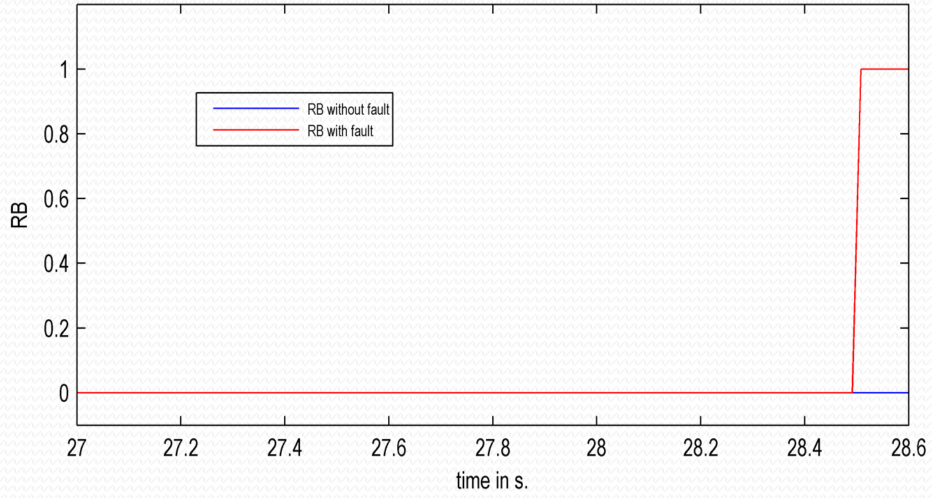


RB at bus 8 in WSCC 9 bus system for fault during unstable power swing.

Case D: Voltage Instability in WSCC 9 bus system

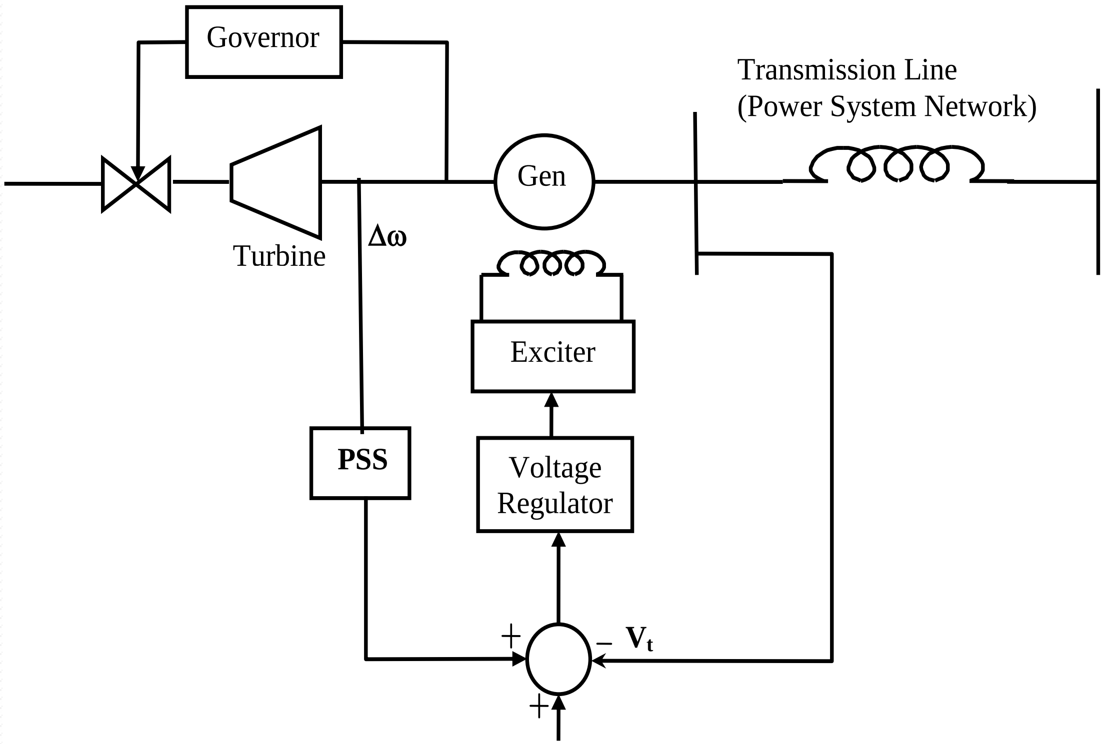


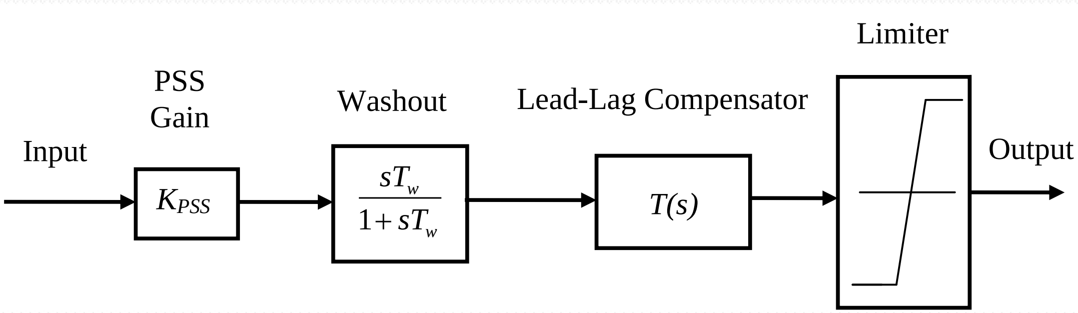
Voltage at bus 7 in WSCC 9 bus system for fault during voltage instability.



