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Power System Stability Analysis Using Wide Area Measurement System

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Collaborative Work (NSERC Industry Grant)

- GE Grid Solutions, Markham, Canada

  a) Dr. Mital Kanabar, R&D Applications Engineering Manager.

  b) Mr. Ilia Voloh, Applications Engineering Manager

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Outline

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- Introduction
- Review of Some of the Current Methods
- Proposed Synchrophasor Based Transient Stability Prediction Method
- RTDS Results
- Proposed Method with Actual PMUs (GE N60 Relays)
- Conclusion

Introduction

- Develop a method for predicting stability of the power system using wide area measurements.
- Optimum PMU Location.
- Compare the performance with the classical rate of change of impedance method and SCV method.
- Test the proposed method using actual PMU in GE N60 relay

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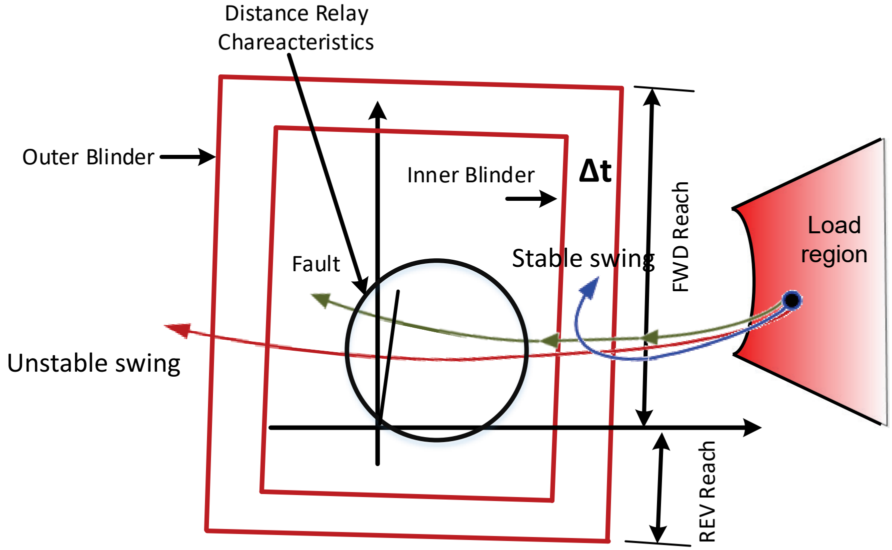
Standard Industry Based Methods:

❖ Local Measurement Based

- Rate of change of impedance based methods
- Swing Center Voltage (SCV)
- R-Rdot Technique
- Equal Area Criterion in Time Domain
- Frequency Deviation of Voltage Method
- Power versus Speed Deviation Method

Rate of Change of Impedance Based Method



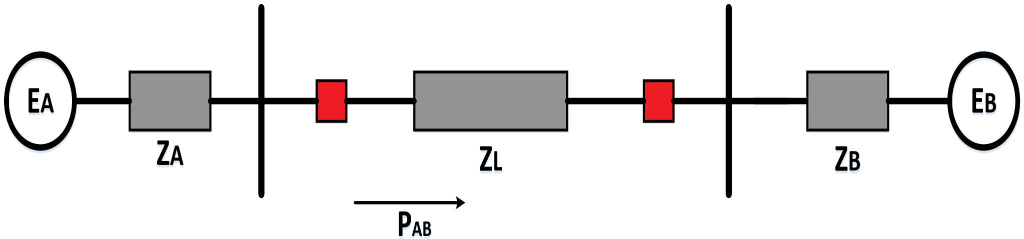
- Commonly used rate of change of impedance method (blinder method, Quad Scheme).
- Disadvantage:-

  Needs number of offline studies to find the parameters

  Prone to incorrect operation

N60 Network Stability and Synchrophasor Measurement System UR Series Instruction Manual, N60 revision: 6.0x ed., GE Multilin, 2011.

Swing Center Voltage (SCV) Method



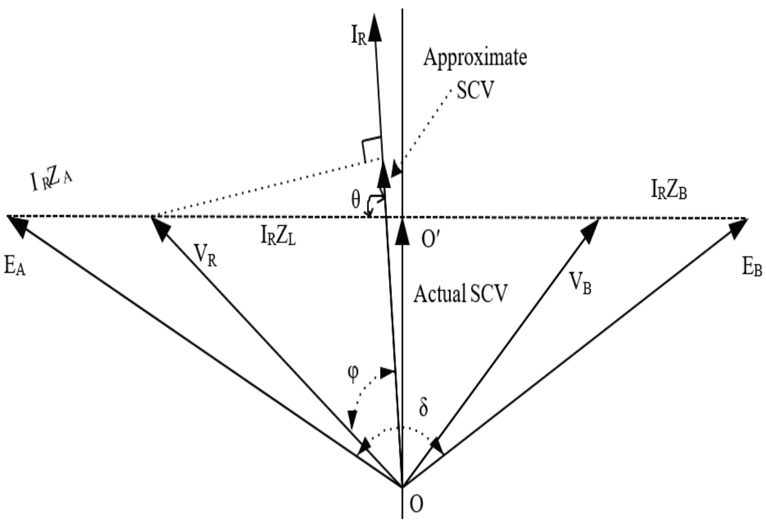
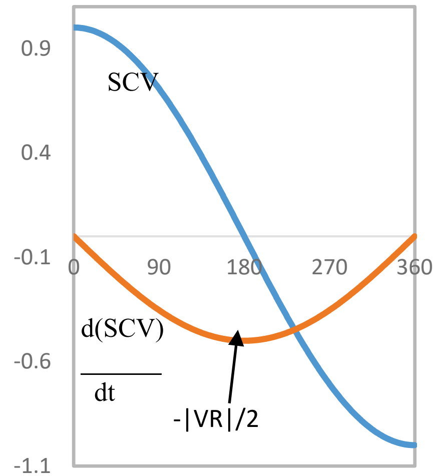


Fig 1: Estimating SCV using local measurements



SCV1 and its rate of change with unity source voltage magnitude and slip rate of 1 rad/s

The approximation of SCV using VR is given

$$SCV = |V_R|\cos\varphi$$

Simplified form using the phase angle difference

$$SCV = |V_R|\cos\frac{\delta}{2}$$

The rate of change of SCV is used for detecting the power swing.

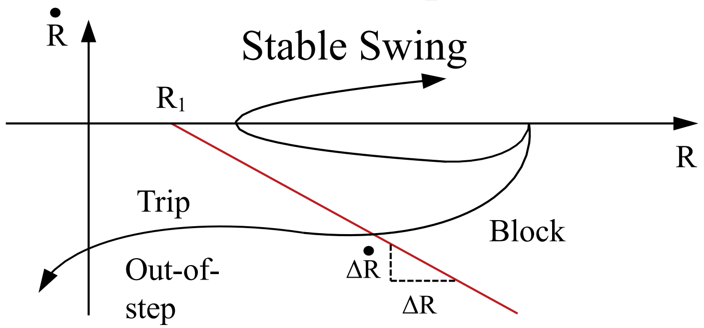
$$\frac{d(SCV)}{dt} = -\frac{|V_R|}{2}\sin\frac{\delta}{2}\frac{d\delta}{dt}$$

- Advantage: Independent of source and line parameter
- Disadvantage: Detection at voltage angle close to 180 deg.

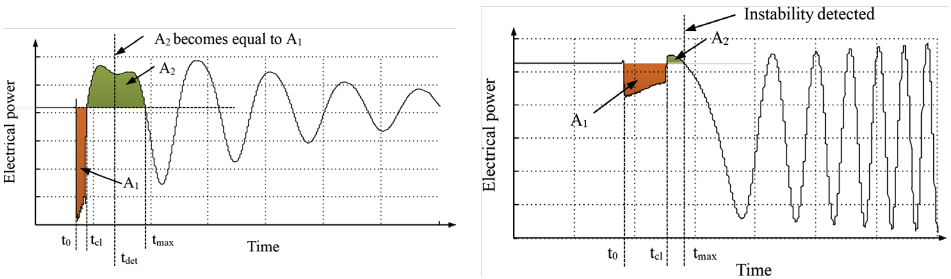
D. Hou, G. Benmouyal, and D. Tziouvaras, Zero-setting power-swing blocking protection," IEEE Conference Publications, vol. 2005, no. CP508, pp. 249-254, 2005.

