

URTDSM Initiative in India and Controlled Islanding using PMU Measurements

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- Infrastructure
- Overview of Analytics
- Motivation for Controlled Islanding
- Controlled Islanding Scheme

Unified Real Time Dynamic State Measurement (URTDSM)

- **Phase-1** (Completed)

- No of PMUs (lines) - 1186
 - Substations at 400kV level and above in the State & Central grids
 - All generating stations at 220kV level and above
 - HVDC terminals
 - Important inter-regional connection points
 - Inter-national connection points
- No of PDCs - 59
 - All SLDCs, RLDCs and NLDC

- **Phase-2**

- No of PMUs - 483
- Unique feature of this architecture is that every line is monitored by PMUs from both ends.
- Therefore, analytics basket has monitoring, control and protection functions.

Unified Real Time Dynamic State Measurement (URTDSM)

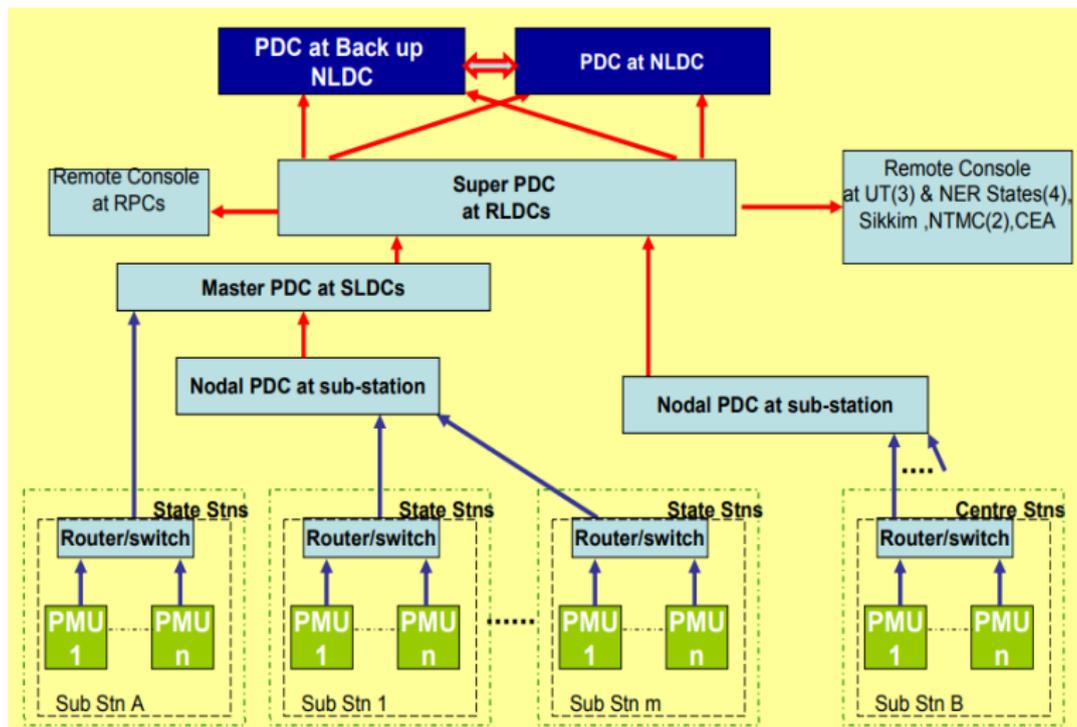


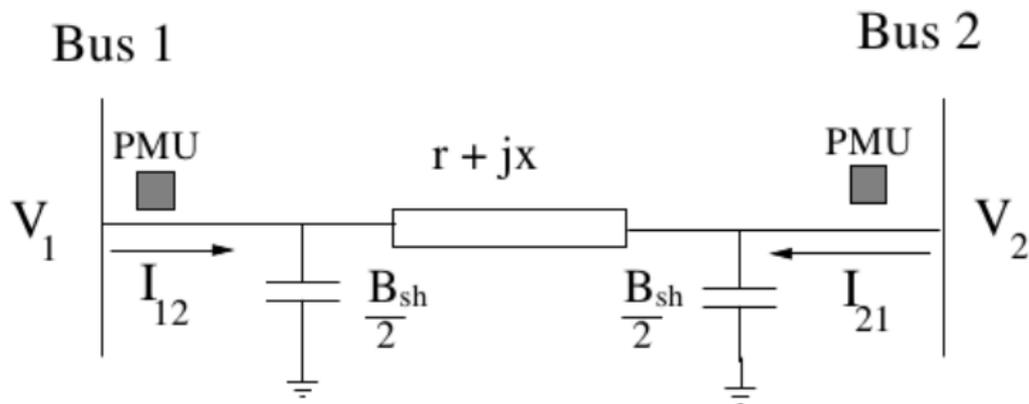
Figure: Hierarchy of URTDSM

- Development of analytics for
 - Line Parameter Estimation
 - Online Vulnerability Analysis
 - Linear State Estimation
 - CT/CVT Calibration
 - Supervised Zone-3 Distance Protection
 - Control Schemes for Improving System Security

- Development of analytics for
 - Line Parameter Estimation
 - Online Vulnerability Analysis
 - Linear State Estimation
 - CT/CVT Calibration
 - Supervised Zone-3 Distance Protection
 - Control Schemes for Improving System Security - Ongoing research
- } Deployed at RLDC/ NLDC
- } Undergoing field tests

Line Parameter Estimation

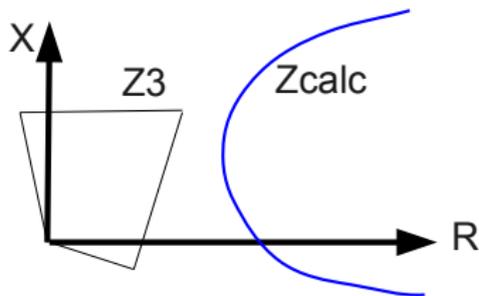
- State estimation software use line parameters for estimating the system states
- Distance relays use impedance information of the lines for proper zone settings
- Application of total least squares (TLS) method.¹



¹K. Dasgupta and S. Soman, "Line parameter estimation using phasor measurements by the total least squares approach," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, IEEE, 2013, pp. 1–5.

Online Vulnerability Analysis of Distance Relays

- Mimic relay operation from PMU data at control center.
- Identify relays that are vulnerable to tripping.
- Define a vulnerability index and rank vulnerable relays.
- Hidden failures in distance relays are identified before they can cause any bigger damage to system.
- This analytic could have alerted system operator of impending false trip of Gwalior-Bina line which initiated the Indian grid blackout of 2012.



- Estimation of bus voltage magnitude and angle i.e., system states from raw measurements is defined as state estimation.
- The state estimator also includes the three important functions - network topology processor (NTP), observability analysis and bad data detection.
- The control centre makes use of state estimation to take decisions on system economy and security.
- Synchronized PMU measurements can be utilized to formulate a linear state estimator.
- In the URTDSM project, LSE will be running in all RLDCs/ SLDCs. This will be in parallel with the SCADA based state estimator.

