Methods for Optimal PMU Placement, Machine Internal State Estimation, Voltage Stability Prediction and Adaptive Distance Relaying

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Research Activities on WAMS at IIT Kanpur

- Development of algorithms for
  - Wide Area Measurement based Voltage Stability Assessment & Control
  - Wide Area Measurement based Angular Stability Assessment & Control
  - Wide Area Monitoring System Applications in Controller Design and Adaptive Relaying
- A sponsored project on “Wide Area Measurement and Control for Improving Observability and Stability of Power Systems” approved for funding by Central Power Research Institute, India (in collaboration with Power Grid Corporation of India Ltd.)

Few Preliminary Works Carried Out

- Method for Optimal PMU Placement to ensure complete system observability under system intact condition and contingencies.
- A Global Dynamic Stability Index to assess Voltage Stability of the System.
- Estimation of Machine Internal State Estimation using a Divide by Difference Filter (DDF).
- An ANN based Adaptive Distance Relaying Scheme in Presence of UPFC.

Optimal PMU Placement For Complete Observability of the Power System

1. A two-step approach is developed. First a basic optimal PMU placement is carried out using an Integer Linear Programming (ILP) to ensure topological observability.

$$\min \sum_{i=1}^{N} C_i x_i \quad \text{(minimizes PMU cost)}$$

subject to $f_j(X) \geq 1$ inequality at each node.

and $x_i = (0/1)$ a binary variable showing presence of PMU.

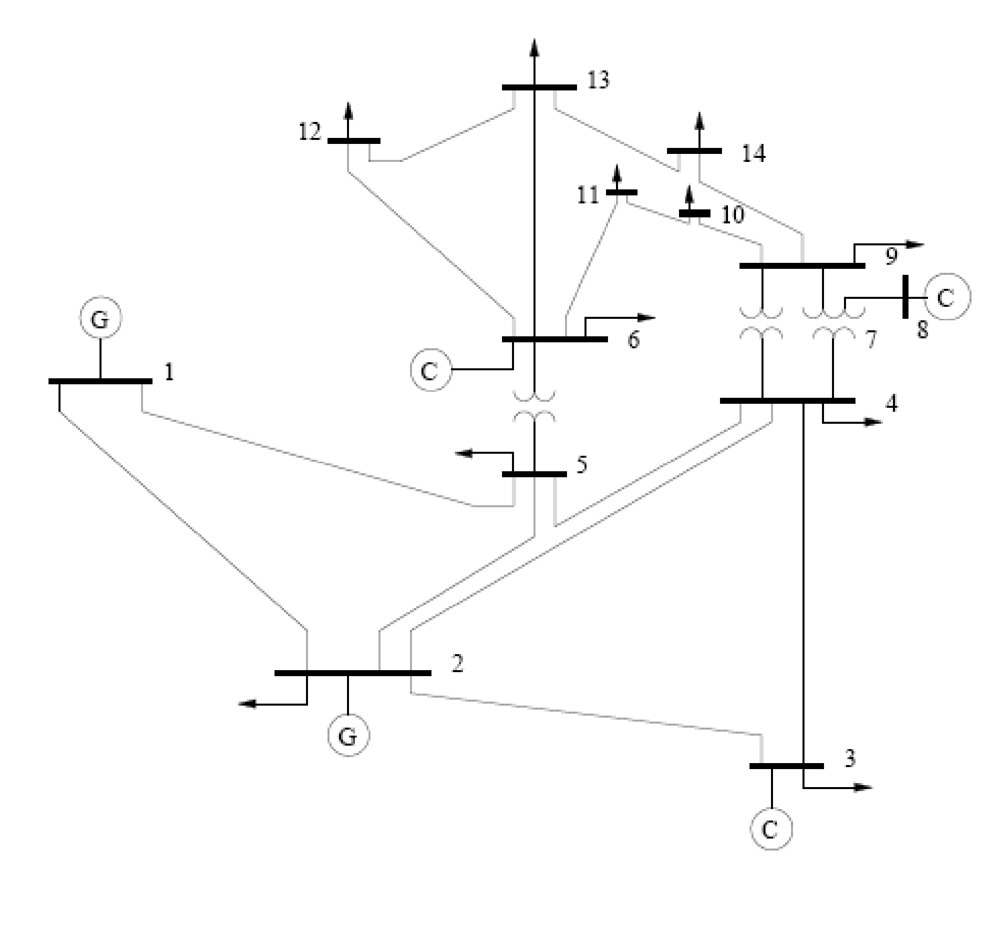
2. Next the Measurements are obtained from the basic optimal PMU set and the measurement Jacobian matrix is formed and checked for its full rank. Few more PMUs are added, if required, to make the system also numerically observable. Power injections and power flows are taken as measurements.