RB at bus 7 in WSCC 9 bus system during voltage instability

Local Stabilizing Control: Power System Stabilizers



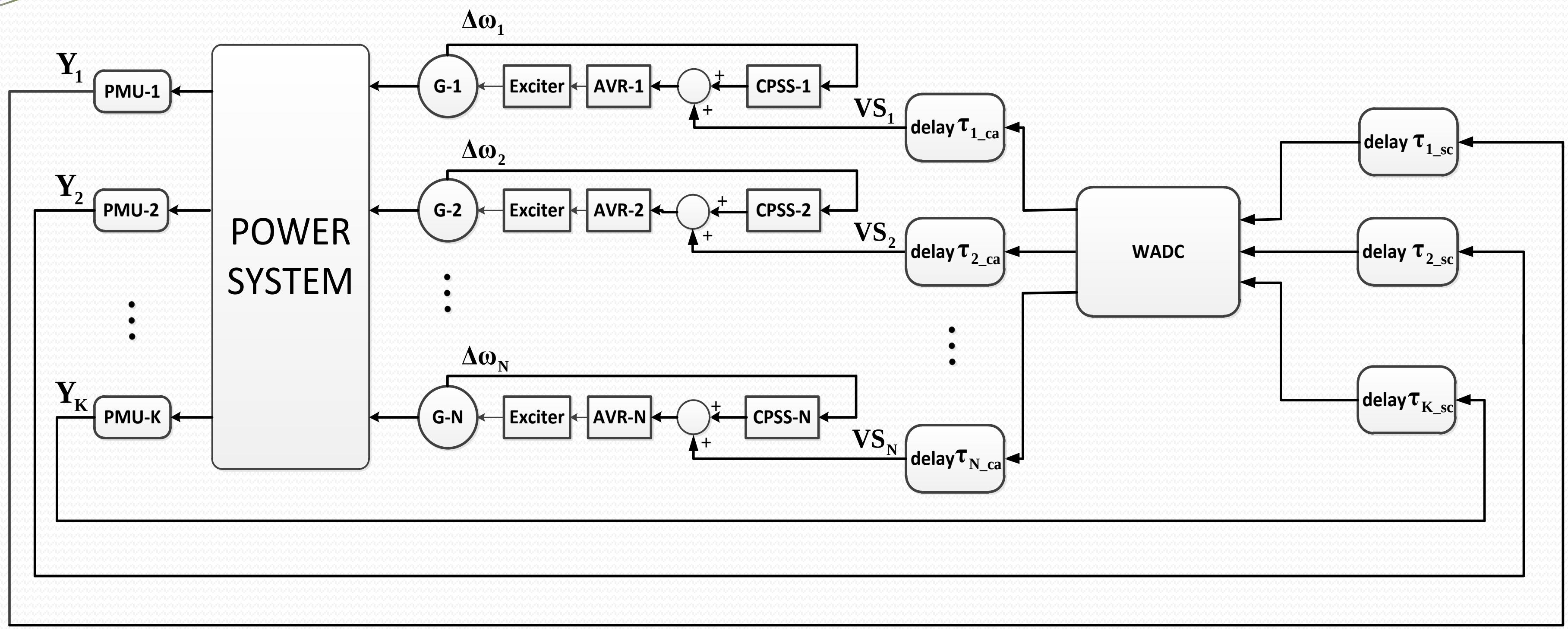


- It provides damping to the oscillations in the range of 0.2Hz-3 Hz, by modulating generator field excitation.
- The input signal can be rotor speed or frequency or line power flow power deviation.

Major Problems

- Robustness towards multiple operating conditions and topology-needs retuning.
- Lack of global observation.
- Coordination of multiple controllers

Centralized Wide Area Damping Controller

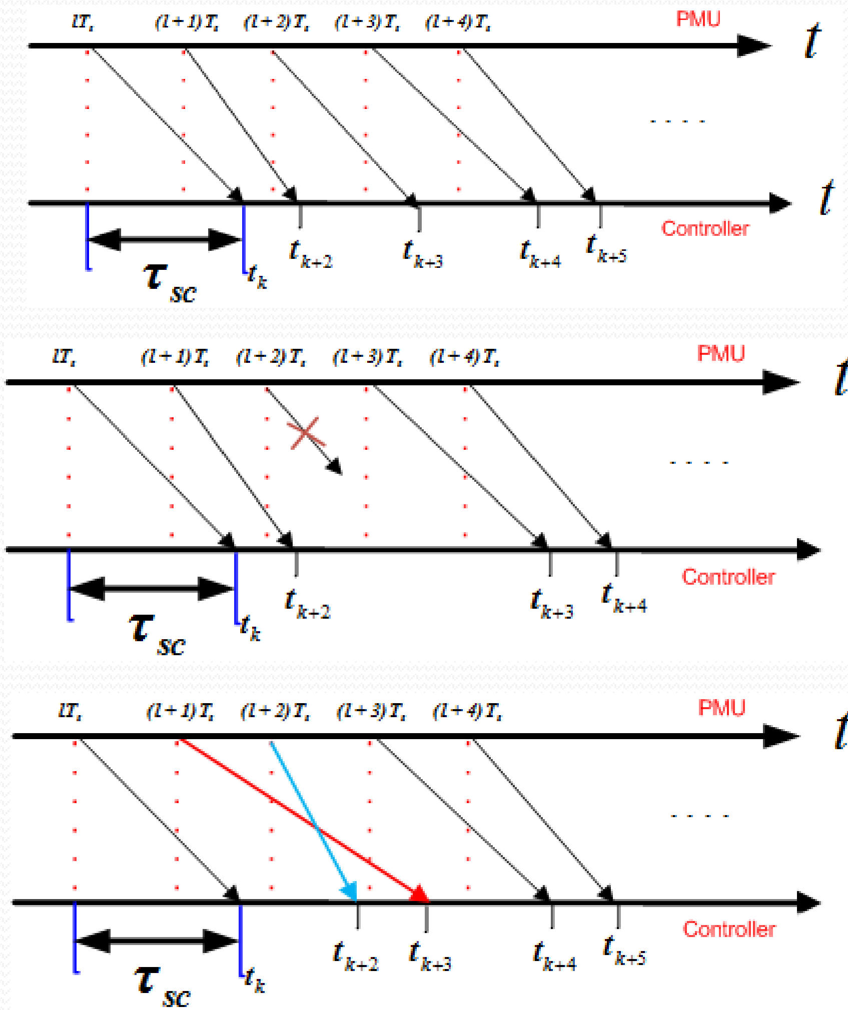


- A two-loop framework of a wide-area stability control system.
- The Wide-Area Damping Controller (WADC) in the higher level receives remote signals, $[Y_1 \quad Y_2 \quad \cdots \quad Y_K]$ from few pre-selected PMUs located in a wide-geographical area in the network & provides additional supplementary damping signals, $[VS_1 \quad VS_2 \quad \cdots \quad VS_N]$ to some of the pre-decided generators/FACTS devices

Issues with Wide-Area Damping Controller

Some of the major issues:

- The choice of the control I/O signals
- Control law or algorithm
- Latency in communication network
- Packet Loss
- Packet Disorder
- Channel Bandwidth
- Communication Failure



Wide-Area TS Fuzzy Output Feedback Controller with Input/Output Signal Selection

- Coherency based approach* for input/output signal selection
  - Data transformed into orthogonal space to make correlated variables uncorrelated by applying Principal Component Analysis (PCA).
  - Self-Organizing Map (SOM) for final data clustering. For clustering data, few critical line contingencies were considered.
- Producing better damping effect to the critical inter-area modes of oscillations. TS-Fuzzy Controller (WATSF) was applied**. Results compared with existing H2/H∞ Controller (called as WARDC)+.

* B.P. Padhy, S.C. Srivastava, and N.K. Verma, "A Coherency-Based Approach for Signal Selection for Wide Area Stabilizing Control in Power Systems", IEEE Syst. Journal, vol.7, no.4, pp.807-816, Dec. 2013.

**B.P. Padhy, S. C. Srivastava, and N. K. Verma, “Robust Wide-Area TS Fuzzy Output Feedback Controller for Enhancement of Stability in Multimachine Power System”, IEEE Systems Journal, vol.6, no.3, pp.426,435, Sept. 2012.