PMU Field Data for Jabalpur substation on February 19, 2014

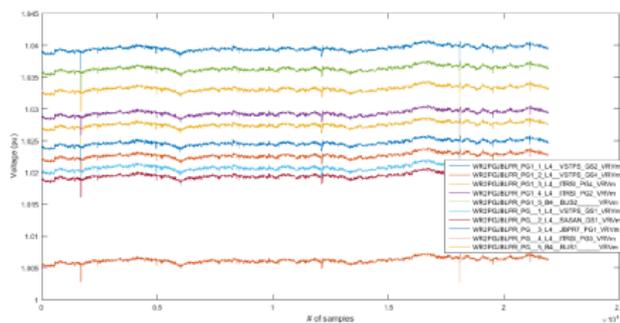


Figure: Phase a voltage magnitude

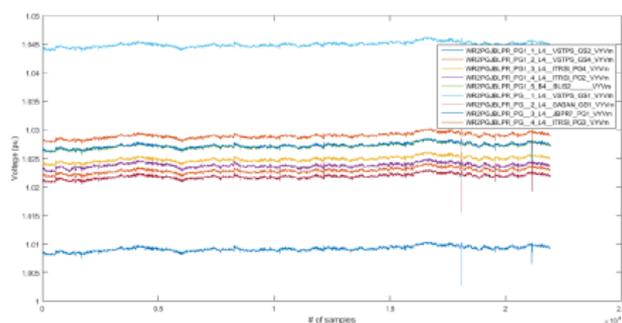


Figure: Phase b voltage magnitude

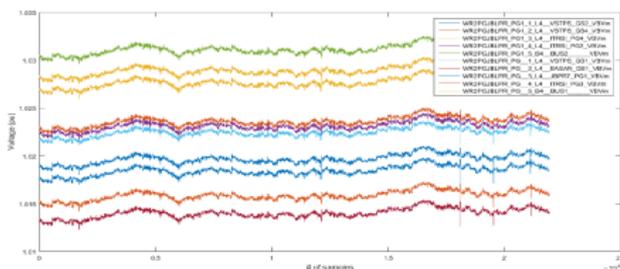


Figure: Phase c voltage magnitude

- Measured phase a voltage varies from 1.005 pu to 1.04 pu!
- Similar variations are observed in the other two phases.
- Substation state estimation may be used.
- Calibration of CVTs is required.

PMU Field Data for Khandwa substation

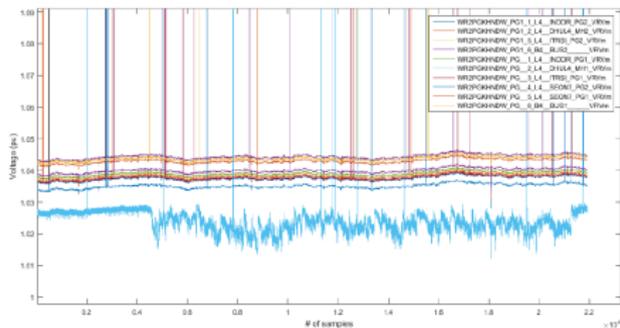


Figure: Phase a voltage magnitude

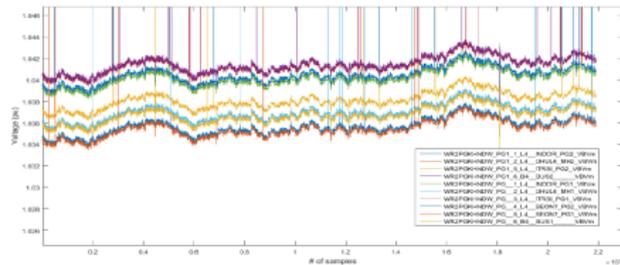


Figure: Phase c voltage magnitude

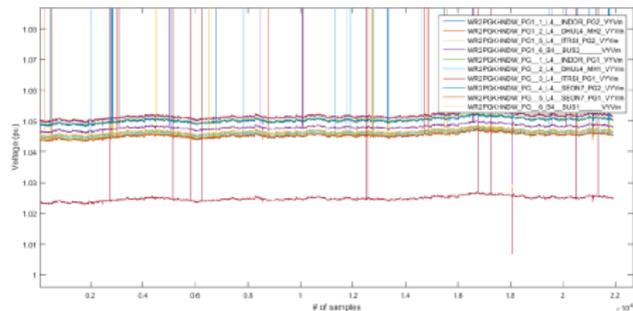


Figure: Phase b voltage magnitude

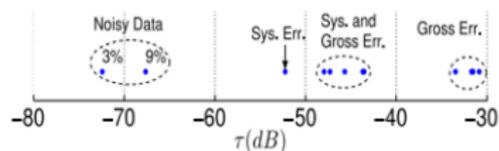
Observations:

- Noisy data in one of the PMUs of phase a.
- Significant data loss.
- It can adversely impact protection and emergency control schemes.

- CVT parameters drift due to aging, temperature and environmental conditions introducing bias (systematic error) in measurements.
- Performance of CTs is influenced by nonlinearity of iron, burden introduced by secondary leads, primary current, etc.
- It is difficult to ascertain accuracy of any instrument transformer on the site once it is installed.
- With one VT and CT as reference, PMUs can “soft calibrate” the remaining system.²

²K. V. Khandeparkar, S. A. Soman, and G. Gajjar, “Detection and correction of systematic errors in instrument transformers along with line parameter estimation using pmu data,” *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3089–3098, 2017.

Bias Error Detection (BED) Test



Distribution of Errors in dB scale

The dB Score is calculated as,

$$\tau = 10 \log_{10}(\text{MAD of } \tilde{g}_{sh}(t))$$

Mean Absolute Deviation (MAD) is calculated from mean zero.

$$\tilde{g}_{sh}(k) = \text{Re} \left(\frac{\bar{I}_s^{avg}(k) + \bar{I}_r^{avg}(k)}{V_s^{avg}(k) + \bar{V}_r^{avg}(k)} \right)$$

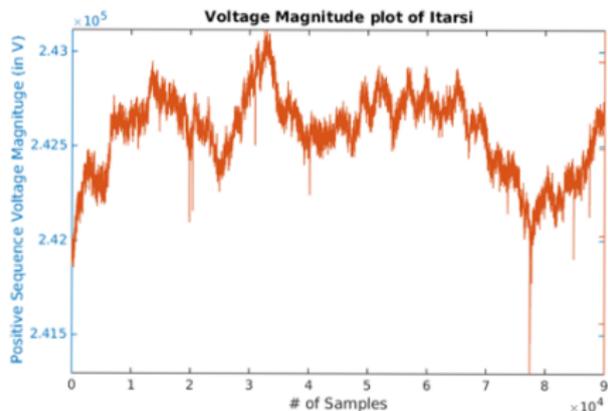
- Itarsi-Jabalpur dB score falls between -60 dB which implies presence of bias error.
- Manesar-Neemrana is a newly commissioned line and has no bias.

Transmission Line	Itarsi-Jabalpur	Neemrana-Manesar
Time Interval	dB score	dB score
2 minutes	-47.8027	-64.4887
5 minutes	-50.3197	-64.7522
10 minutes	-50.9230	-63.9615

The Bias Error Detection Test is formulated as,

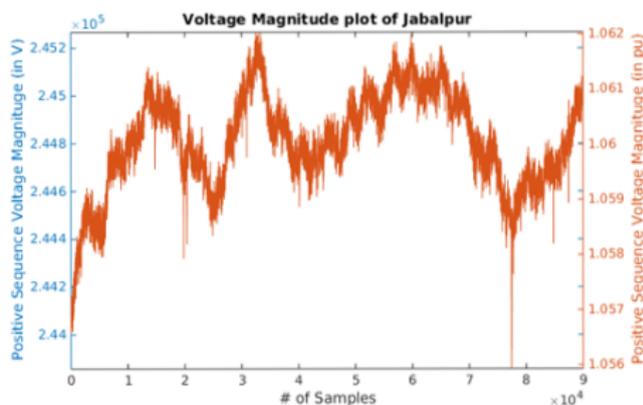
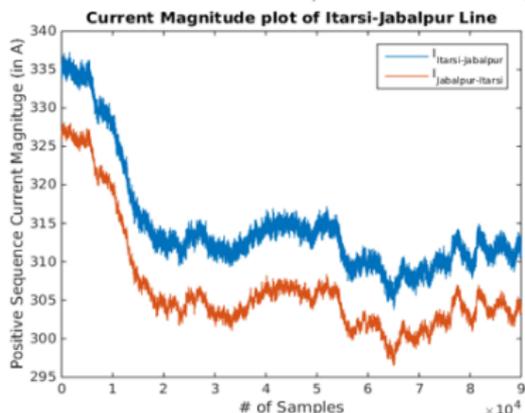
$$0 + j \frac{b_{sh}}{2} = \frac{\mathbb{E}[\bar{I}^*] + \mathbb{E}[\bar{I}^r]}{\mathbb{E}[V^*] + \mathbb{E}[V^r]}$$