3. Voltage Stability based critical contingency ranking* (based on RVI and binary search) is carried out.

$$RVI_i = \sum_{j=1}^{N_q} (Q_{ji}^{no} - Q_j^{\max})$$

4. Steps 1-2 repeated for few critical contingencies.

* M K Verma, "*Voltage stability constrained power system security assessment and its enhancement using FACTS controllers*", Ph.D. Thesis, Dept. Electrical Eng., Indian Institute of Technology Kanpur, India, 2005.



Test Results: IEEE 14 Bus System

Case	Optimal Locations	No. of locations
Intact	2,6,8,9	4
Line 1-2 outage	4,5,6,8,9	5
Line 2-3 outage	4,5,6,8,9	5
Line 5-6 outage	4,5,6,8,9	5

Optimal PMU Placement for New England 39 Bus System

Case	Optimal Locations	No. of locations
Intact	2,6,9,10,13,14,17,19,20,22,23,25,29	13
Line 16-19 outage	2,6,9,10,13,14,17,19,20,22,23,25,29	13
Line 6-31 outage	1,2,8,10,11,14,17,19,20,22,23,25,29,31	14
Line 19-20 outage	1,2,8,10,11,14,17,19,20,22,23,25,29,31	14

Optimal PMU Placement Results' with Different Methods

Method	IEEE 14 Bus		NE 39 Bus		Indian 246 bus	
	w/o	w/c	w/o	w/c	w/o	w/c
DFS	6	5	16	16	88	89
DST	4	4	10	14	65	75
DNST	8	7	18	14	144	146
Proposed	4	5	13	14	70	71

- w/o = without contingencies
- w/c = with contingencies
- DFS = Depth First Search
- DST = Direct Spanning Tree
- DNST = Direct N-1 Spanning Tree

A Global Dynamic Voltage Stability Index

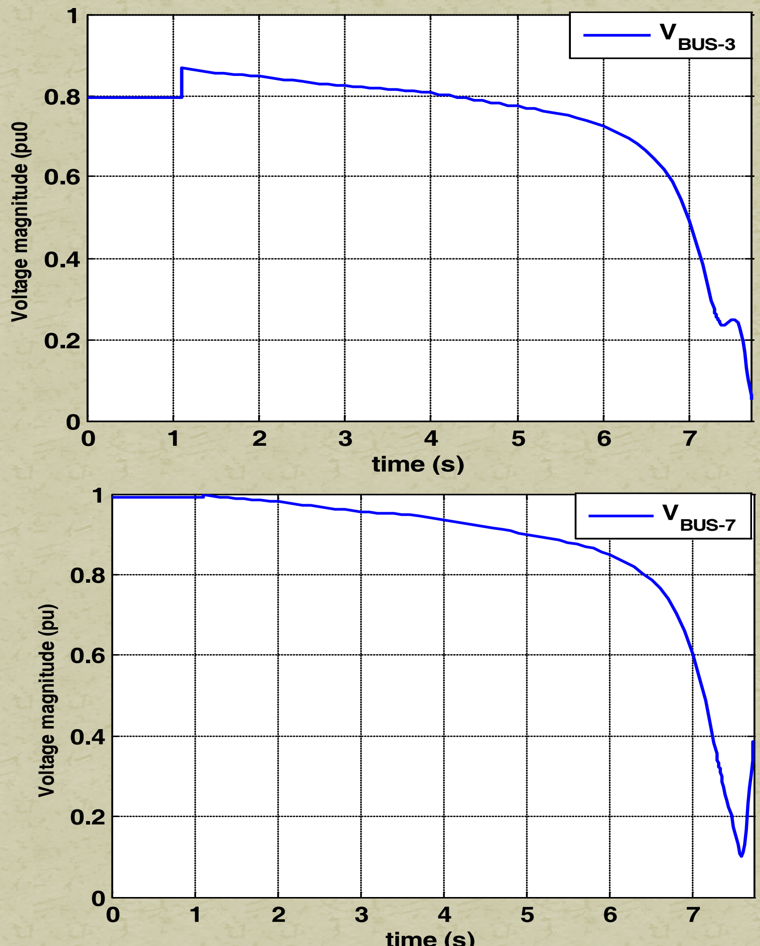
- The proposed index is based on tracking voltage magnitude **V** and rate of change of voltage (d**V**/dt) at different buses (referred as the two criteria), readily available from the PMU outputs. The rate of change of voltage at any sampling instant can be determined as [{**V**(t)-**V**(t-τ)}/dτ], where τ is the sampling interval.
- If M_{ij} is the measured value of criterion *j* at time *i*, M_{0j} is value of criterion *j* at stable base case (or its desired value), T_j is threshold value for criterion *j*, set to signify approaching unstable state (taken as 0.6 pu for voltage and 2000 pu/sec for dV/dt). Variation *Vij* in criterion *j* at time instant *I*, can be defined as.