+ Y. Zhang and A. Bose, "Design of Wide-Area Damping Controllers for Inter area Oscillations," *IEEE Transactions on Power Systems, vol. 23, no. 3, pp. 1136*-1143, Nov. 2008.

Implementation of the proposed method

Dynamic Contingency Index (39-bus system)

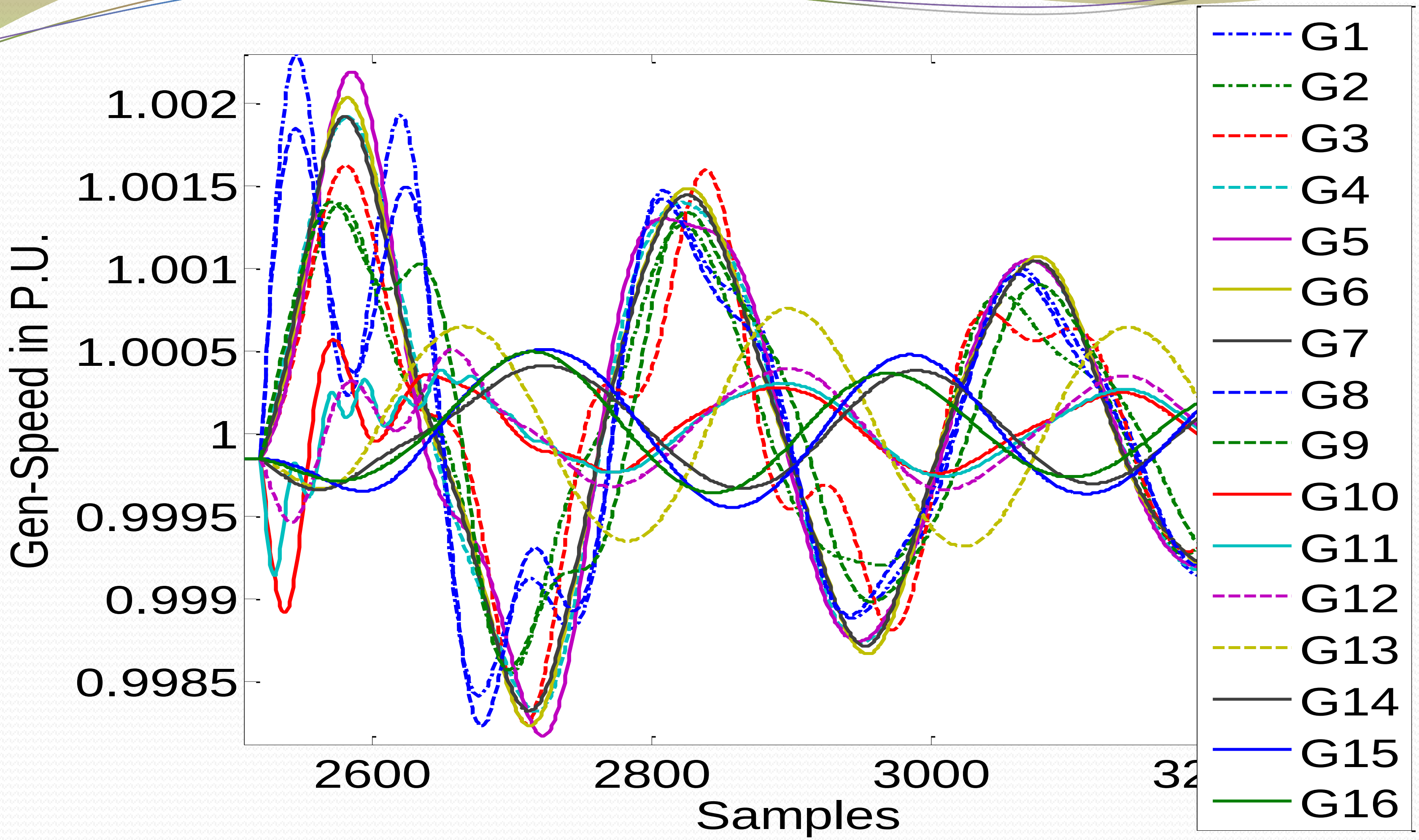
Line Outage Contingency	Index Value
L_{28-29}	1.2463
L_{1-39}	1.2073
L_{1-2}	1.1953
L_{2-25}	0.3666
L_{16-21}	0.1280

Dynamic Contingency Index (68-bus system)

Line Outage Contingency	Index Value
L_{1-2}	0.096
L_{8-9}	0.064
L_{2-25}	0.058
L_{21-22}	0.039
L_{16-21}	0.0374

Dynamic contingency index is defined

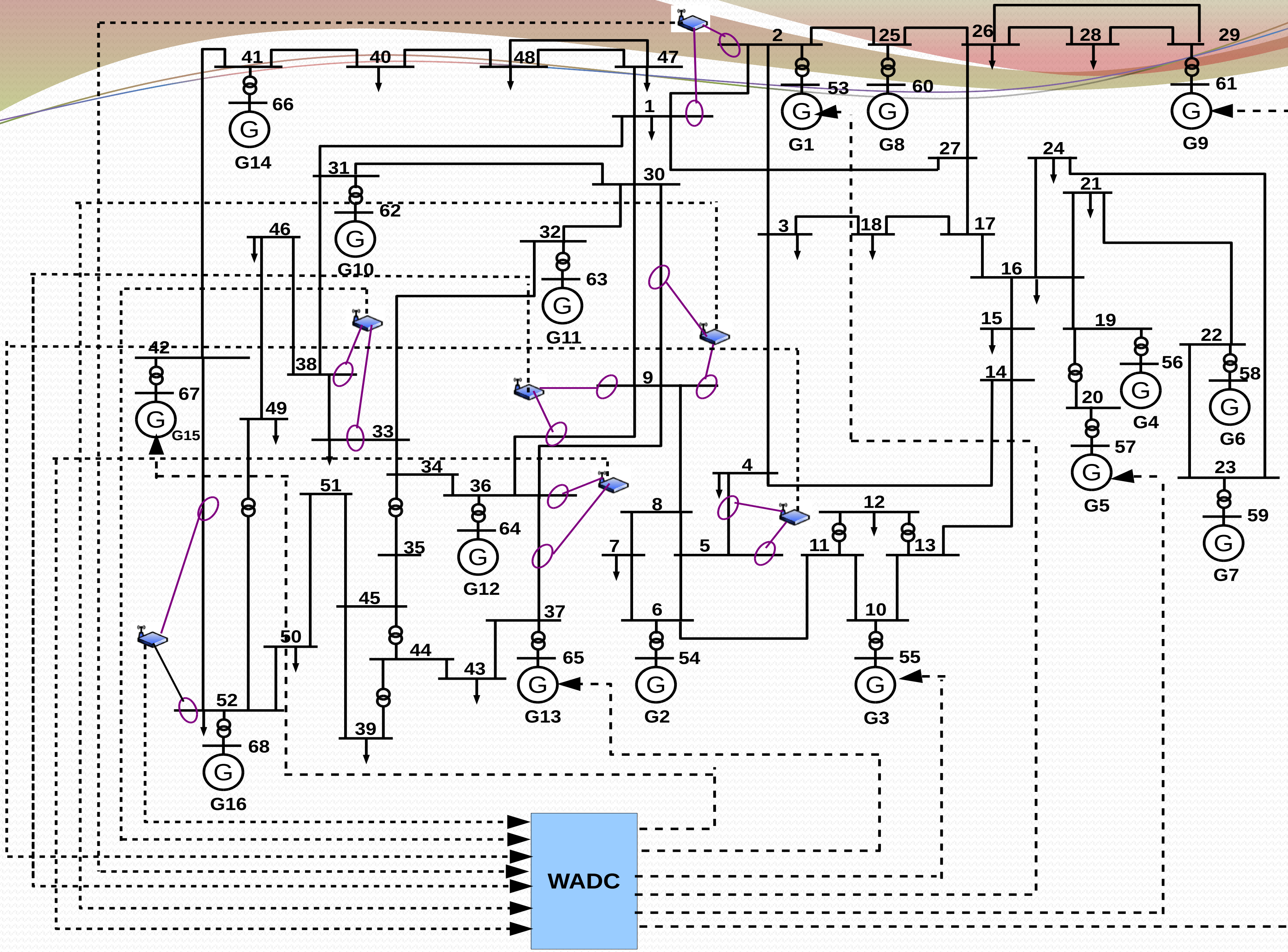
$$DCI_J = \frac{\xi I_{sys} - \xi J_{sys}}{\xi I_{sys}}$$