Recorded PMU Data on Itarsi-Jabalpur line

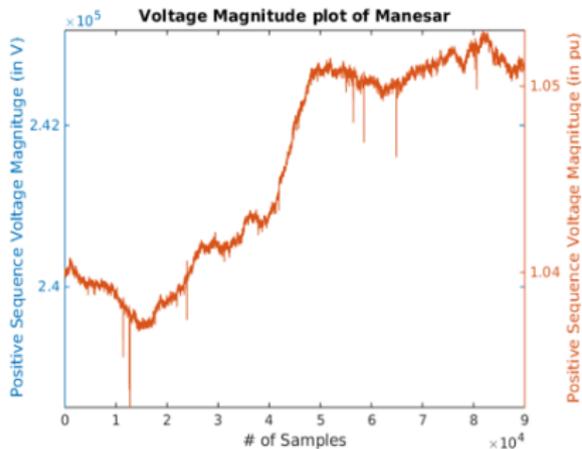


Positive Sequence Voltage Magnitude (in pu)

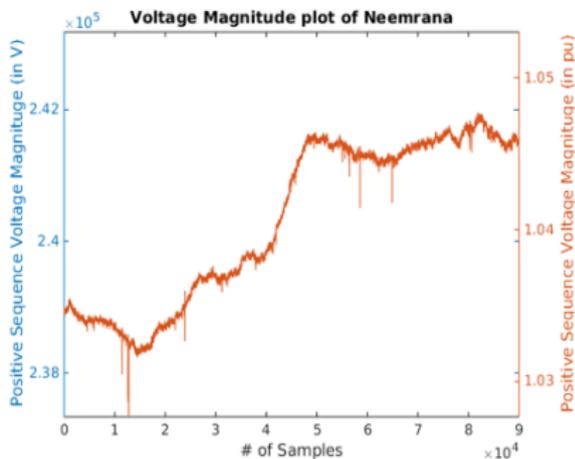
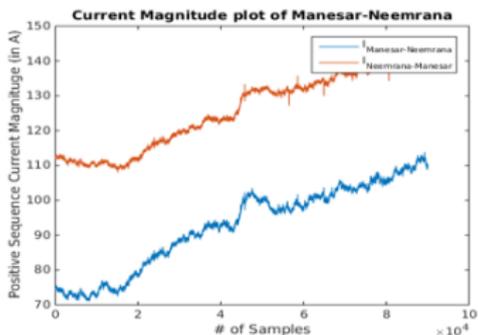
Transmission Line: Itarsi-Jabalpur (400 kV)
Line Length: 232 km
Date : February 19, 2014
Duration: 23:30 to 00:30 (1 Hour)



Recorded PMU Data on Manesar-Neemrana line



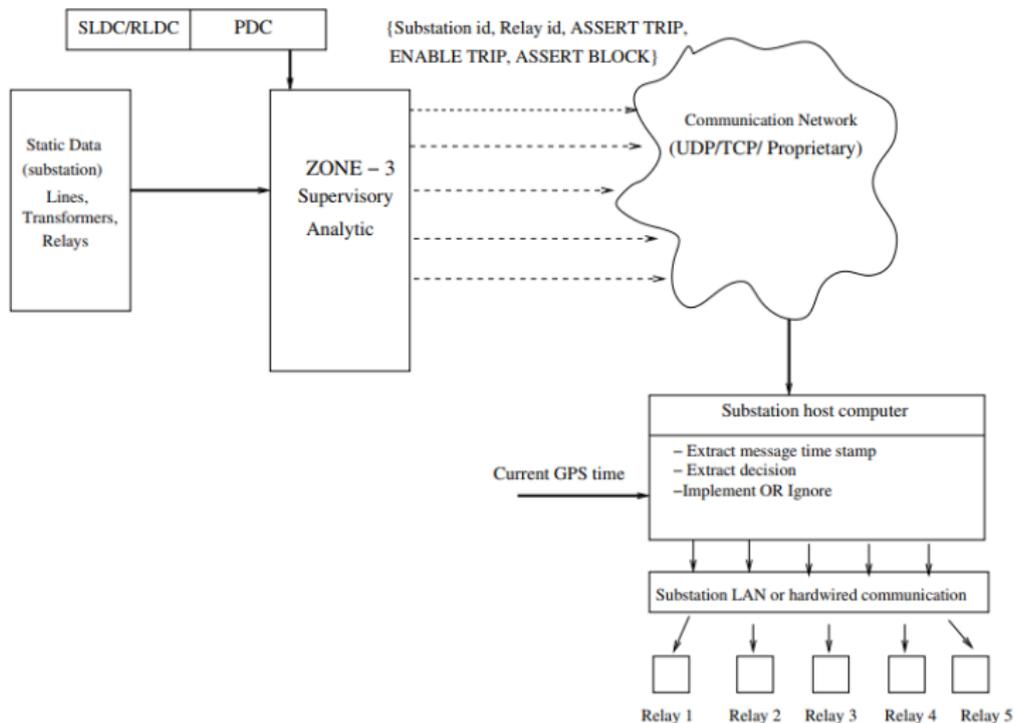
Transmission Line: Manesar-Neemrana (400 kV)
Line Length: 67 km
Date: September 10, 2017
Duration: 00:00 to 01:00 (1 Hour)



Supervised Zone-3 Distance Protection

- With PMUs placed at both ends of the transmission lines, differential currents can be computed.
- Once differential currents for all backed up lines are available, decision to block or not block Zone-3 of the back up relay can be taken.
- The whole procedure
 - obtaining synchrophasors from PMUs
 - differential currents computation
 - communicating appropriate decision to relayshould happen well within one second.
- Prototype testing on Manesar-Neemrana line with false data injection was successfully completed. The round trip latency was observed to be around 200 ms.
- Two variants - relay centric and subsystem approach have been developed to achieve resiliency.

Supervised Zone-3 Distance Protection



Out-of-Step Tripping

Out-of-Step Condition

- A generator or a group of generators losing synchronism with the rest of the generators in the system.
- Electrical center(s) is created when an out-of-step condition occurs.
- Distance relays perceive it as a bolted three phase fault and trip.
- Power blackouts are a consequence of uncontrolled system separation due to mal-operation of distance relays.

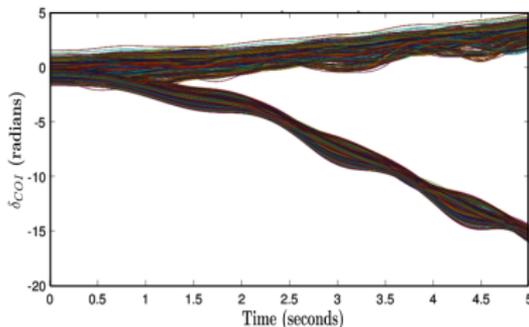


Figure: Loss of synchronism

Blackout in Indian Power Grid on 30th July, 2012

- Tripping of distance relays on load encroachment and power swing caused blackouts in the Indian power grid on July 30 and July 31, 2012.