$$V_{ij} = \frac{M_{ij} - M_{0j}}{T_j - M_{0j}}$$

- Define dynamic stability index at time *i*, $DVSI_i = \sum_{j=1}^{2} \alpha_j V_{ij}$, αj is the relative weightage to jth criterion. (α1+ α2=1.0).
- $DVSI_{il}$ can be calculated for each bus-*l* in the system. At a given instant of time *i*, a Global Dynamic Voltage Stability Index ($GDVSI_i$) has been defined as $GDVSI_i = \max_{l \in \beta_L} DVSI_{il}$ $\beta_L =$ No. of buses being monitored.
- This index will be 0 at the base case and 1 at the voltage unstable point.

Simulation Results

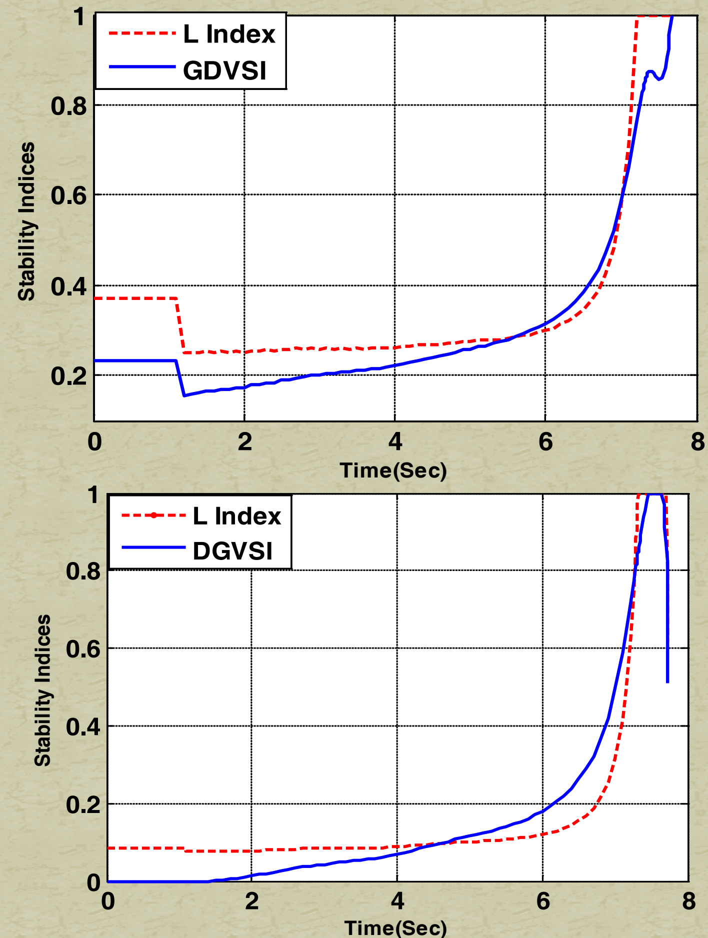
- The performance is compared with a dynamic L-index method*.
- TEST CASE 1– NEW ENGLAND 39 BUS SYSTEM, LINE 17-18 OUTAGE AT T = 1.1 SECOND