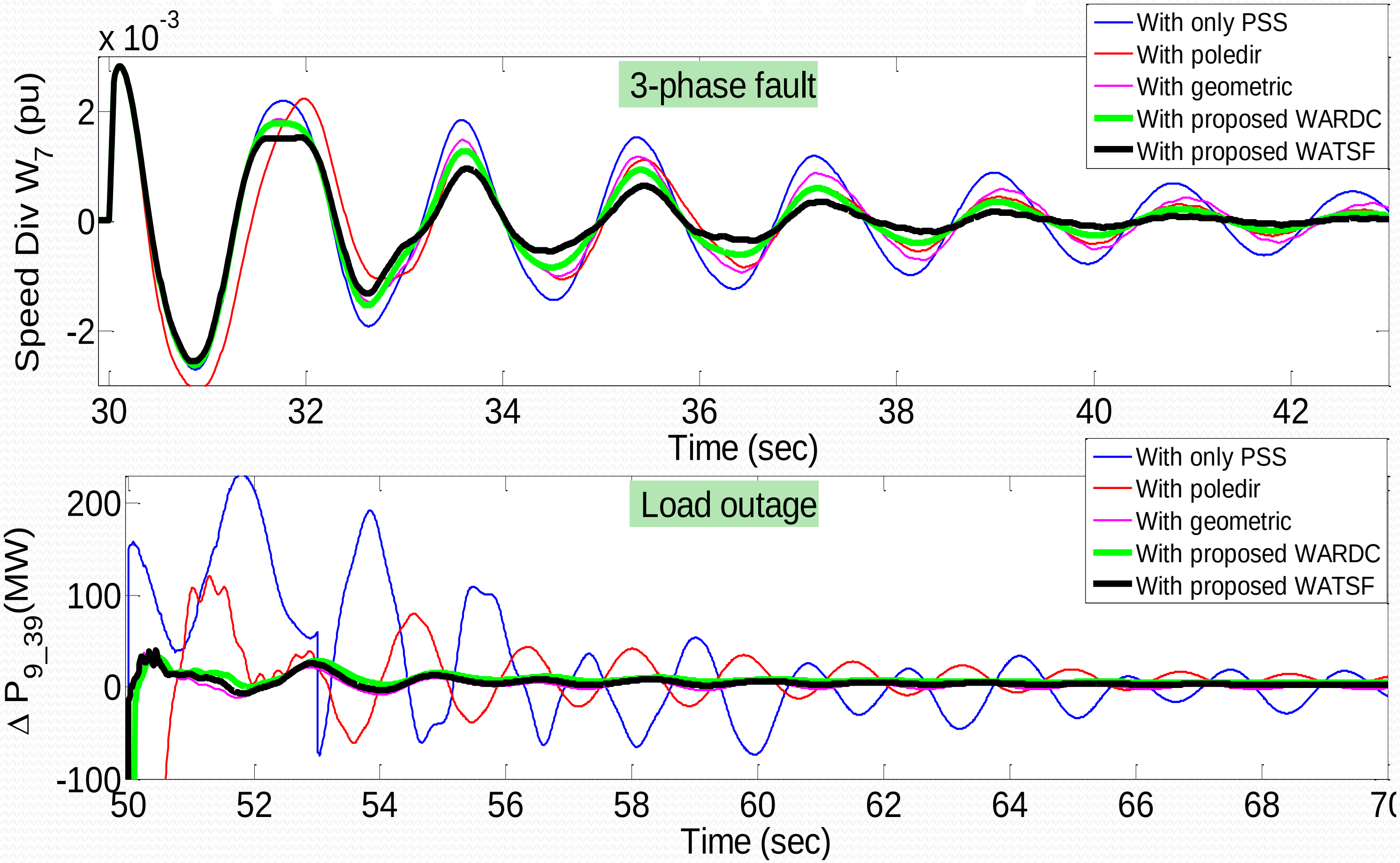
Gen Speed of 68-bus system for line $L_{1\text{-}2}$ outage –Data used as input to the signal selection algorithm

Signal Selection for 39-Bus and 68-Bus Systems

	Type.	Pole vector approach	Geometric approach	Proposed approach
39-bus New England System	Generators	G1, G5, G7, G9	G3, G7, G8, G9	G3, G5, G9, G10
	Power Flow In Lines	L(8-9), L(1-2), L(2-3), L(14-15), L(3-18)	L(9-39), L(16-17), L(2-3), L(2-25), L(4-5)	L(17-27), L(16-19), L(9-39), L(2-25), L(8-9)
68-bus New England New York System	Generators	G11, G12, G13, G14, G15, G16	G3, G9, G10, G13, G14, G16	G1, G3, G5, G9, G13, G15
	Power Flow In Lines	L(36-37), L(50-52), L(40-41), L(34-36), L(1-30), L(9-36)	L(1-2), L(42-52), L(1-47), L(33-38), L(26-27), L(9-30)	L(36-37), L(1-2), L(9-30), L(50-52), L(9-36), L(4-5)



New England and New York Interconnected 68-bus system showing selected input and output signals with the proposed method