Other Local Measurement Based Methods

- R-Rdot Technique

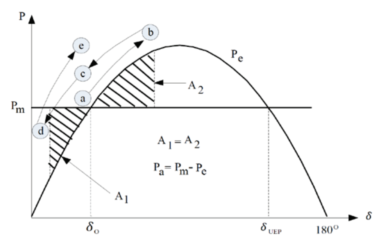


- Equal Area Criterion in Time Domain

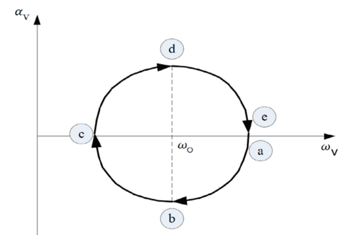


Electrical power versus time curve for stable and unstable case

- Frequency Deviation of Voltage Method

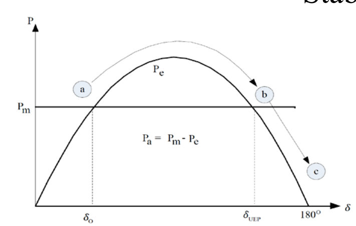


(a) Power-angle curve

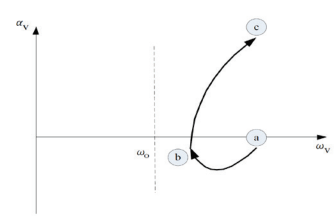


(b) Plot of α_v vs. ω_v

Stable Case



(a) Power-angle curve



(b) Plot of α_v vs. ω_v

Unstable Case

Power vs Integral of Accelerating Power Method

Electrical power deviation relates to rotor acceleration

$$\frac{d}{dt}\Delta\omega = \frac{1}{2H}(\Delta P_m - \Delta P_e)$$

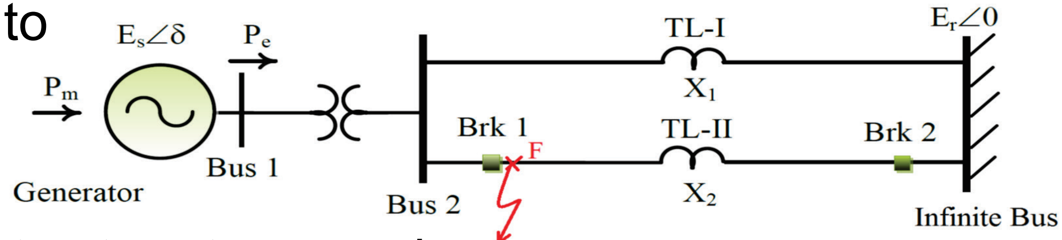
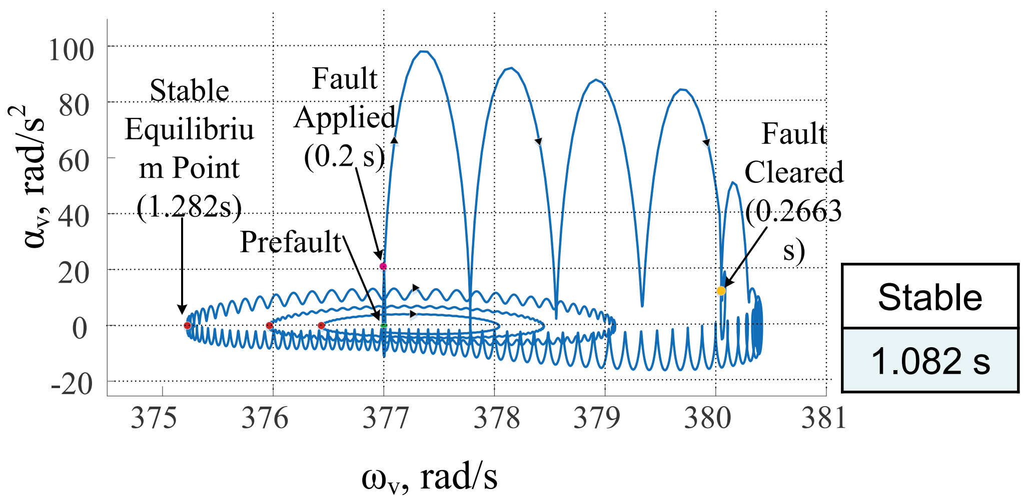


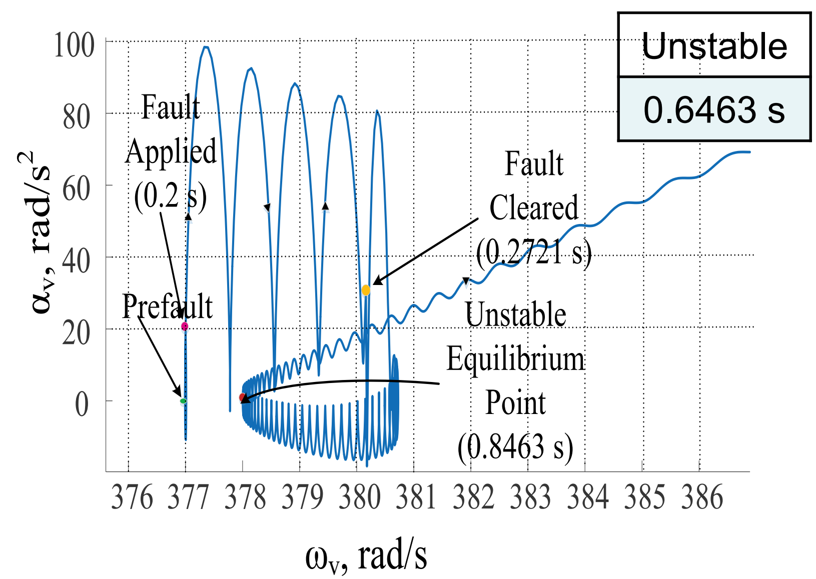
Fig: SMIB system (Kundur's Book)

Integral of accelerating power relates to rotor speed

$$\Delta\omega = \frac{1}{2H}\int(\Delta P_m - \Delta P_e)dt$$

Case 1: Three Phase fault applied in TL-II right after the breaker at 0.2 s and cleared at 0.266 s.

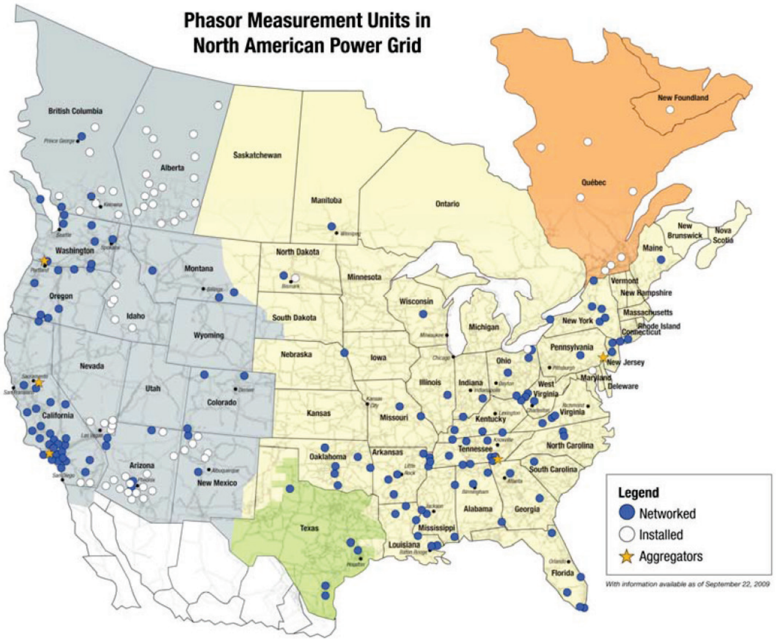




Case 2: Three phase fault applied in TL-II right after the breaker at 0.2 s and removed at 0.27 s.

IEEE PSRC J5 WG Document, Application of Out-of-Step Protection Schemes for Generators," Draft-14, May 2017.

Wide Area Measurement System



NASPI PMU locations, September 2009

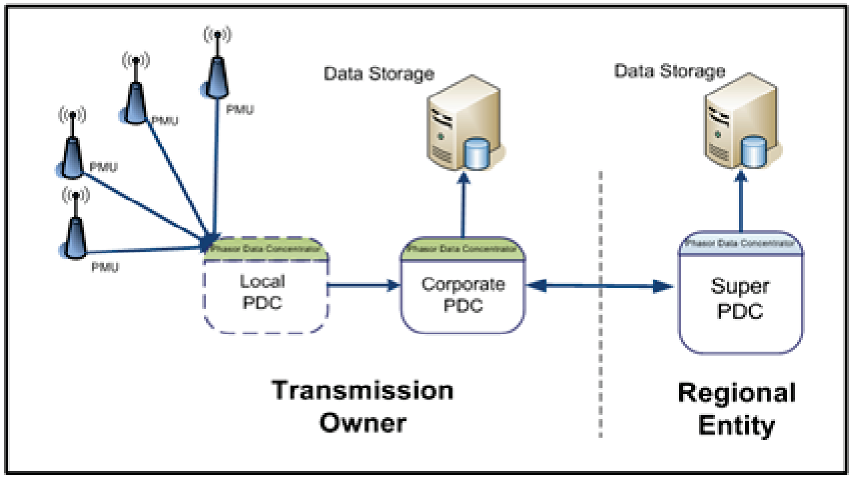


*Fig: Synchrophasor data system**

❖ Advantage:-
- Accurate measurements from different locations
- Power oscillation monitoring
- Voltage monitoring
- Finding system operating limits, event detection

* NERC Real-Time Application of Synchrophasors for Improving Reliability (10/18/2010)

❖ Transient Stability Prediction Methods (Wide Area Measurement Based)

- *Linear Rotor Angle Prediction*

D Fan and V. Centeno, "Adaptive out-of-step protection schemes based on synchrophasors," IEEE PES General Meeting, July 2014.

- *Polynomial Rotor Angle Prediction*

J. Hazra, R. K. Reddy K. Das, D. P. Seetharam, and A. K. Sinha, "Power grid transient stability prediction using wide area synchrophasor measurements," 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Oct 2012.