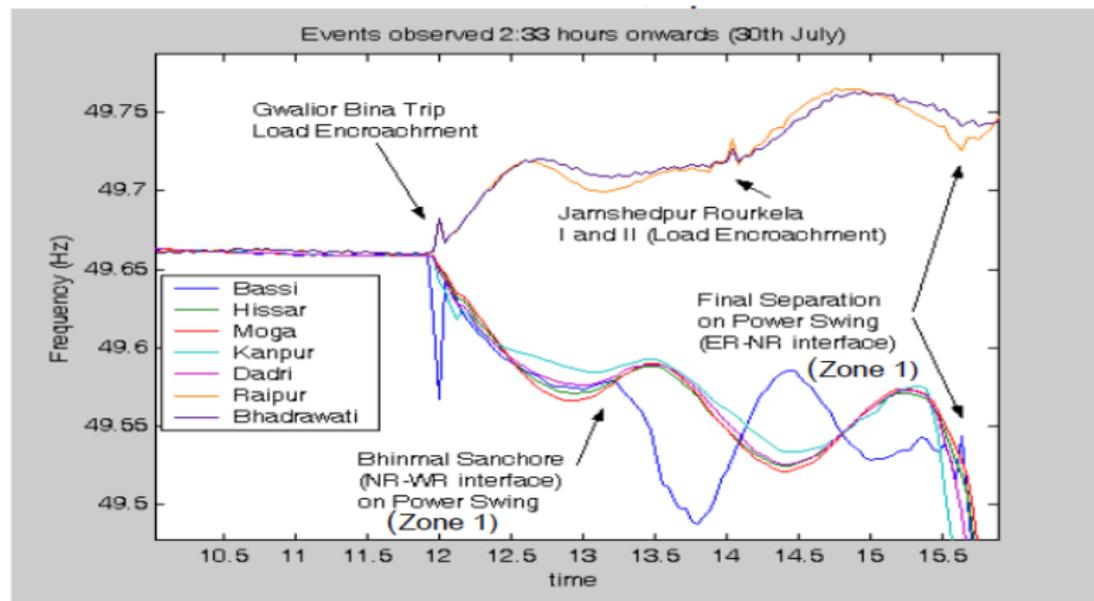


Figure: Snapshot of PMU data

Zone-1 trippings at ~2:33:15, due to large angular separation ---- **NR becomes an island**

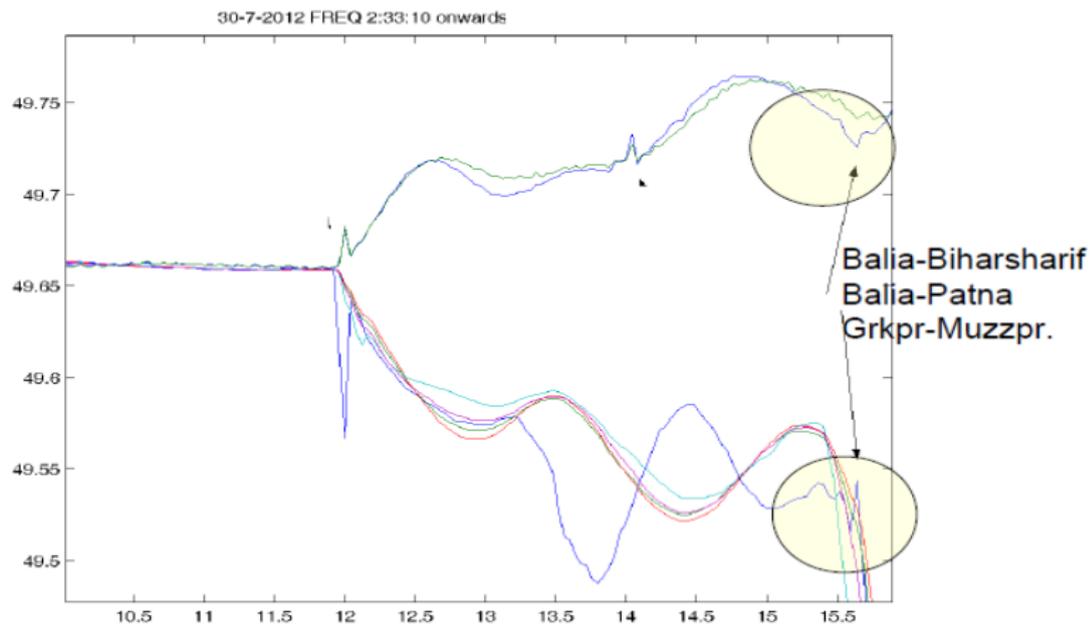


Figure: Zone 1 tripping on power swing

Blackout in the Indian Power Grid on 30th and 31st July, 2012

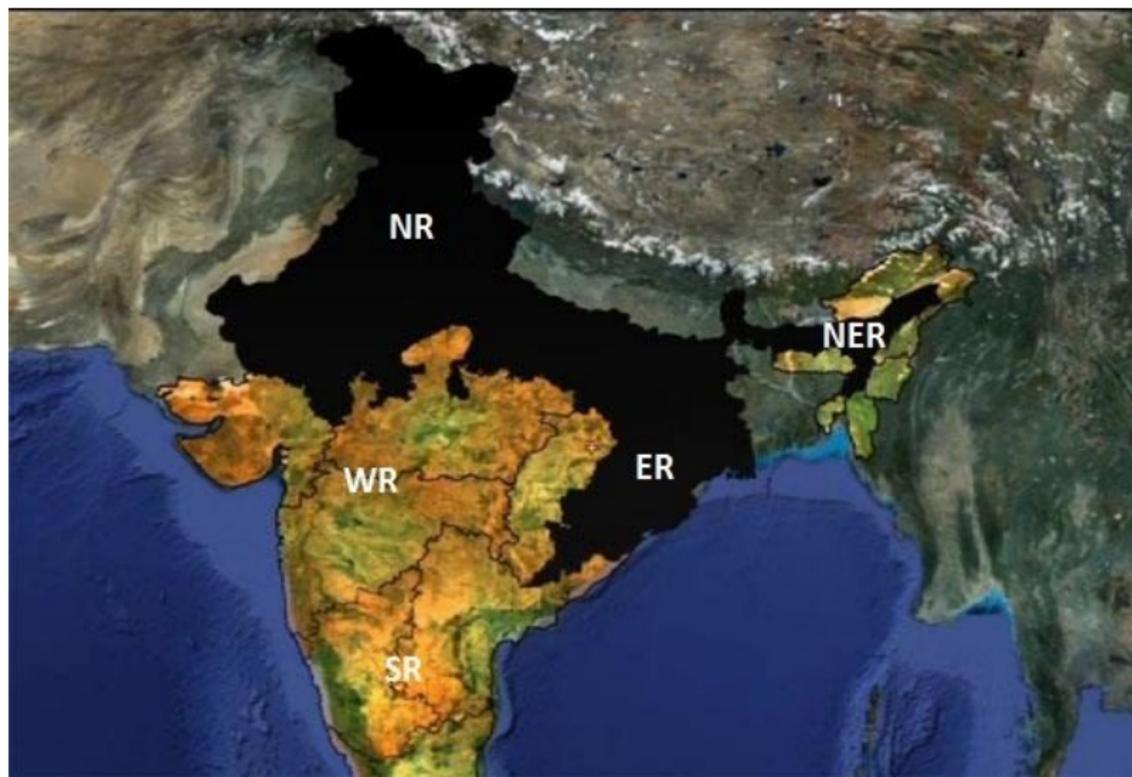
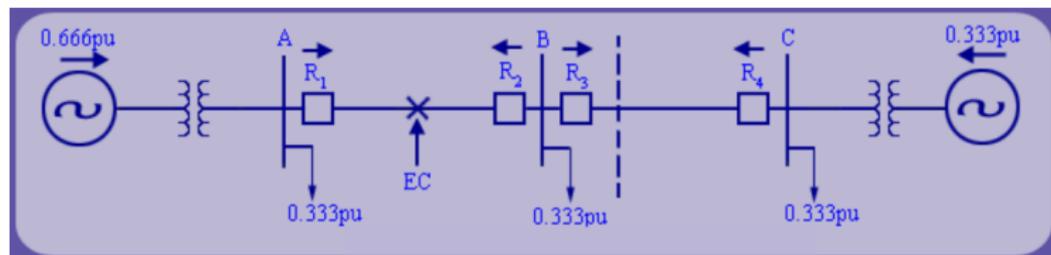