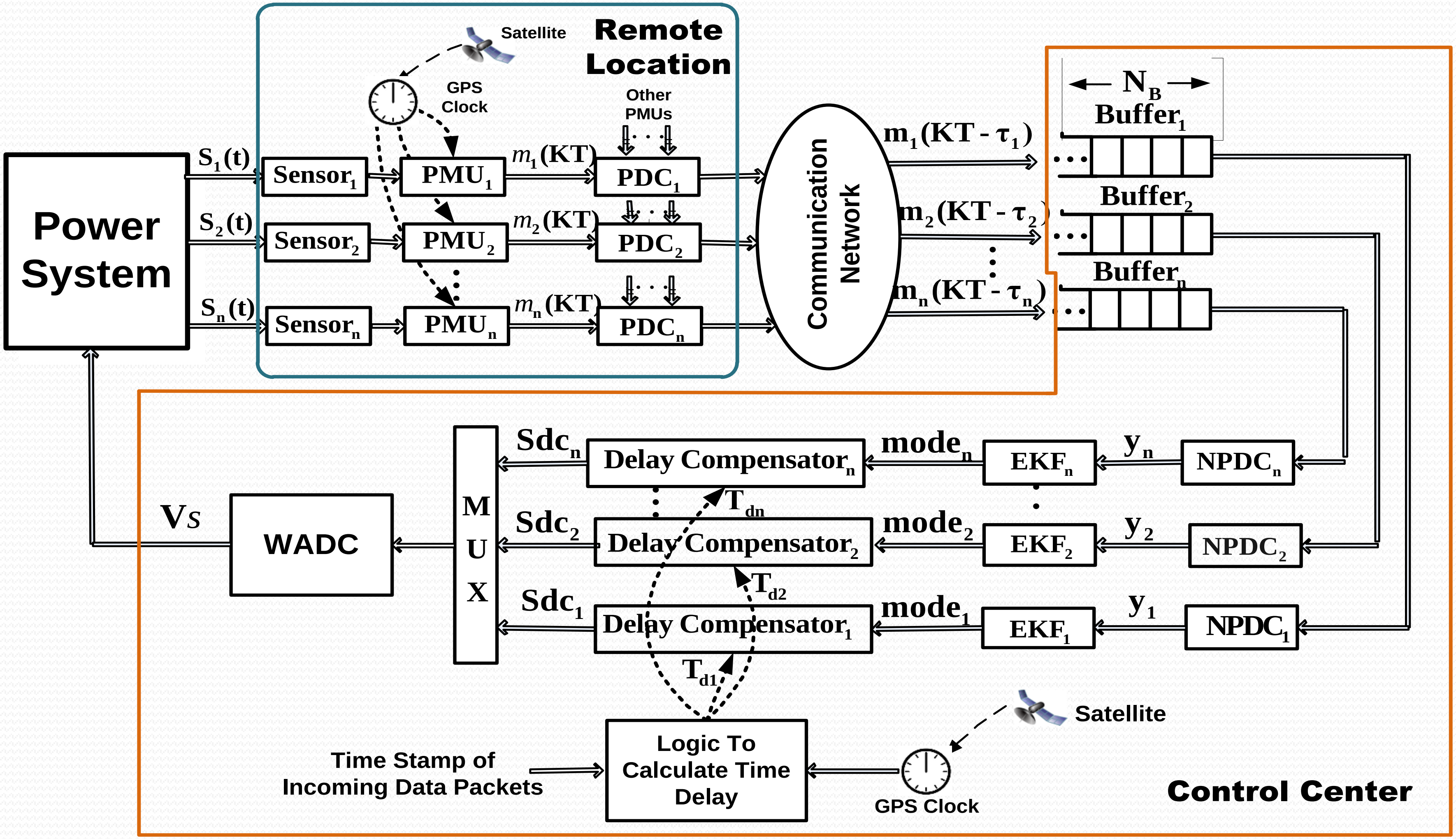


Speed deviation of Gen 7 and power deviation in line 9-39 due to 3-Φ fault and load outage (68-bus system)

Network Delay & Packet drop Compensation*

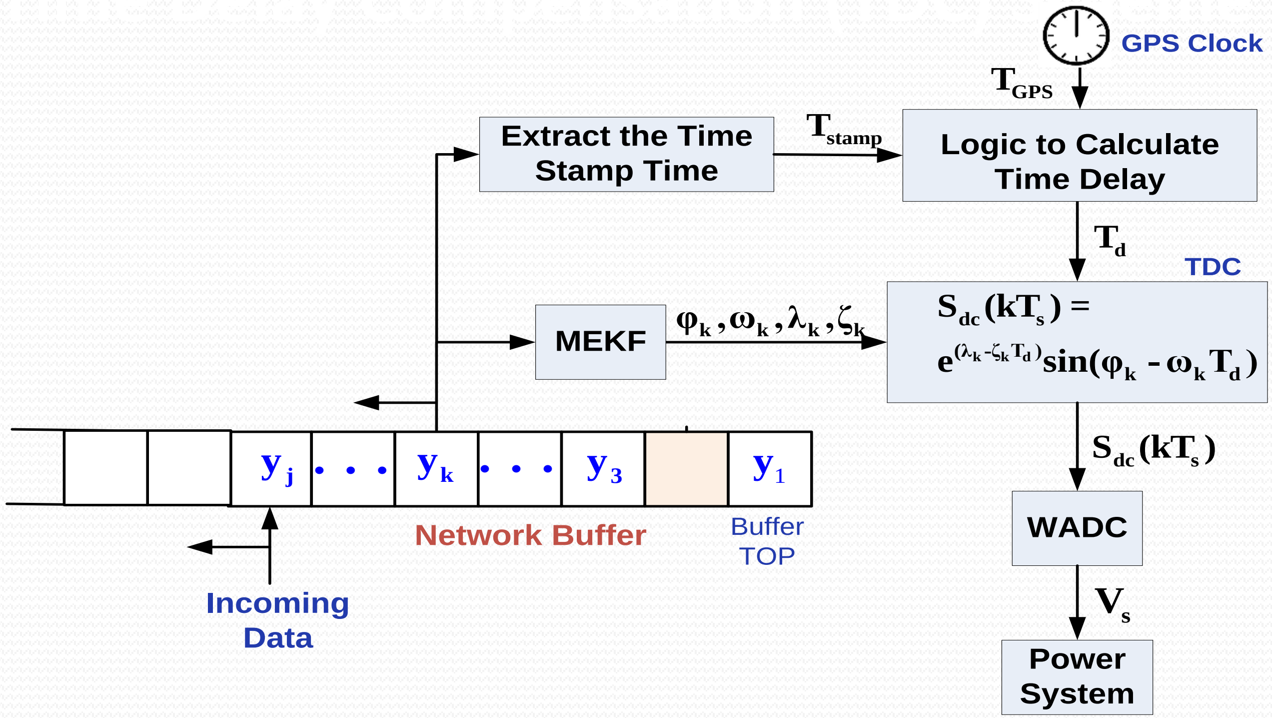
- A New Time Delay Compensation (TDC) technique with packet drop has been proposed.
- The network latency considered in the application of synchrophasor assisted wide area control for the Static Var Compensator (SVC).
- The power oscillation modes are estimated online by Modified Extended Kalman Filter (MEKF) approach.
- Delay has been compensated by predicting the dynamics of the delayed measurement signal.
- The performance of the proposed delay compensation scheme has been tested on 39-bus and 68- bus systems.
- An insertion sort algorithm has been used for chronological sequence restoration of the data in case of packet disorder.