Voltage profile at buses 3 and 7

Bus 3

Bus 7

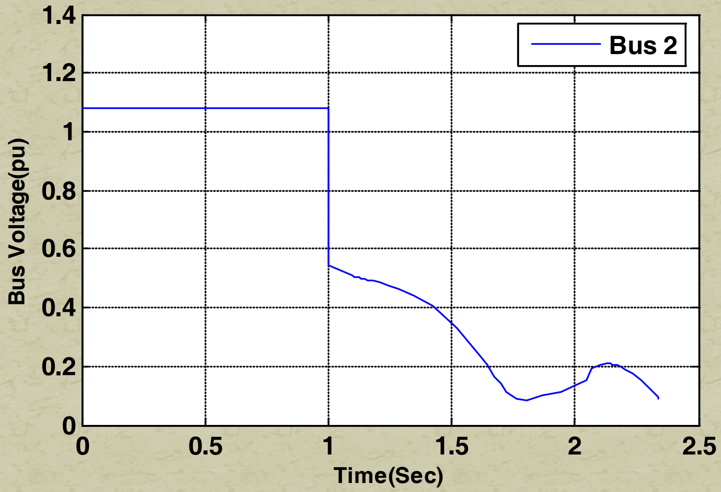


GDVSI and L index at buses 3 and 7.

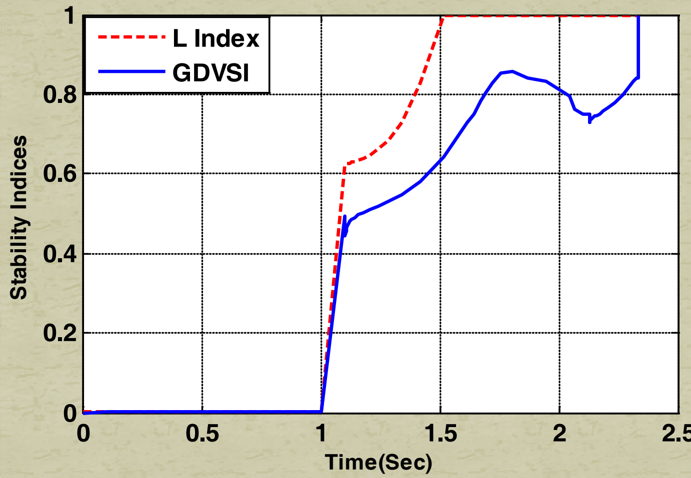
*G.M.Huang and N.K.C.Nair, "Detection of dynamic voltage collapse.", Power System Research Engineering Centre, 2001. Available: www.pserc.wisc.edu/ecow/get/publication/2002public/dynamic_summer.pdf.

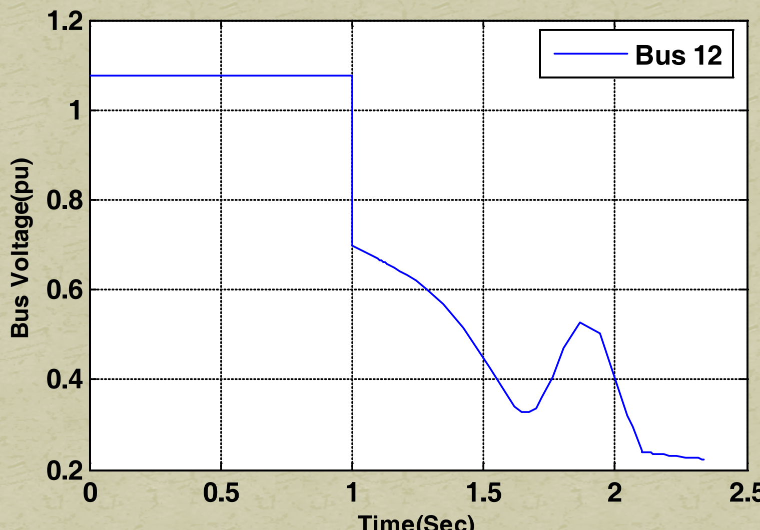
Simulation Results (Contd.)

- TEST CASE2 – NEW ENGLAND 39 BUS SYSTEM, 3-PHASE FAULT AT BUS-3 at T = 1 SEC.