- *Finite Difference Based Prediction*

D. E. Echeverra, J. L. Rueda, J. C. Cepeda, D. G. Colom, and I. Erlich, Comprehensive approach for prediction and assessment of power system transient stability in real-time," in IEEE PES ISGT Europe 2013, Oct 2013.

- *Post-Disturbance Voltage Trajectory based Prediction*

D. R. Gurusinghe and A. D. Rajapakse, "Post-disturbance transient stability status prediction using synchrophasor measurements," IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3656-3664, Sept 2016.

Methods developed based on pre-simulated events

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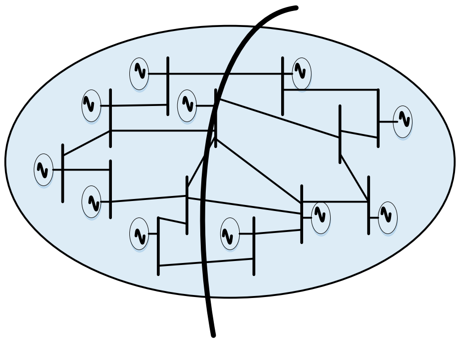
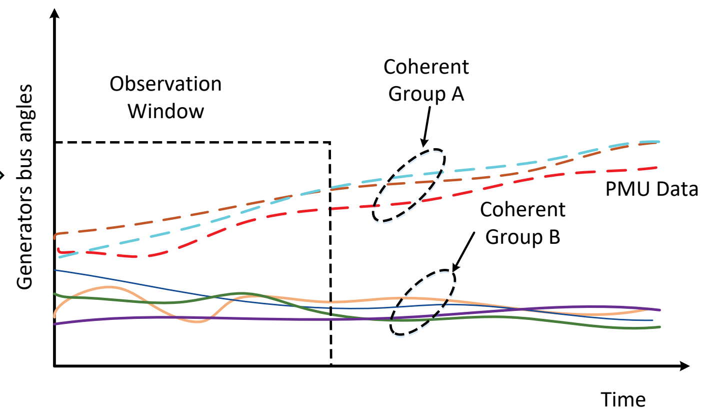
Proposed Synchrophasor Transient Stability Prediction Method

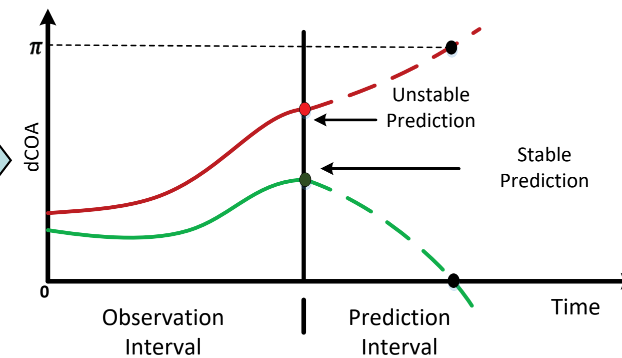
- Uses time series model ARI (autoregressive Integrated modeling) to predict the separation of coherent groups of generators.



Identification of optimal placement sites

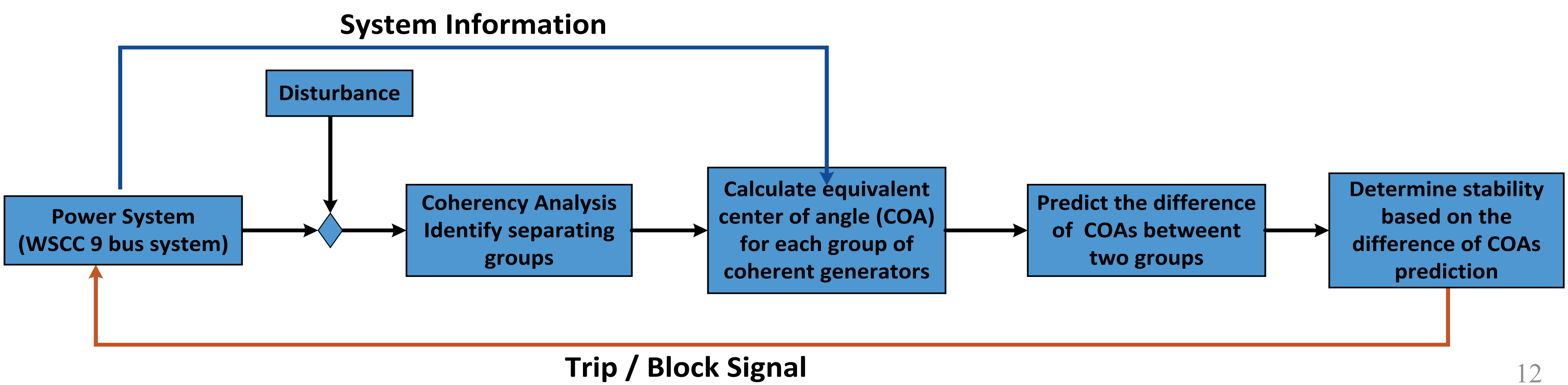


Real-time coherency determination



Approach to determine swing outcome

Flowchart :



Optimum PMU Location

- PMU Placement for Full Observability of the System
- Integer quadratic programming

  - Minimize the required number of PMUs.

  - Maximize the measurement redundancy.

S. Chakrabarti, E. Kyriakides, and D. G. Eliades, Placement of synchronized measurements for power system observability," IEEE Transactions on Power Delivery, vol. 24, no. 1, pp. 12-19, Jan 2009.

Optimal PMU Placement in WSCC 9 Bus System

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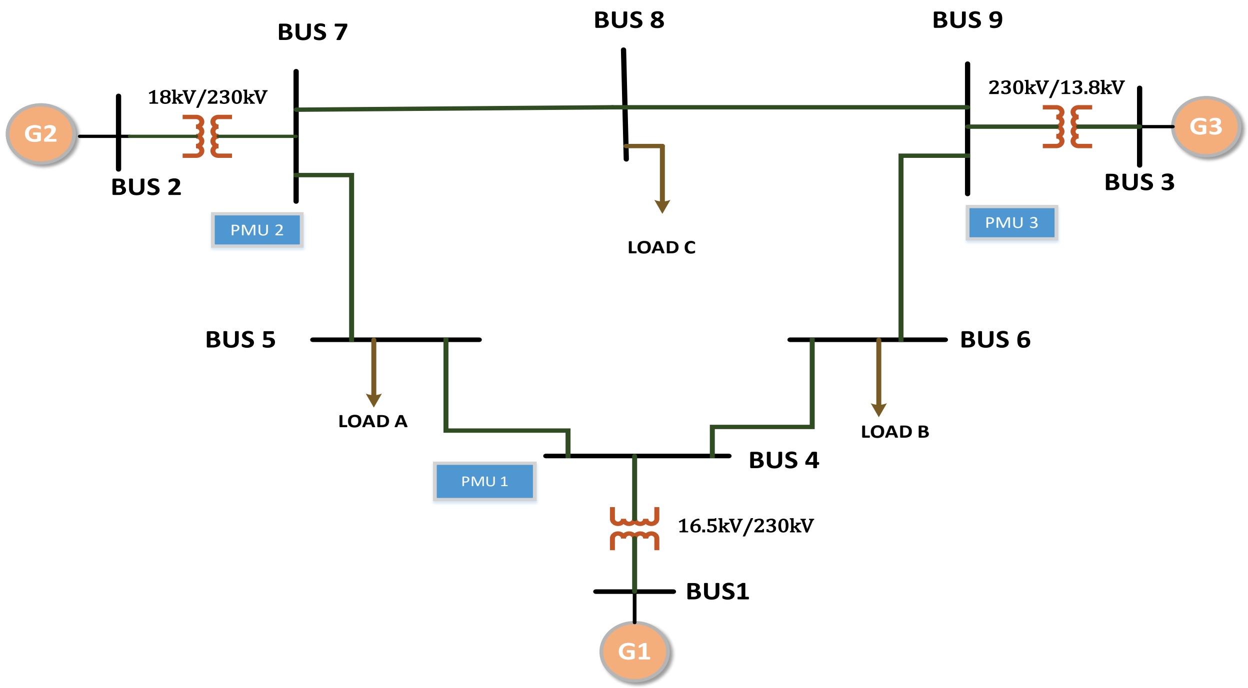
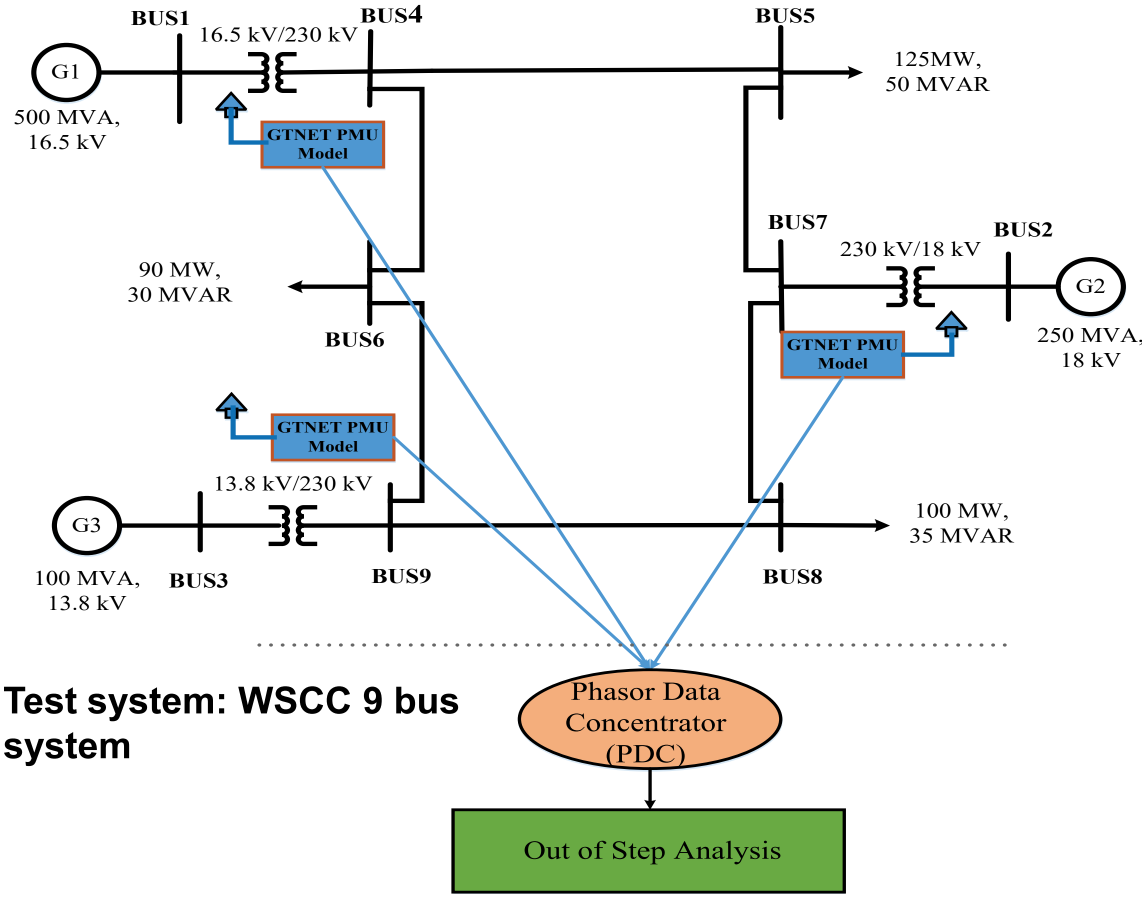