* Bibhu P. Padhy, S.C. Srivastava and Nishchal K. Verma, “A Network Delay Compensation Technique for Wide-Area SVC Damping Controller in Power System,” IEEE PES Transmission & Distribution Conference & Exposition, Chicago, USA, April 14-17, 2014.



Remote Location
Satellite
GPS Clock
Other PMUs
Power System
S1(t)
S2(t)
Sn(t)
Sensor1
Sensor2
Sensorn
PMU1
PMU2
PMUn
m1(KT)
m2(KT)
mn(KT)
PDC1
PDC2
PDCn
Communication Network
m1(KT - τ1)
m2(KT - τ2)
mn(KT - τn)
NB
Buffer1
Buffer2
Buffern
NPDCn
NPDC2
NPDC1
yn
y2
y1
EKFn
EKF2
EKF1
moden
mode2
mode1
Delay Compensatorn
Delay Compensator2
Delay Compensator1
Tdn
Td2
Td1
Sdcn
Sdc2
Sdc1
MUX
WADC
Vs
Logic To Calculate Time Delay
Time Stamp of Incoming Data Packets
Satellite
GPS Clock
Control Center

Time Delay Compensation (TDC) Scheme



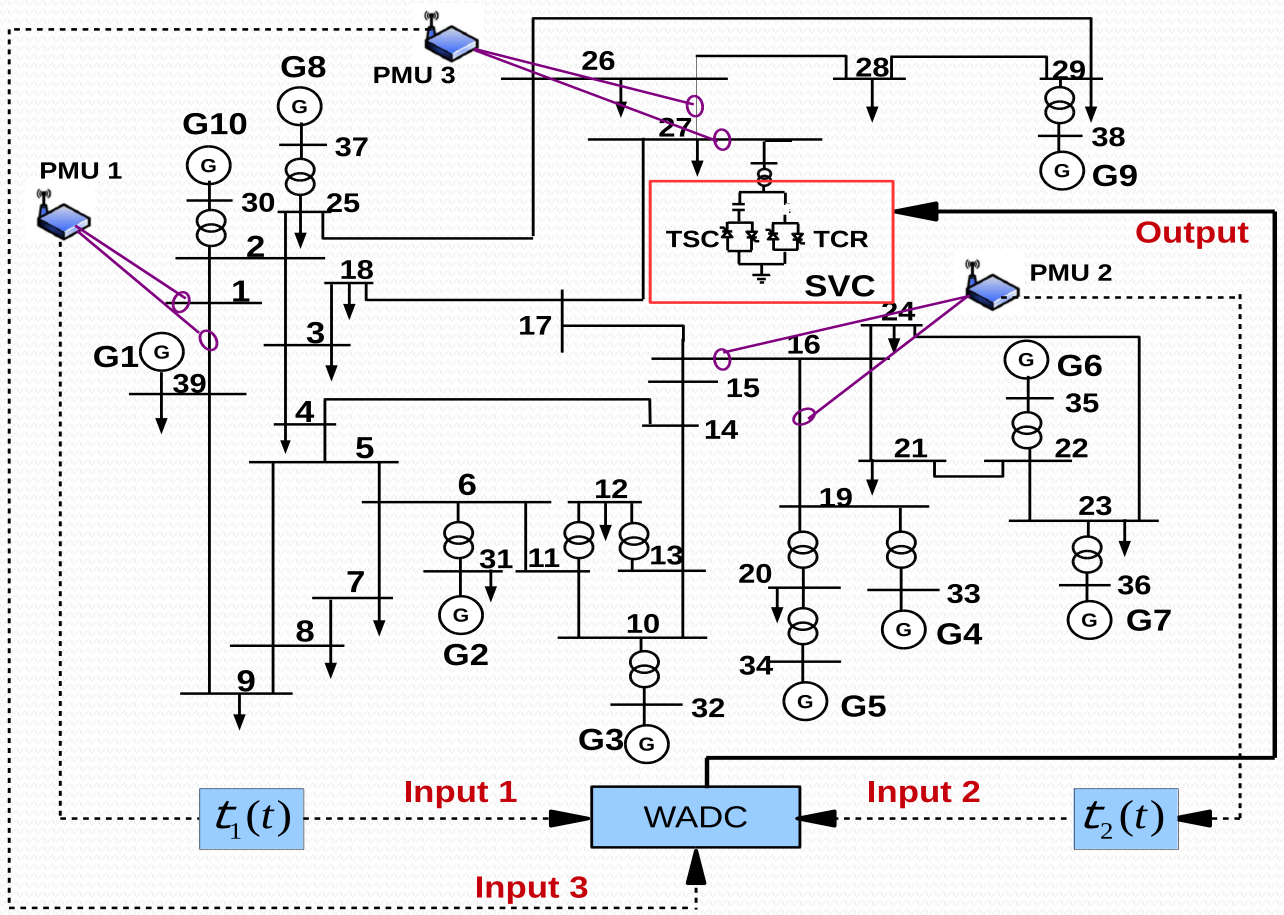
The delay compensated signal can be represented as

$$S_{dc,k} = y_{k+T_d/T_s} = \sum_{i=1}^{N} e^{x_{i,3,k+T_d/T_s}}.\sin(x_{i,1,k+T_d/T_s}) = \sum_{i=1}^{N} e^{(\ln A_{i,k} - x_{i,4,k} - T_d x_{i,4,k})}.\sin(x_{i,2,k} + \theta_{i,k} + T_d x_{i,2,k})$$

$$= \sum_{i=1}^{N} e^{(\lambda_{i,k} - T_d \omega_{i,k})}.\sin(\phi_{i,k} + T_d \omega_{i,k})$$

39 Bus Test System

- The input/output signal selection using the coherency approach.
- The remote input signals to the WADC are $\mathbf{P}_{16\text{-}19}$, $\mathbf{P}_{1\text{-}39}$ and $\mathbf{P}_{26\text{-}27}$