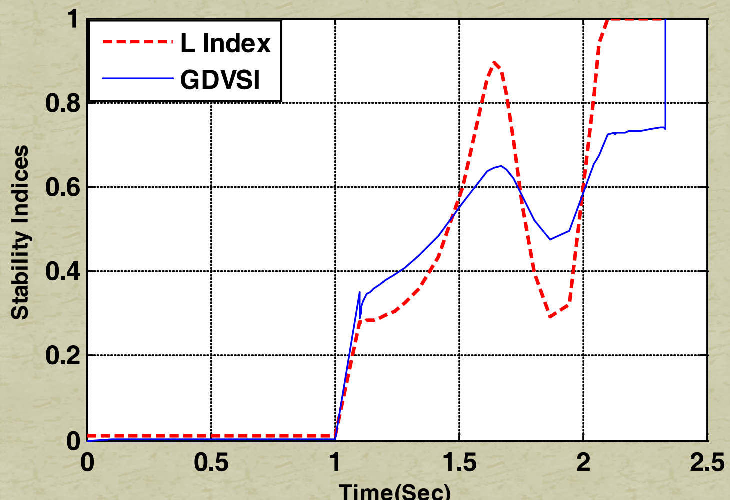
Bus 2 →





Voltage profile at buses 2 and 12

Bus 12 →



GDVSI and L index at buses 2 and 12.

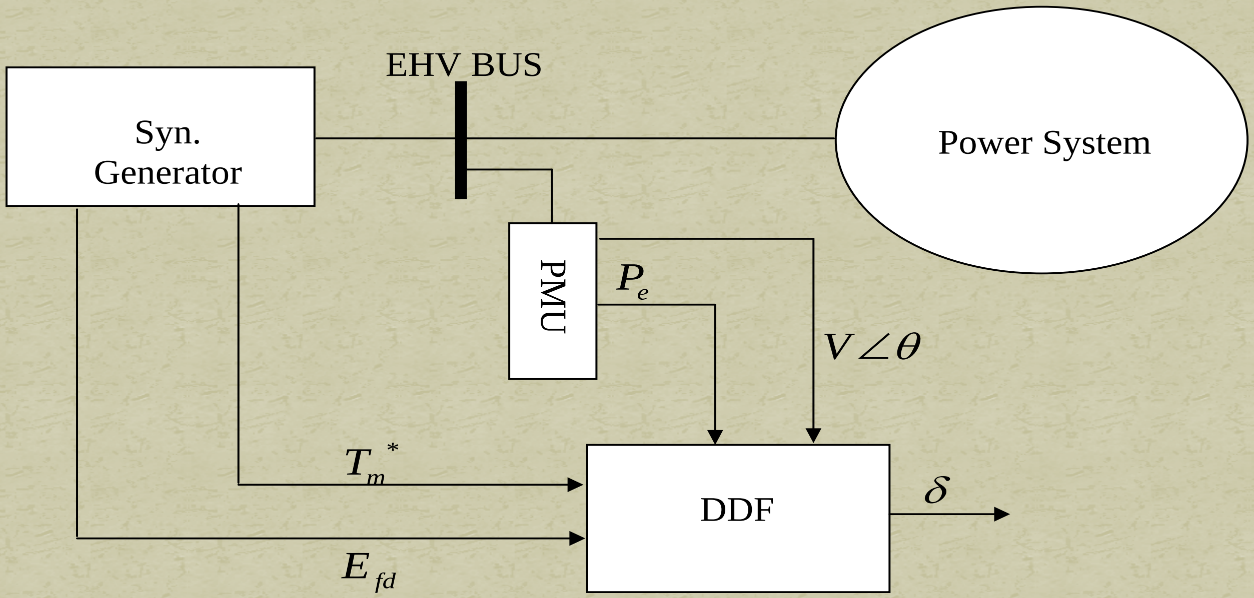
GVDSI more accurate and much simpler to adopt for voltage stability monitoring.