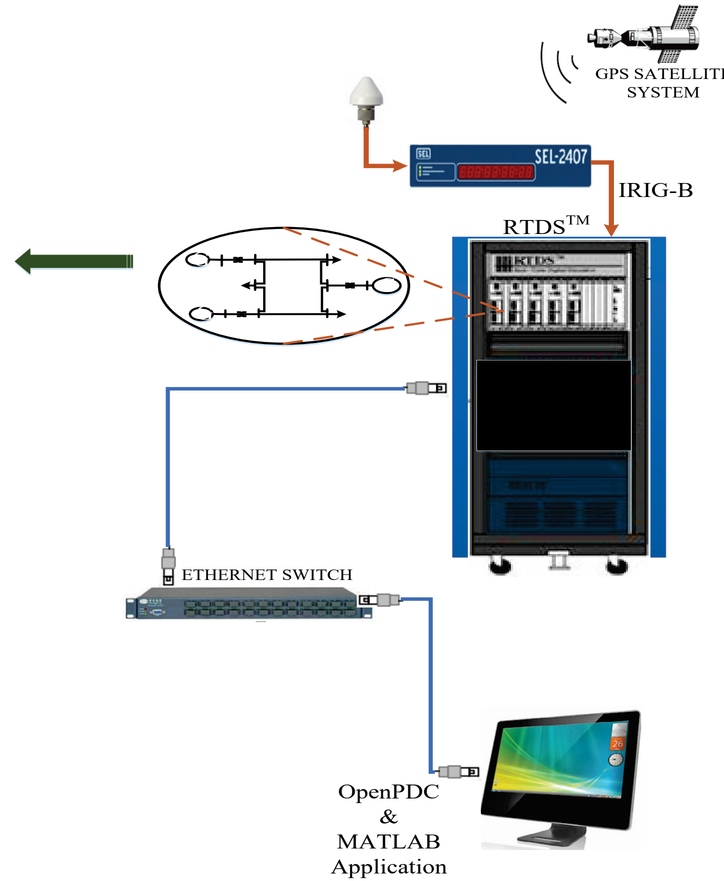
PMU Placement in Buses									O(p) objective	No of PMU
BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 7	BUS 8	BUS 9		
0	0	0	1	0	0	1	0	1	2.48	3
0	0	1	1	0	0	1	0	0	2.546667	3
0	1	0	1	0	0	0	0	1	2.546667	3
1	0	0	0	0	0	1	0	1	2.546667	3

Number of times a bus is observed by the PMU placement set: 4, 7, 9								
BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 7	BUS 8	BUS 9
1	1	1	1	2	2	1	2	1
1	1	1	1	2	1	1	1	1
1	1	1	1	1	2	1	1	1
1	1	1	1	1	1	1	2	1

Number of PMUs	3
PMU 1 Location	BUS 4
PMU 2 Location	BUS 7
PMU 3 Location	BUS 9
V(x) Objective Function	2.48

Experimental Setup





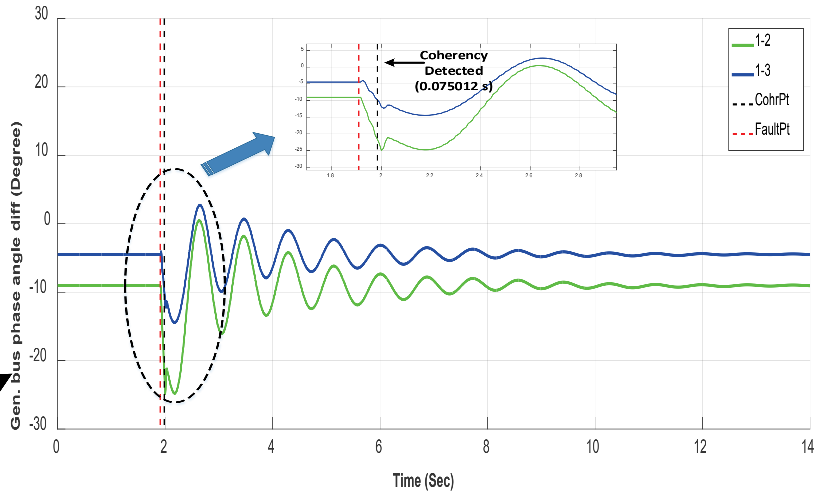
Test system: WSCC 9 bus system

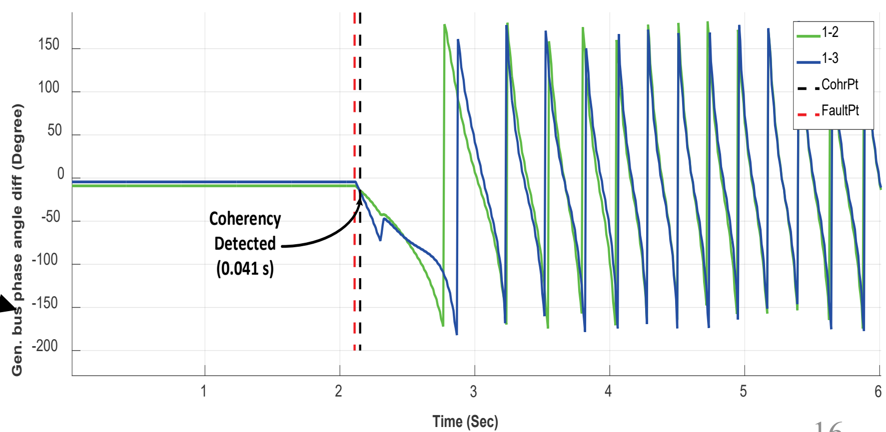
- PMU reporting rate: 120 frame/sec
- PMU class: P-type
- GPS timing signal (UTC): SEL 2407 (IRIG-B format)

Coherency Analysis

- Coherent groups identified with the threshold value of angular separation greater than 5 degrees from the reference generator (G1) bus.