Figure: Areas affected during blackout

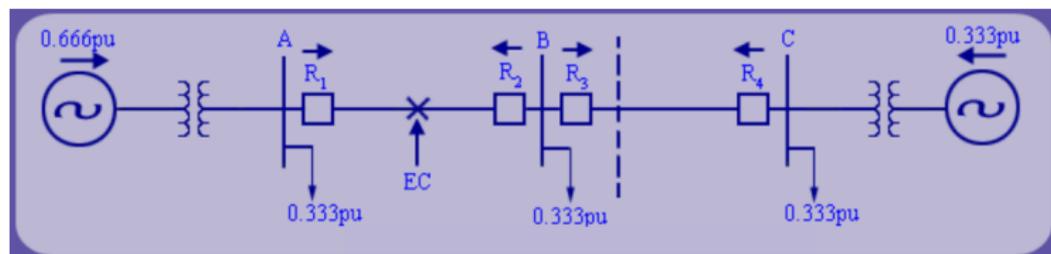
- During an out-of-step condition, the power system should be islanded.
- Objective of controlled islanding is to create self-sufficient islands.
- The coherency of generators as well as good load-generation balance in the formed islands is of utmost importance.
- Controlled islanding is usually followed by some form of load shedding or generation rejection to maintain the frequency within permissible limits.

Emergency Control Scheme - Controlled Islanding



- Assume that the system is unstable and electrical center forms on the line AB.
- Relays R_1 and R_2 perceive the out of step condition as a bolted three phase fault and will issue a trip decision.
- The generator at A ($P_G = 0.666$ pu) islands with a load of 0.333 pu and generator at B ($P_G = 0.333$ pu) islands with a load of 0.666 pu.
- The resulting loss of load is 0.333 pu in island B and loss of generation in island A is 0.333 pu if frequency is maintained at 50 Hz.

Emergency Control Scheme - Controlled Islanding



- However, if islanding was done by tripping line BC, an ideal solution of zero load or generation shedding would have been achieved.
- So, during unstable swings, we should block the relays from operation.
- More selective tripping can be initiated to achieve the desirable islands.

- Most of the controlled islanding techniques proposed in literature determine coherent groups of generators before finding the final islanding boundaries.
 - Slow coherency-based methods³
 - Grouping of generators is identified offline.
 - Unforeseen network topology changes could induce a different grouping of coherent generators.
 - Real-time coherency identification⁴ - increases the computational complexity.

³H. You, V. Vittal, and X. Wang, "Slow coherency-based islanding," *IEEE Transactions on Power Systems*, vol. 19, no. 1, pp. 483–491, 2004.

⁴O. Gomez and M. A. Rios, "Real time identification of coherent groups for controlled islanding based on graph theory," *IET Generation, Transmission & Distribution*, vol. 9, no. 8, pp. 748–758, 2015.

- Three stages:
 - Predict out-of-step (OOS) condition in advance using PMU measurements
 - with a high level of confidence.
 - Identify the relays vulnerable to Zone 1 infringement.
 - Transfer tripping to more appropriate locations.
 - Minimize load shedding.
 - Coherent generators in the islands.
- Advantages:
 - No need to identify coherent groups of generators.
 - Only real-time voltage and current measurements from PMUs are required to execute the controlled islanding approach.
 - The functionality can be completed end-to-end in 200 ms.

Proposed Controlled Islanding Methodology

- To prevent an uncontrolled system separation, a block decision is issued to the distance relays on the line on which Zone 1 encroachment is predicted.
- The vulnerable lines are examined to determine if they form a cutset.
- Once the cutset has been ascertained in advance, we can identify the two areas which are separated by them.
- The real power flows on the cutset are examined to identify the generation-rich and load-rich islands.
- Subsequently, a new set of lines is opened which transfers some of the load buses from the load-rich island to the generation-rich island to improve the load-generation imbalance in both islands.

16-generator system

- 3- ϕ fault on Bus 4. $T_{\text{fault}}=0.3$ s; $T_{\text{clear}}=0.2$ s
- Generators at buses 66 (generator 14), 67 (generator 15) and 68 (generator 16) go out of step w.r.t rest of the generators.

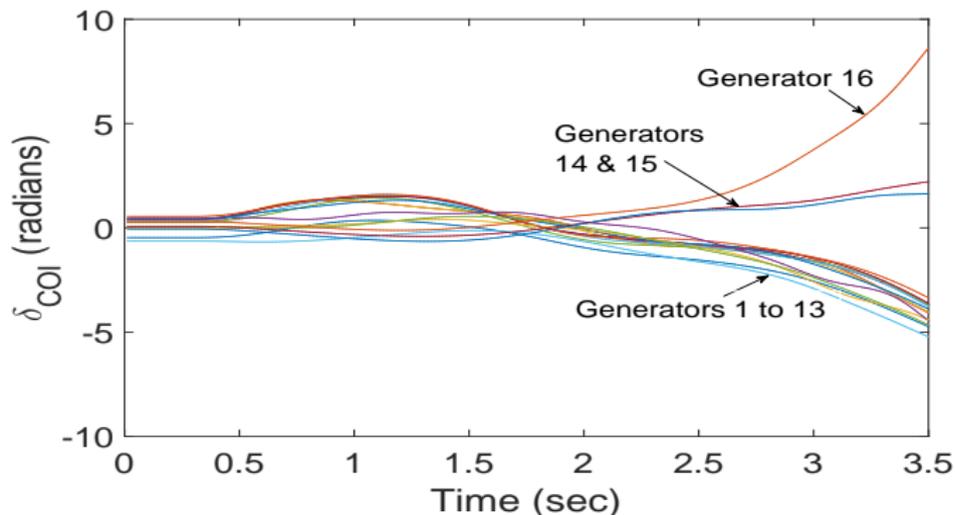


Figure: Generator rotor angles (center of inertia) after 3- ϕ fault on Bus 4.