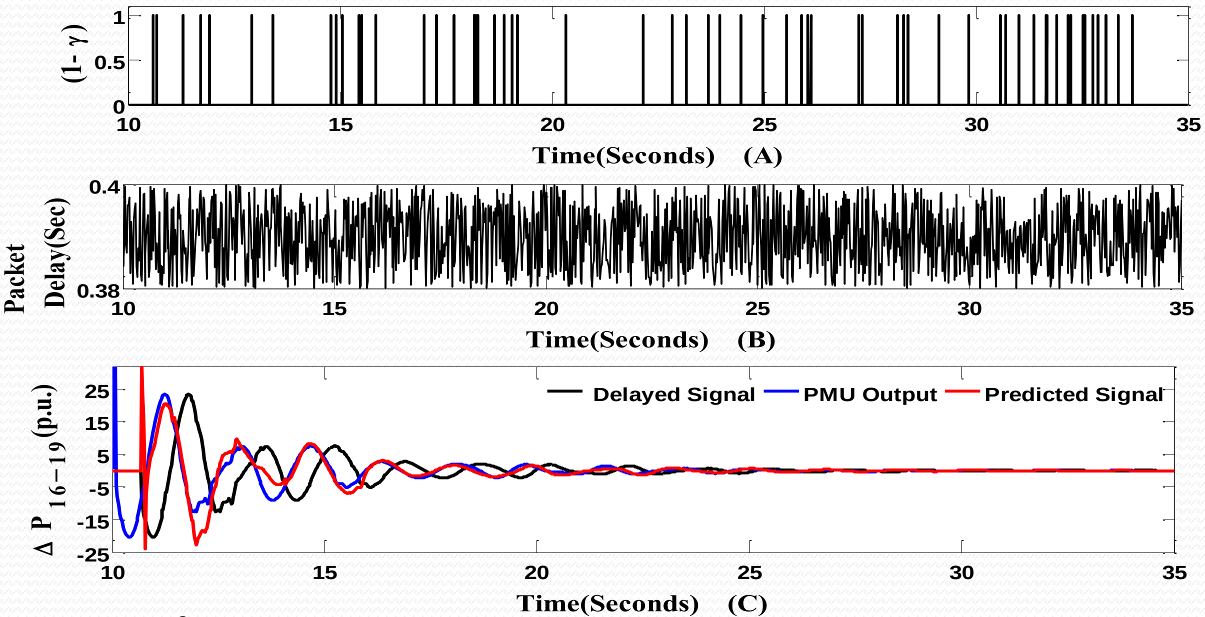
Implementation Results

- A random input delay of maximum value 1sec has been created in the input channel-1($P_{16\text{-}19}$) , 400 ms in the input channel-2($P_{1\text{-}39}$), and zero delay created in channel-3($P_{26\text{-}27}$) as this is a local signal
- Packet drop probability is considered as 4%

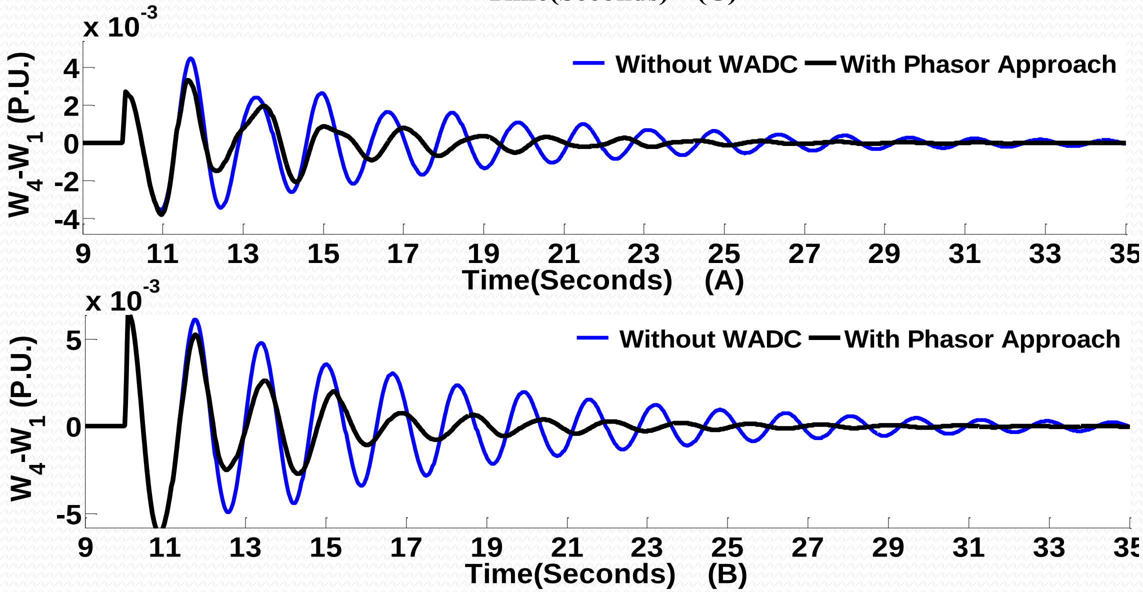
Test Cases:

- A 3-phase fault was applied at bus-16 and bus-26 for 70ms.
- A load outage at bus-16 and 28
- 3-phase fault at bus- 4 followed by $L_{4\text{-}14}$ outage
- Bus connecting 21-22 line contingency