3 Phase Fault Location	Fault Duration (cycles)	Coherency detection time after fault (s)
BUS 5	6	0.0829
	13	0.0830
Line between BUS 5-7	5	0.0750
	12	0.0749
BUS 9	6	0.0410
	11	0.0410





- Coherency detected: within 100 ms

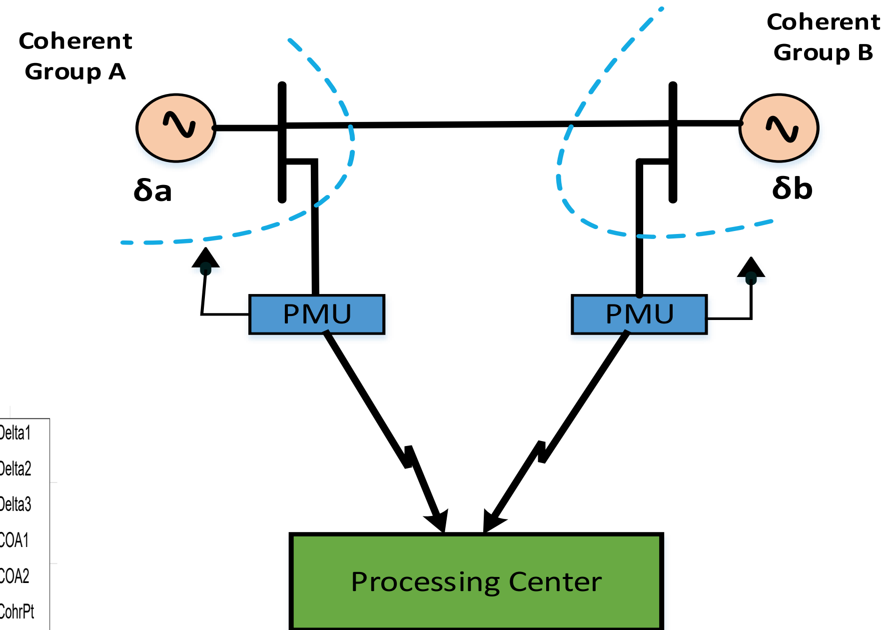
Equivalent System Formulation

- With the information of the voltage and current at generator bus, the rotor angle of the machine calculated using generator classical model.

$$COA1\ (\delta_a) = \frac{\sum M_i \delta_i}{\sum M_i} \quad i \in A$$

&

$$COA2\ (\delta_b) = \frac{\sum M_j \delta_j}{\sum M_j} \quad j \in B$$



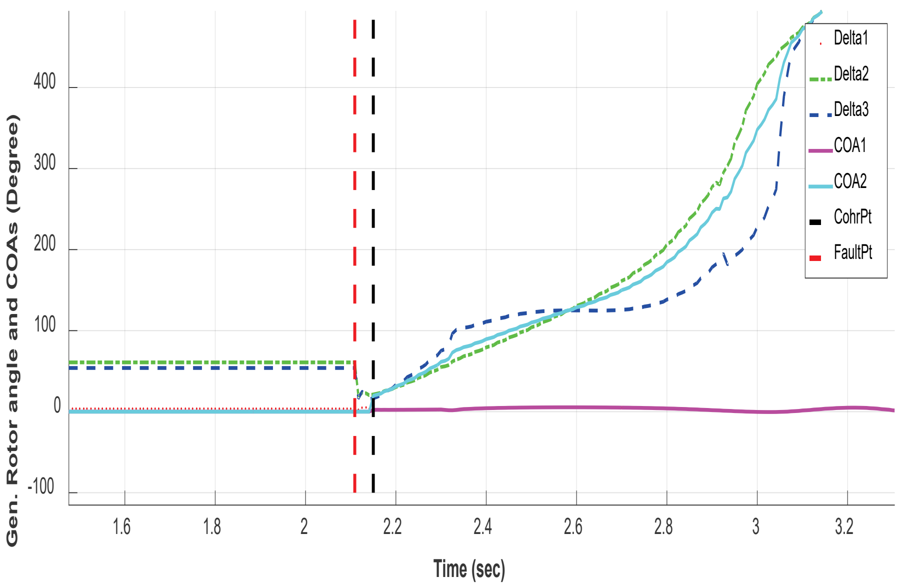


Fig 2: Generators rotor angle for 3 phase fault at Bus 9 and fault cleared after 183 ms.

Coherent Group A: Gen 1

Coherent Group B: Gen 2 & Gen 3

Difference of COAs

$$dCOA = \boldsymbol{\delta_a - \delta_b}$$

Time Series Analysis

- Autoregressive Model (AR): Simplest model and practical

  AR(1): $z_t = c + \varphi_1 z_{t-1} + \varepsilon_t$

  AR(p) : $z_t = c + \varphi_1 z_{t-1} + \varphi_2 z_{t-2} + \cdots + \varphi_p z_{t-p} + \varepsilon_t$

- Moving Average Model (MA) : Linear regression of future value of the series using random errors of previous values

  MA(1): $z_t = \mu + \beta_1 \varepsilon_{t-1} + \varepsilon_t$

  MA(p): $z_t = z_t = \mu + \beta_1 \varepsilon_{t-1} + \beta_2 \varepsilon_{t-2} + \cdots + \beta_q \varepsilon_{t-q} + \varepsilon_t$

- Autoregressive Moving Average Model (ARMA) : Combination of AR and MA time series model

- Autoregressive Integrated Moving Average Model (ARIMA) : Generalized ARMA model to account for non-stationarity of the signal.

Time Series Model Selection

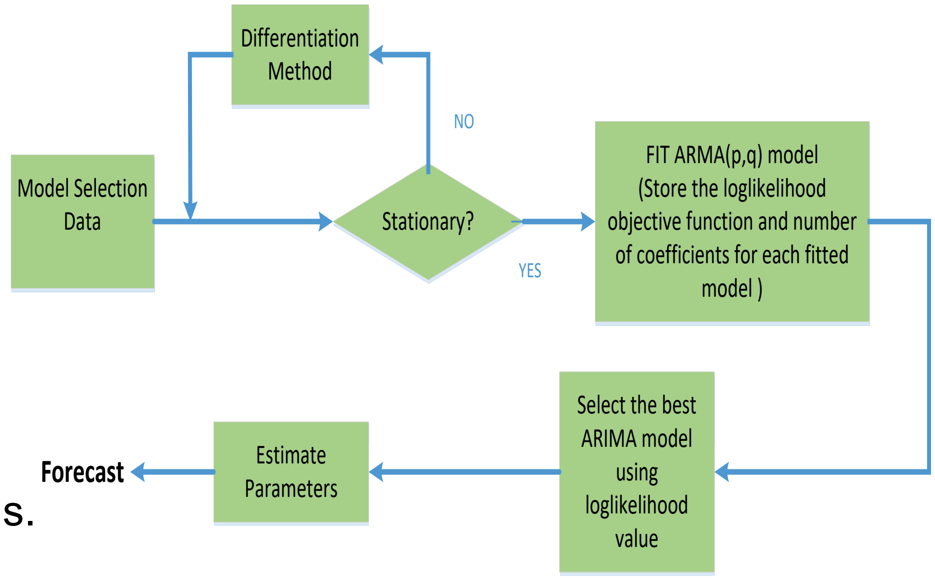
- Akaike Information Criteria (AIC)

$$AIC(p) = n\ln(\hat{\sigma}_a^2) + 2p$$

- Bayesian Information Criteria (BIC)

$$BIC(p) = n\ln(\hat{\sigma}_a^2) + p\ ln(n)$$

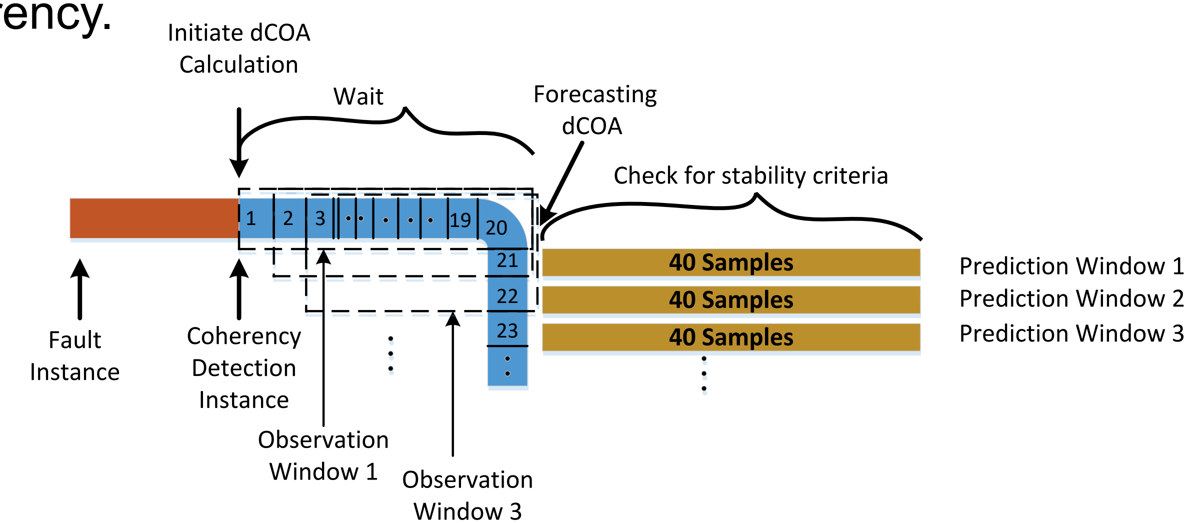
n is the number of observations
p is the number of parameters in the model
$\hat{\sigma}_a^2$ is the sum of the sample squared residuals.