Formation of Electrical Center(s)

- Lines tripping due to appearance of electrical center
 - Line (50-51) at 2.56 s
 - Line (49-52) at 2.60 s
 - Line (41-40) at 2.71 s
- Lead times obtained by the prediction algorithm
 - Line (50-51) - 198 ms
 - Line (49-52) - 470 ms
 - Line (41-40) - 468 ms

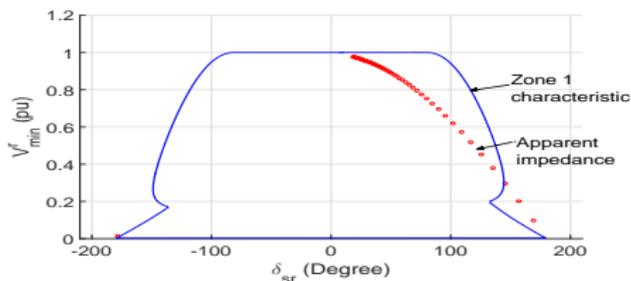


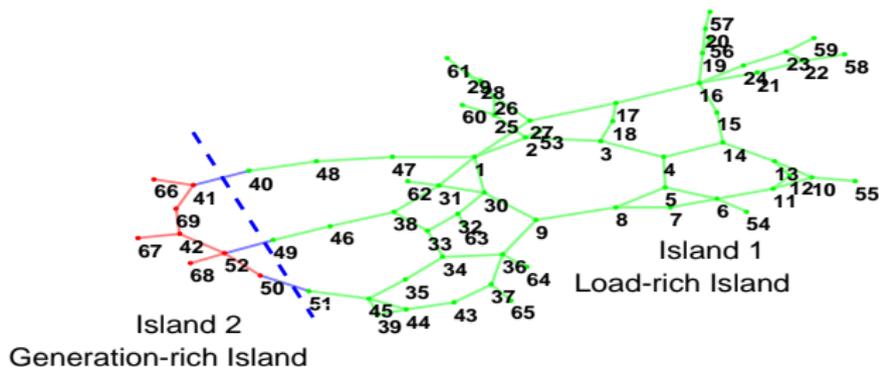
Figure: Mapping of zone 1 characteristic of distance relay at Bus 50 and apparent impedance seen onto $V_{min}^r - \delta_{sr}$ plane.

Natural Cutset Formation

- The three lines form a cutset for the system.
- Load-generation imbalance in the islands.

Island 1 (Green): -1975 MW \rightarrow load-rich

Island 2 (Red): 2020 MW \rightarrow generation-rich

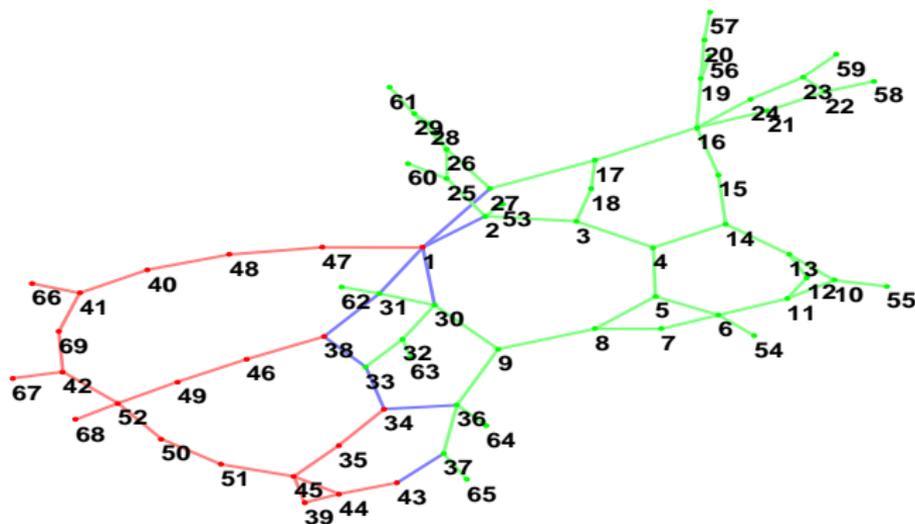


- An analogous situation occurred in the Indian system during the blackout.
- Western Region (WR) is generation-rich and survived because of tripping of generators on overfrequency. The other regions collapsed due to excess load.

- Find adjacent nodes of generation-rich island which lie in the load-rich island (nodes 40, 49, 51).
- Loads on the adjacent buses:
 - Bus 40: 80 MW
 - Bus 49: 170 MW
 - Bus 51: 143 MW
- Transfer the load buses to generation-rich island.
- The imbalance in Island 2 comes down to 1627 MW
- Update the island boundaries.
- This process is continued till the load-generation imbalance of both islands cannot be further reduced.

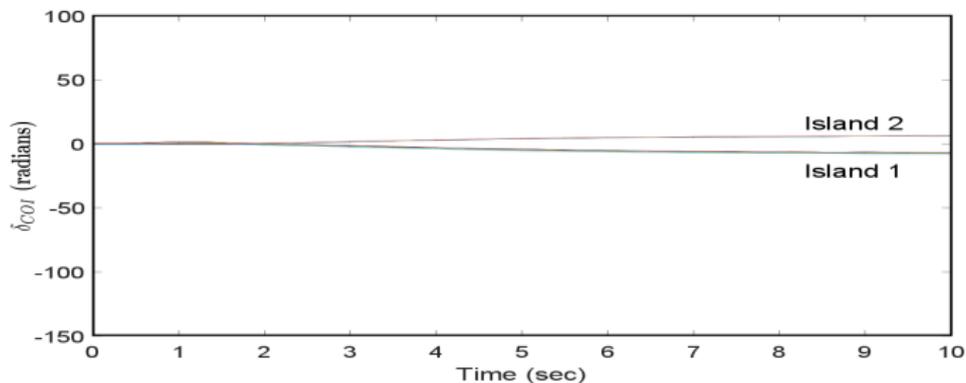
Controlled Islands

- The out-of-step prediction was done ≈ 200 ms prior to first relay tripping on zone 1.
- The proposed islanding scheme ends after four iterations.
- So, the islanding decision can be accomplished within 100 ms.

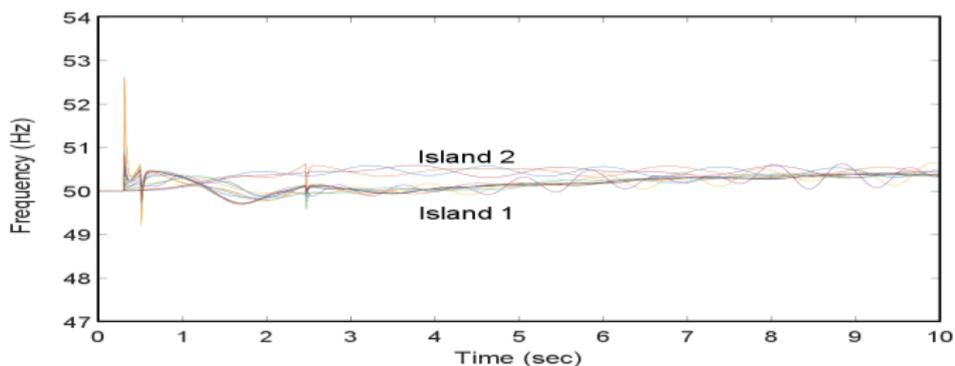


Controlled Islanding

- Generator Rotor Angles



- Generator Frequencies



Final Results

	Uncontrolled System Separation		Controlled Islanding	
	Island 1	Island 2	Island 1	Island 2
Generation (MW)	11513	6785	11513	6785
Load (MW)	13314	4720	11357	6677
Imbalance (MW)	-1976	2021	-19 ✓	65 ✓
No of lines opened	3		9 ✓	

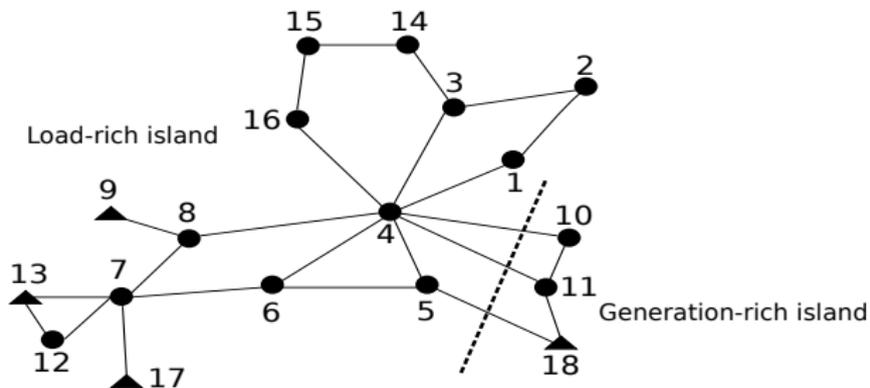
All India System Data used for Simulations