Simulation Results

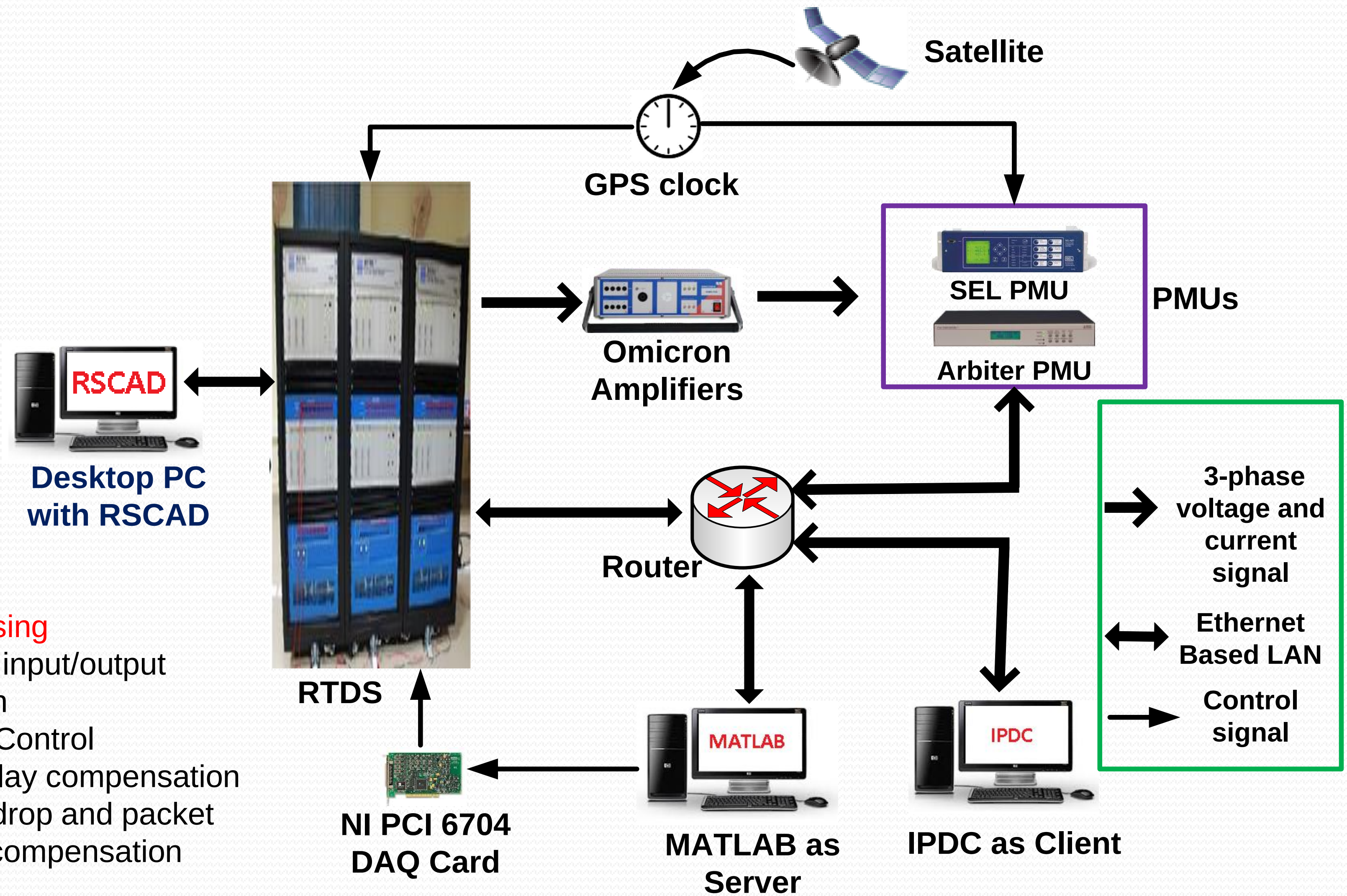


1 (A) Packet drop (B) Random time delay (C) Tracking of PMU signal



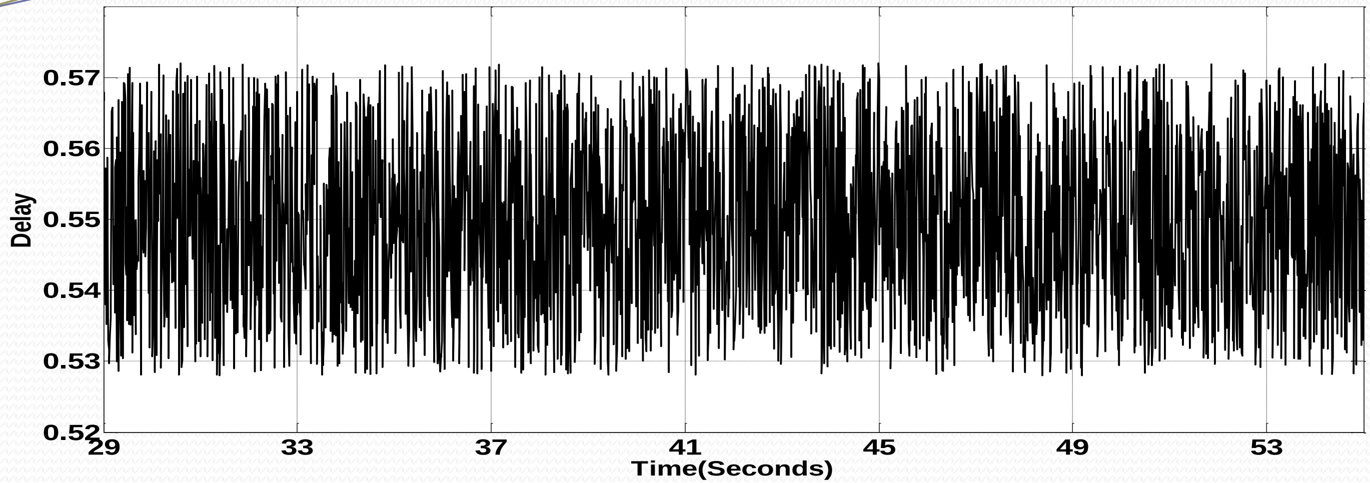
2. (A) 3-phase fault at bus- 26 for 70ms (B) a 3-phase fault at bus- 16 for 70ms

Hardware Lab Setup used for Real-Time Simulation of WADC+

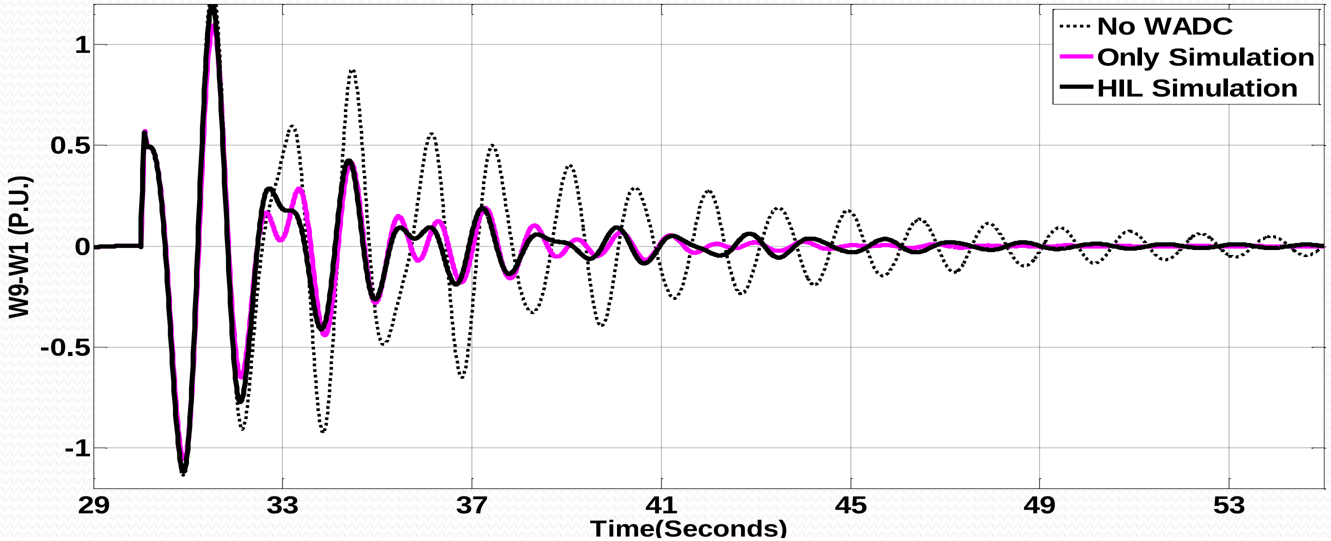


+ Addressing
- Optimal input/output selection
- Robust Control
- Time delay compensation
- Packet drop and packet disorder compensation

WADC Simulation and Validation on RTDS



Delay with time for a 3 phase fault at bus-27 (39 bus NE system)



Oscillations in the speed deviation of the generator

Conclusions

- **Synchrophasor based WAMCP system will form an important component of Smart Grid. It offers new paradigm of real time security monitoring and control.**
- **Large number of PMUs are being deployed in the transmission grid at strategic locations in various countries.**
- **The successful implementation of WAMPC requires development of suitable application tools.**
- **PMUs must be embedded with proper dynamic phasor estimation algorithm, complying with the IEEE standards.**
- **It can be effectively utilized for better situational awareness monitoring impending system instability, and improving inter-area mode damping, important to avoid major disturbances.**

Thank You