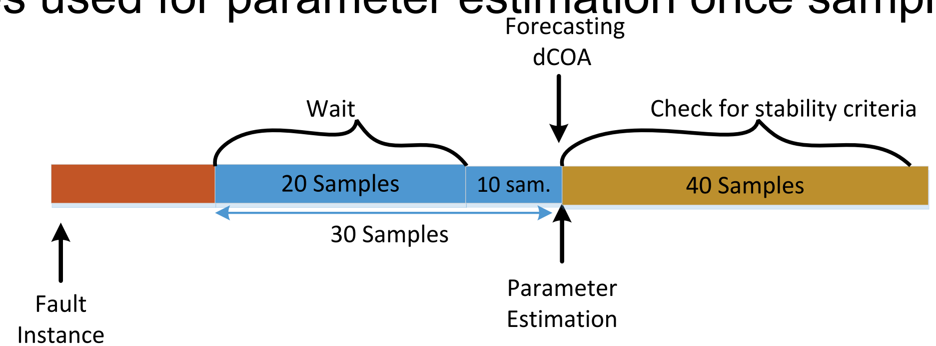
Fault location	Fault duration	Prediction	BIC Value			
			AR(1)	ARIMA(1,1,0)	ARIMA(2,1,0)	ARIMA(3,1,0)
Bus 5	6	Stable	578.132	569.6117	**547.1285**	550.3238
	13	Unstable	683.335	636.4493	631.8222	**560.2741**
Bus 9	6	Stable	570.806	560.1348	**531.6387**	536.1942
	11	Unstable	693.763	636.7355	634.9531	**589.2192**

Forecasting and Stability Prediction

- Relay waits for 20 samples for parameter estimation and then forecasting after the coherency.



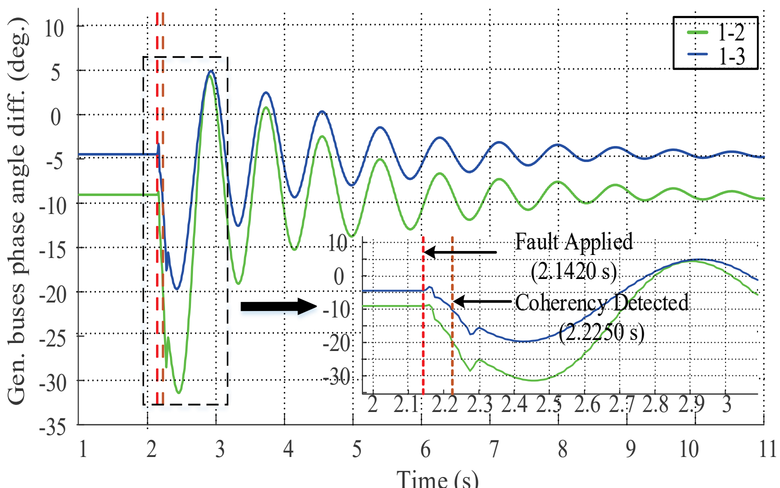
- 30 samples used for parameter estimation once samples are available.



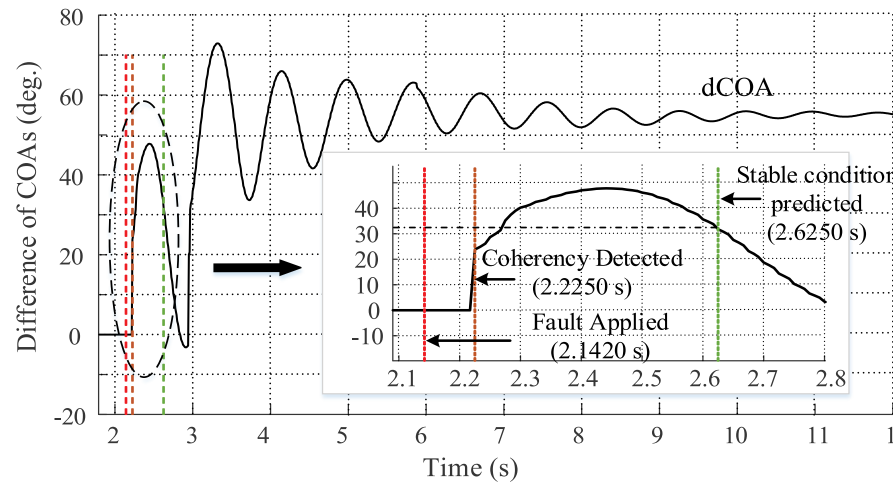
- Three consecutive prediction:
  - Predicted dCOA >180 deg : System will be unstable
  - Predicted dCOA <=0 deg : System will be stable

RTDS Results

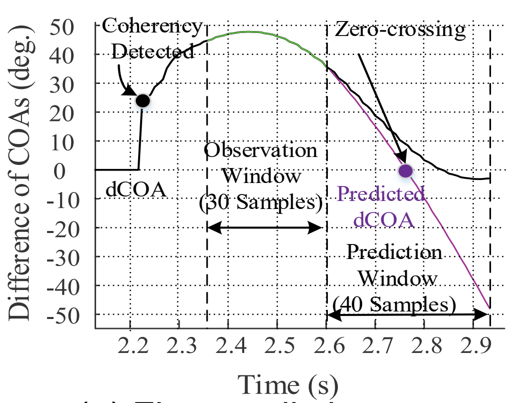
Stable case: Fault at bus 5 for 6 cycles



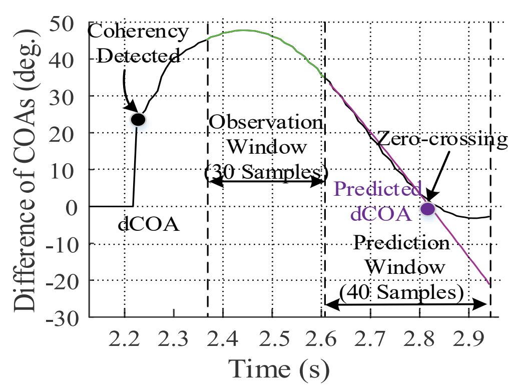
Coherency detected 0.0829 s after fault



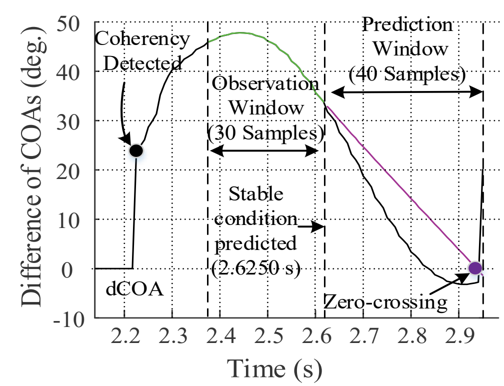
Stable condition predicted at 0.483 s after fault



(a) First prediction



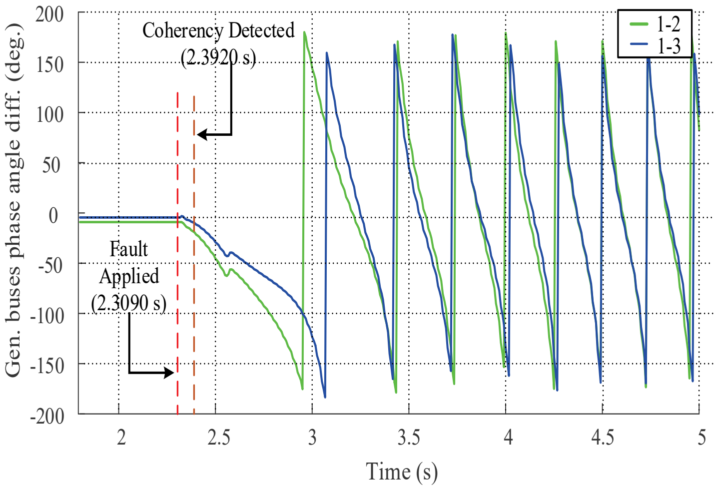
(b) Second prediction



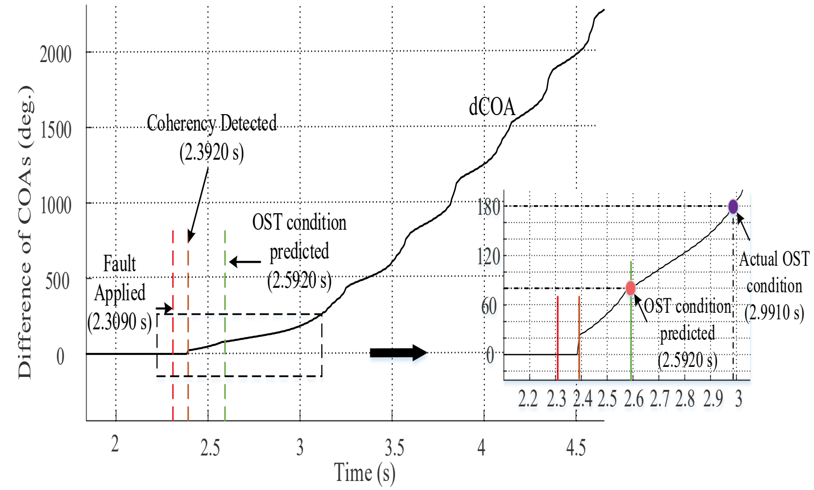
(c) Third prediction

Three consecutive prediction before stable condition confirmed

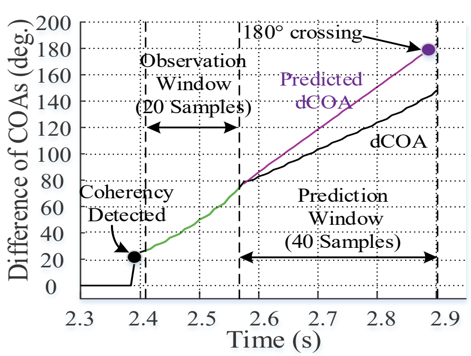
Unstable case: Fault at bus 5 for 13 cycles