No. of Buses	7242
No. of Transmission Lines	8729
No. of Transformers (ICT and GT)	3745
No. of Synchronous Generators	1232
No. of Wind Generators	18
No. of HVDC Links	9
No. of TCSC compensated line	6
No. of SVC	1
No. of fixed shunts	1182
Total load demand in the load flow scenario (GW)	116

All India System - Regions



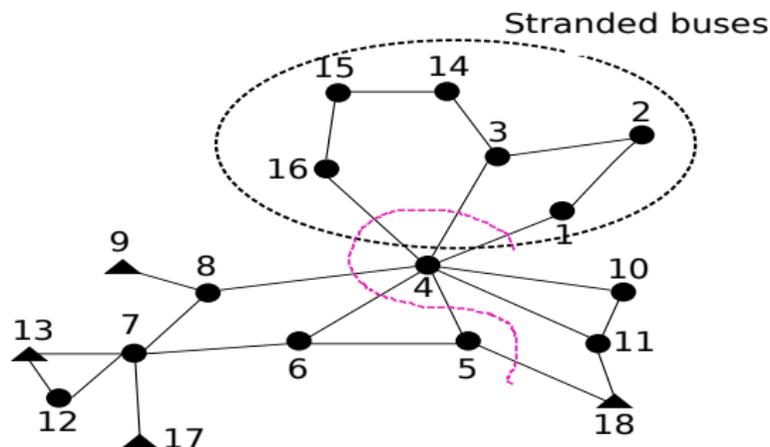
Network Aggregation



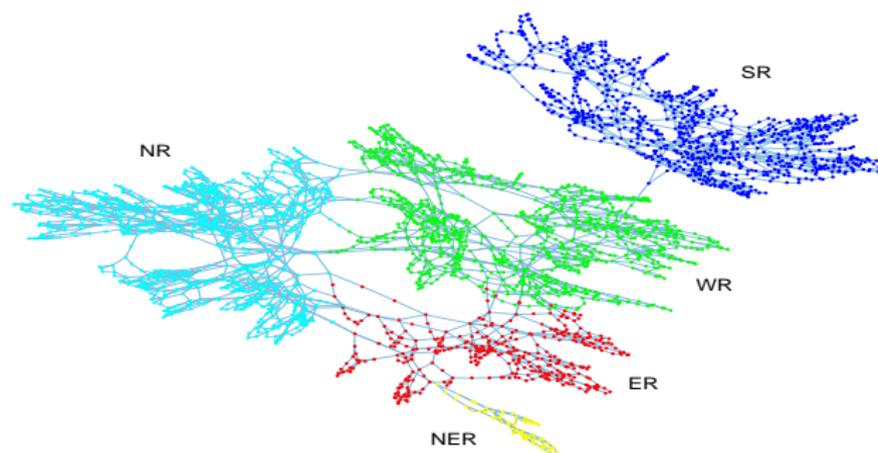
- Triangular nodes - generator buses
Circular nodes - load buses

Moving a block of load buses

- Addition of node 4 to the generation-rich island splits the load-rich island into two groups $S_1 = \{1, 2, 3, 14, 15, 16\}$ and $S_2 = \{5, 6, 7, 8, 9, 12, 13, 17\}$.
- So, group S_1 is lumped into node 4.



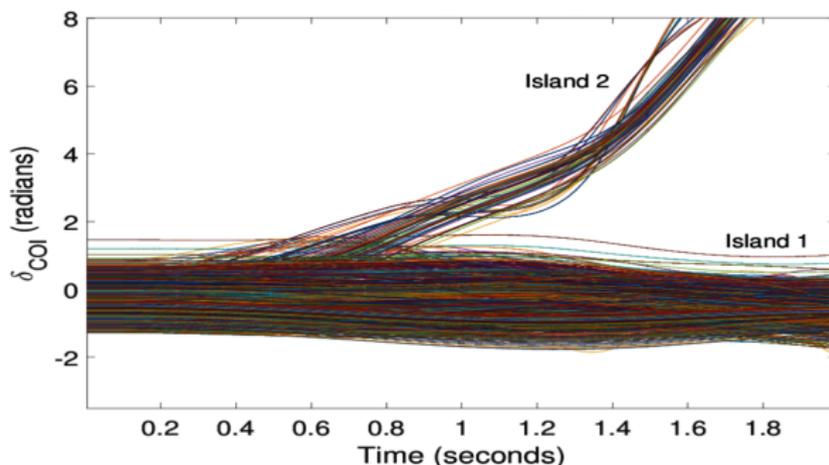
Reduced All India System



	Original System	Reduced System	% Reduction
No. of buses	7242	3478	52
No. of lines	9317	5453	42

All India System

- 3- ϕ fault on Biharsharif 400 kV bus in the Eastern Region.
- Fault inception time = 0.1 s; Fault clearing time = 0.8 s
- Adjacent lines trip to clear fault
- Generators of NER along with some generators of ER lose synchronism with the rest of the grid.



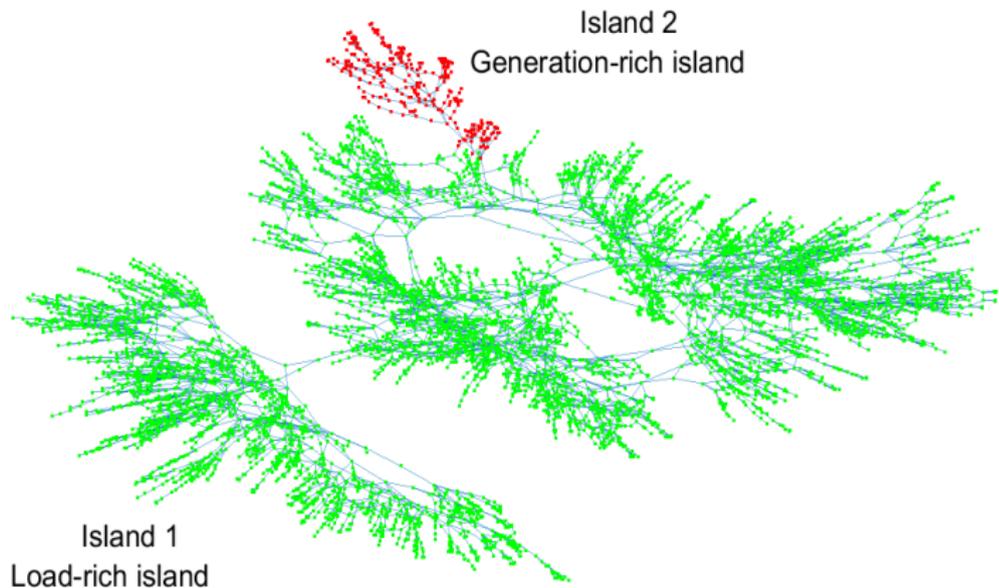
Biharsharif 400 kV 3- ϕ fault

Line (Bus)	Time of electrical center formation (s)	Lead time (ms)
2636 (1191 - 1203)	1.14	199
2621 (1181 - 1183)	1.17	231
2442 (1067 - 1116)	1.18	171