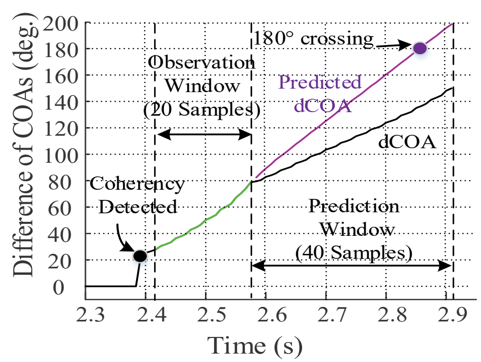
Coherency detected 0.083 s after fault



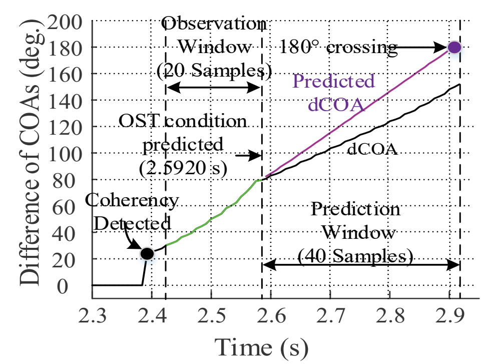
Unstable condition predicted at 0.2829 s after fault



(a) First prediction



(b) Second prediction



(c) Third prediction

Three consecutive prediction before unstable condition is confirmed

System level transient stability prediction time vs actual generator out-of-step instants

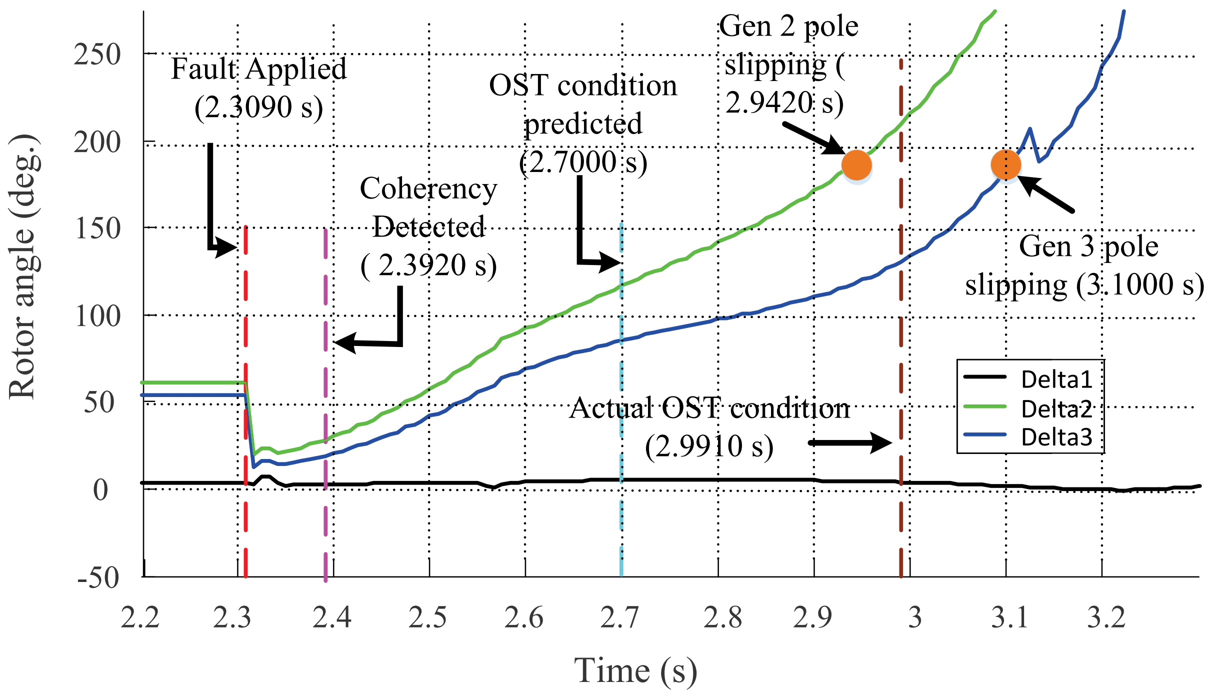


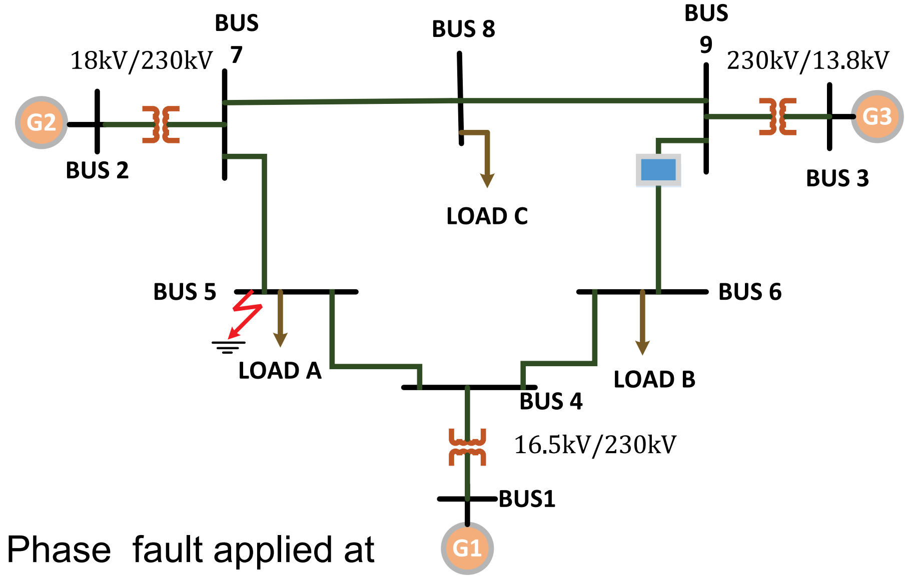
Fig 3: Generator Pole Slipping During Transients

Comparison with Double Blinder

❖ Blinder Scheme: Relay at BUS 9

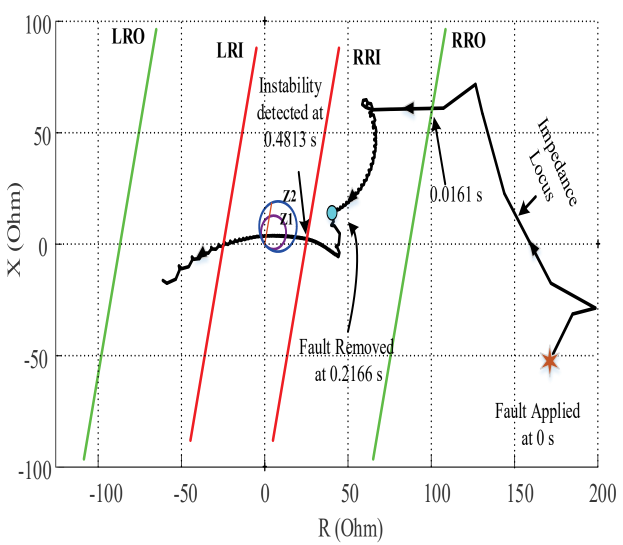
PSBD	2.5 cycle
Slip Frequency	4 Hz

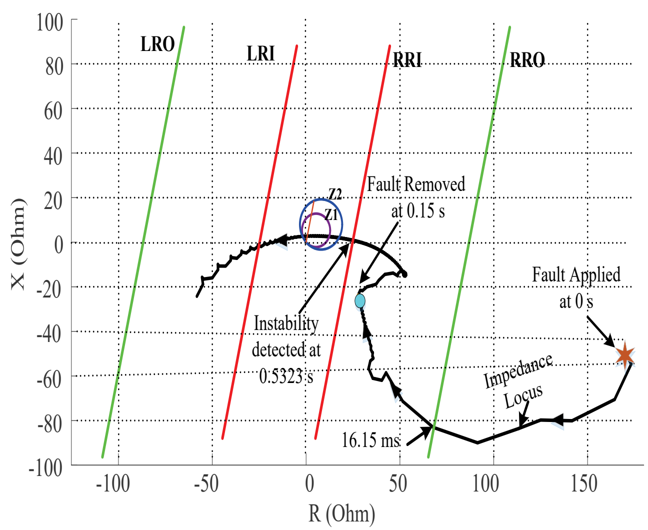
LRI/RRI	24.7692 Ω
LRO/RRO	86.8338 Ω



Case I: Three Phase fault applied at BUS 5 and fault cleared after 13 cycles.

Case II: Three Phase fault applied at BUS 7 and fault cleared after 9 cycles.