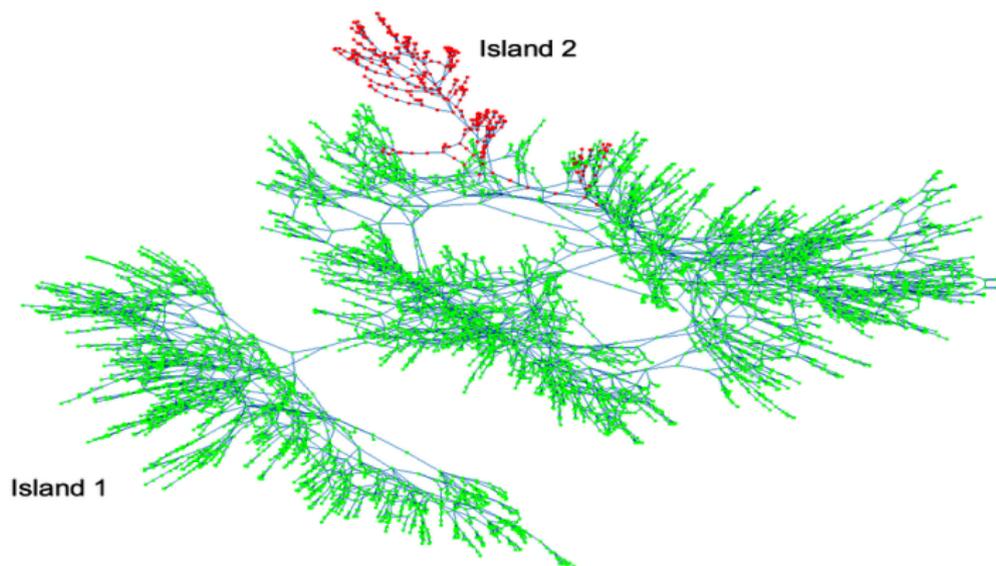
Biharsharif 400 kV 3- ϕ fault

	Uncontrolled System Separation		Controlled Islanding	
	Island 1	Island 2	Island 1	Island 2
Generation (GW)	118	3.5	118	3.5
Load (GW)	115	2.1	114	3.4
Imbalance (MW)	-1318	1327	7 ✓	2 ✓
No of lines opened	3		32 ✓	

Uncontrolled System Separation

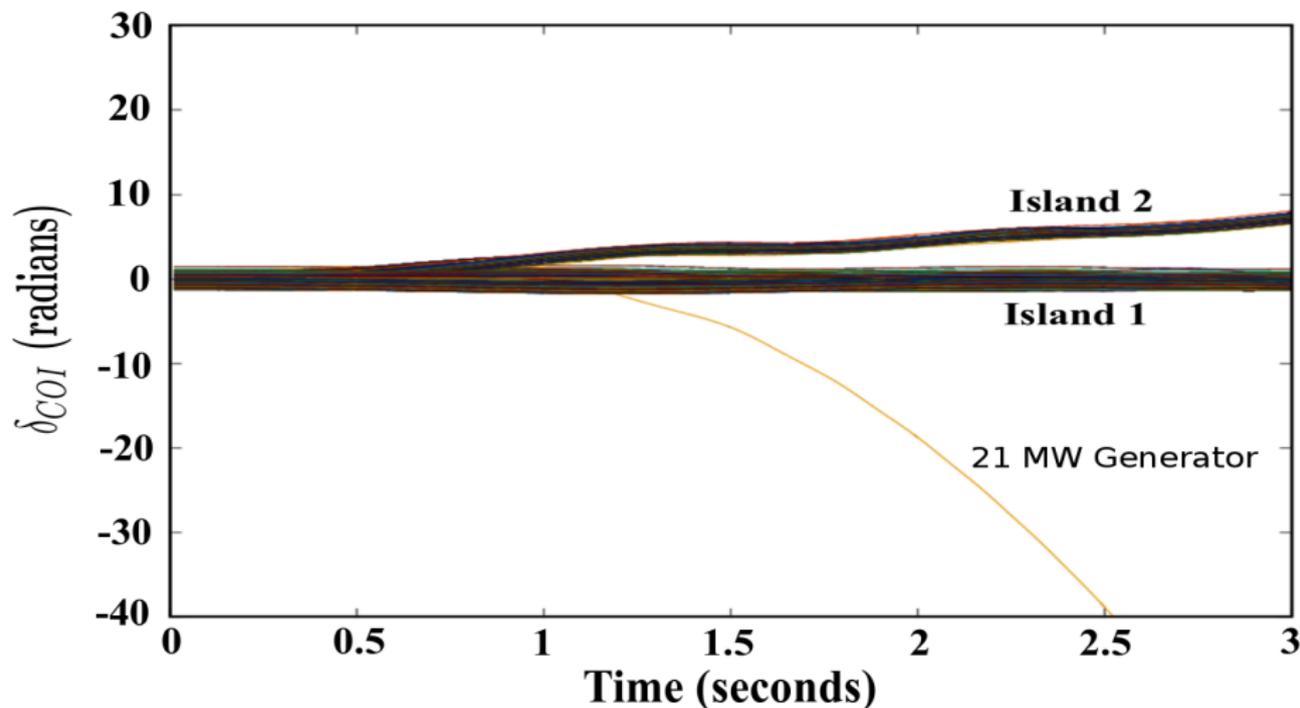


Controlled Islands



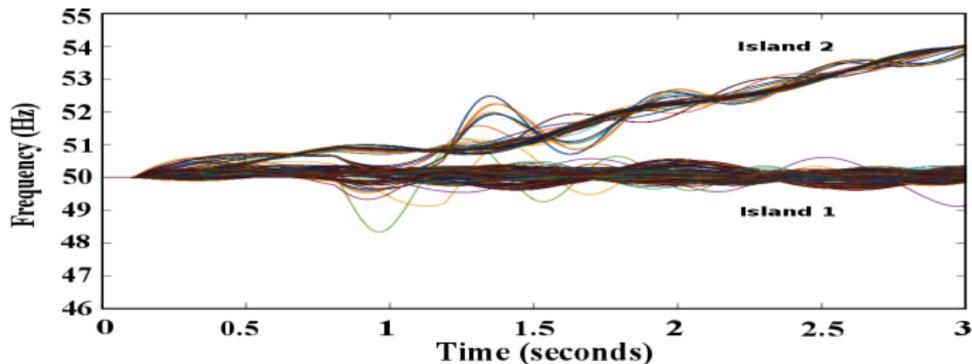
Generator Rotor Angles

- New lines are tripped at 1.04 s (100 ms before first electrical center formation)

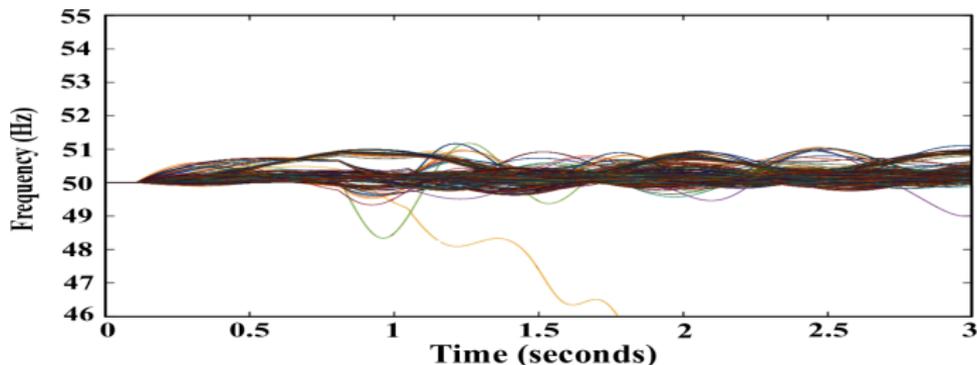


Generator Frequencies

- Uncontrolled system separation



- Controlled islanding



- We thank Powergrid Corporation of India Ltd.(PGCIL) for their financial support.