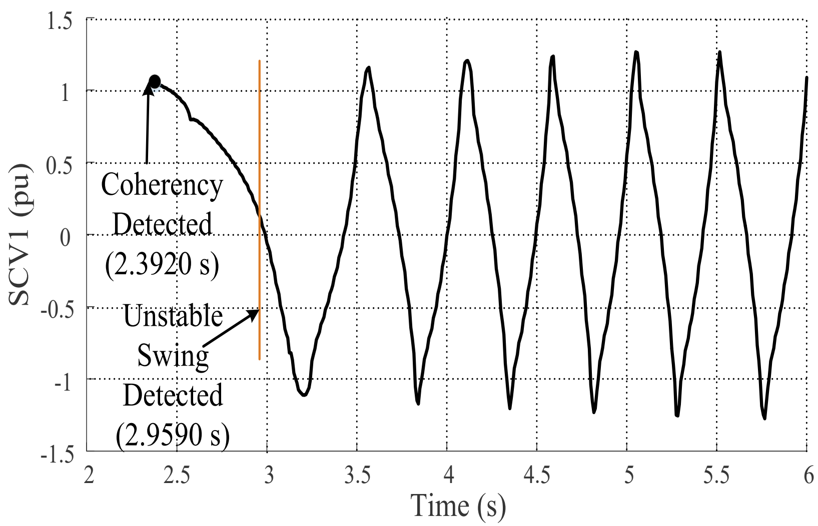
Double Blinder Method		
Case	I	II
Decision	Unstable	Unstable
Dec. Time	0.4813 s	0.5323 s

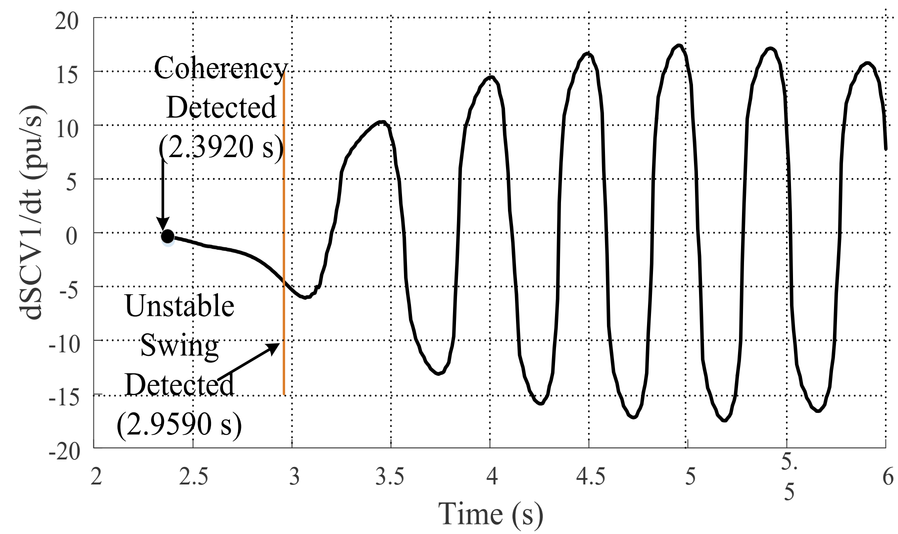
Synchrophasor Technique		
Case	I	II
Prediction	Unstable	Unstable
Pred. Time	0.2830 s	0.5750 s

Comparison with SCV Method

❖ Swing Center Voltage Method: Relay at BUS 9

Case I: Three Phase fault applied at BUS 5 and fault cleared after 13 cycles.





SCV Scheme	
Decision	Unstable
Dec. Time	0.65 s
Groups Sep. Angle	166.4323 deg

Synchrophasor Technique	
Prediction	Unstable
Pred. time	0.2830 s
Groups Sep. Angle	80.4965 deg

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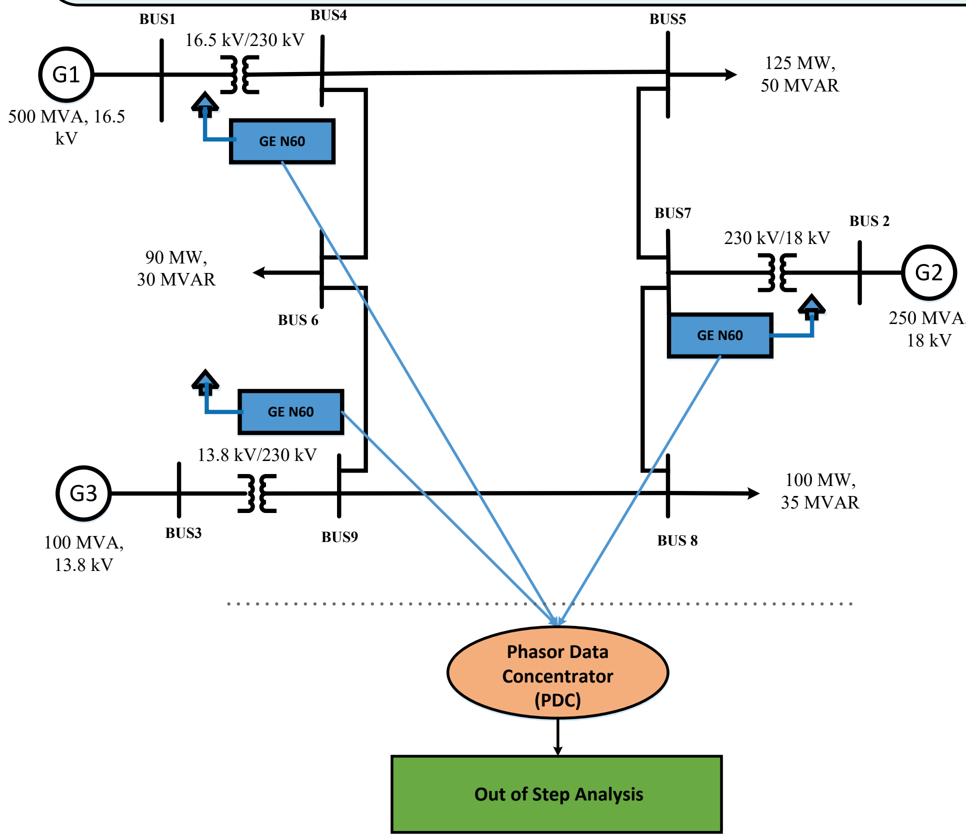
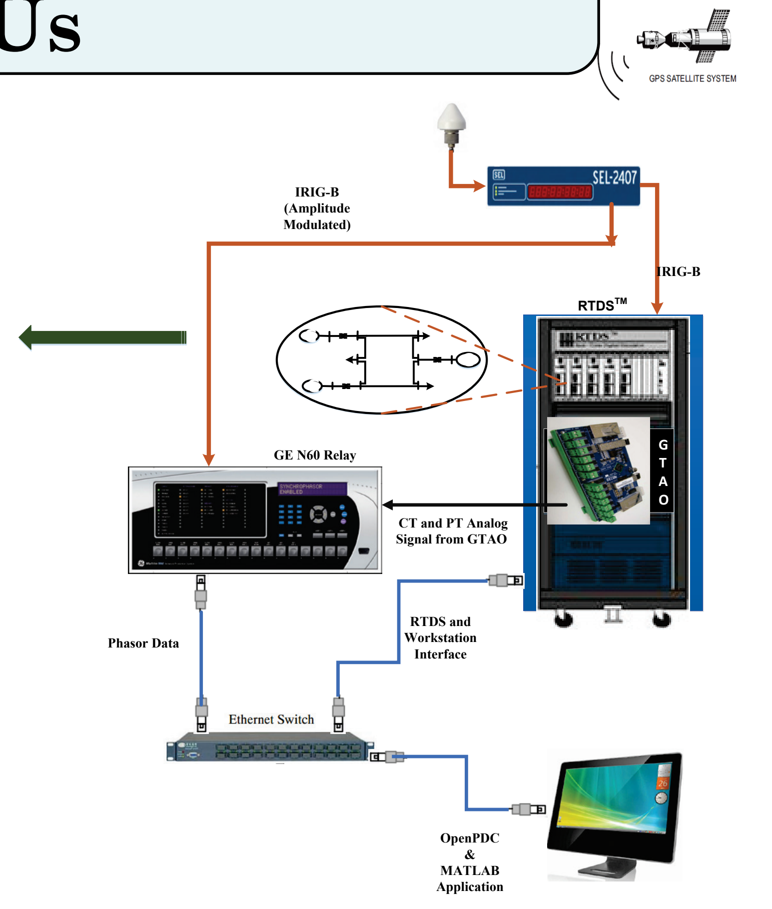
Testing Synchrophasor Method with Actual PMUs





- GE N60 Relay
- GTAO Interface RDTS and N60

Fault Location	Duration (Cycles)	Prediction	PMU Model (RTDS)	Actual PMU (N60)
BUS 4	12	Unstable	0.283 s	0.275 s
Center of line 4-5	12	Unstable	0.375 s	0.3749 s

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Conclusion:

- A synchrophasor-based method to predict the OST condition using an auto-regressive integrated time series model.

- Tested the transient stability prediction method using RTDS & GE N60 relay with PMU capability.

- Correctly predicted transient stability conditions (stable and unstable conditions) at the system level using WAMS.
- Accurately predict instability 8.5 to 24.5 cycles before the system actually enters OST condition.

- Results matched with conventional blinder schemes. Method was also faster than the SCV method.

Thank you!