Machine Rotor Angle Estimation

- A rotor angle estimator is developed, which uses the generator terminal data from PMU, such as its voltage and active power, and also Efd and the pre-fault Tm from generators.
- The estimator uses a Divide by Difference filter (DDF)*, which is a nonlinear estimator. It is based on polynomial approximation as compared to Taylor's series approximation used by EKF method. The measurements update are typically done for every 20ms.
- The design of DDF estimator considers each machine equations separately and utilizes 3rd order model of generators.
- The effectiveness of the estimator is tested on a 9 bus and a practical 68 bus system considering noise in data (Gaussian noise with zero mean and variance of 10^{-4} p.u.).
- The rotor angle estimation time is found be about 0.5 ms on core-2 duo processor PC.

* M. N¢rgaard, N.K. Poulsen, O. Ravn, *New developments in state estimation for nonlinear systems*, Automatica 36 (2000) 1627-1638.

Schematic Diagram of Rotor angle Estimator using DDF

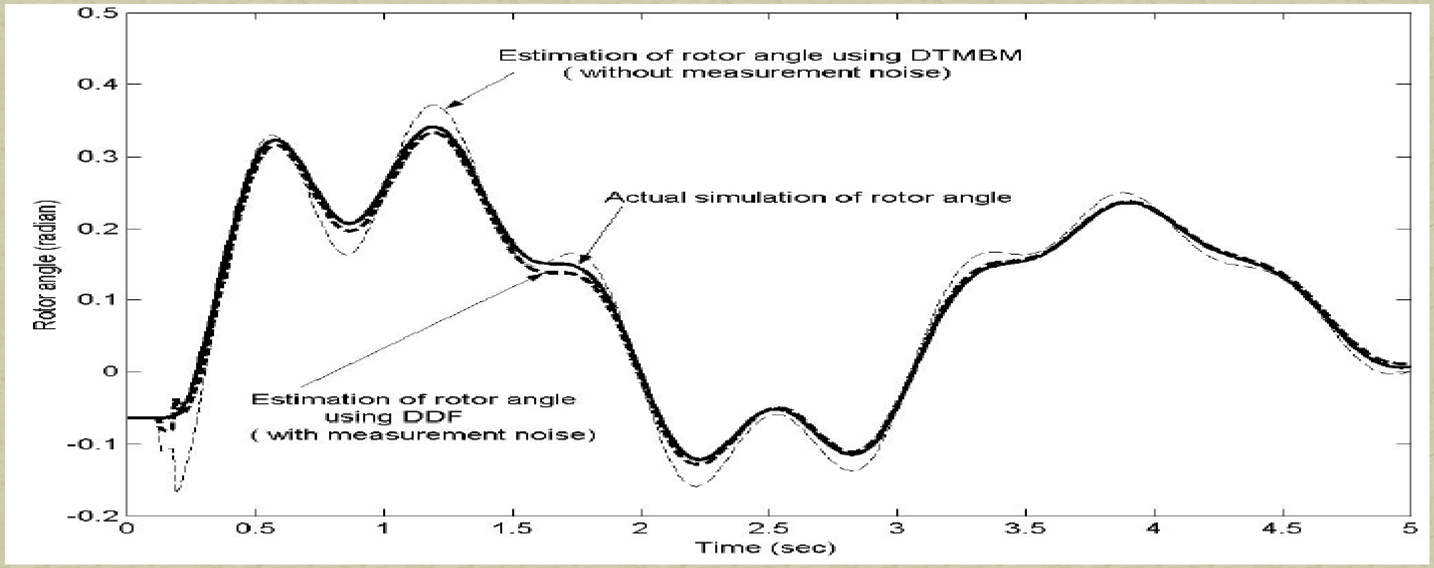


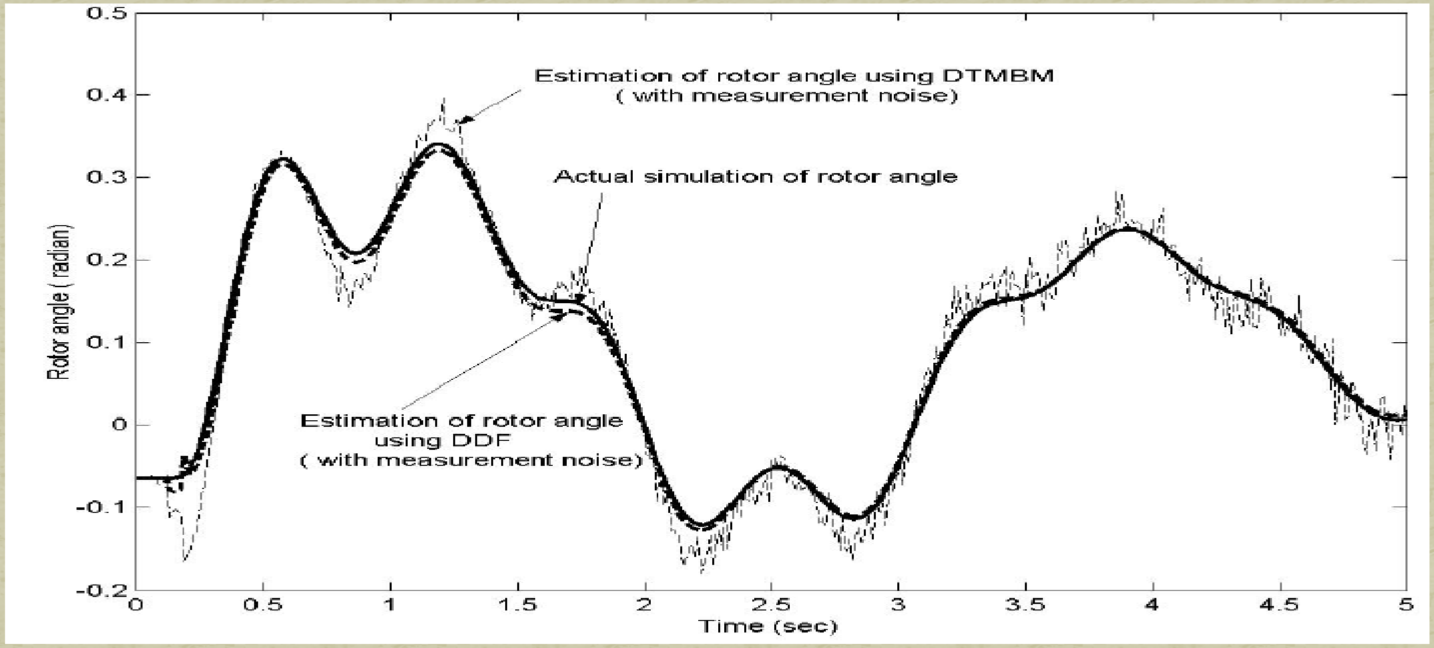
Simulation Results on 68- bus New England – New York Interconnected System

❖ A three phase fault at bus 29 for a duration of 50ms, followed by tripping of line connected between buses 28-29 creates oscillation of generator connect to bus 63. The effectiveness of the method is compared with Direct Terminal Measurements Based Method (DTMBM)*.

* V. Venkatasubramanian, R.G. Kavasseri, Direct Computation of Generator Internal States from Terminal Measurements, Proceedings of the 37th Hawaii International Conference on System Science, 2004, Hawaii, USA.

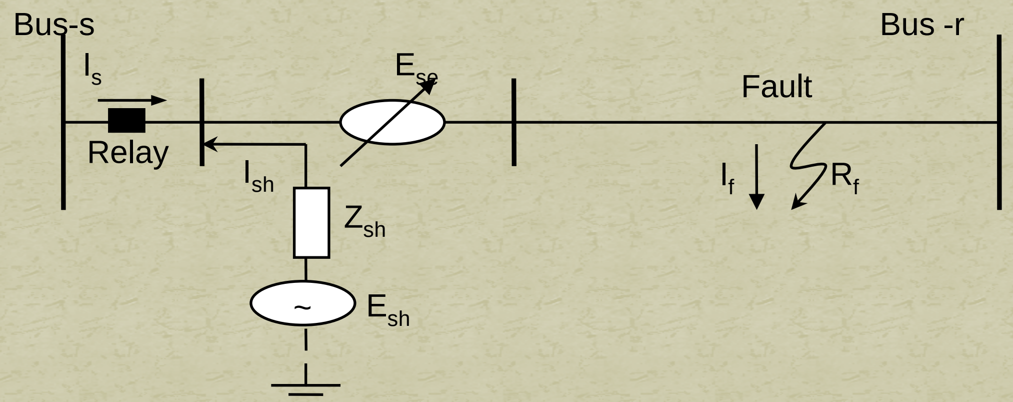
Simulation Results on 68- bus System





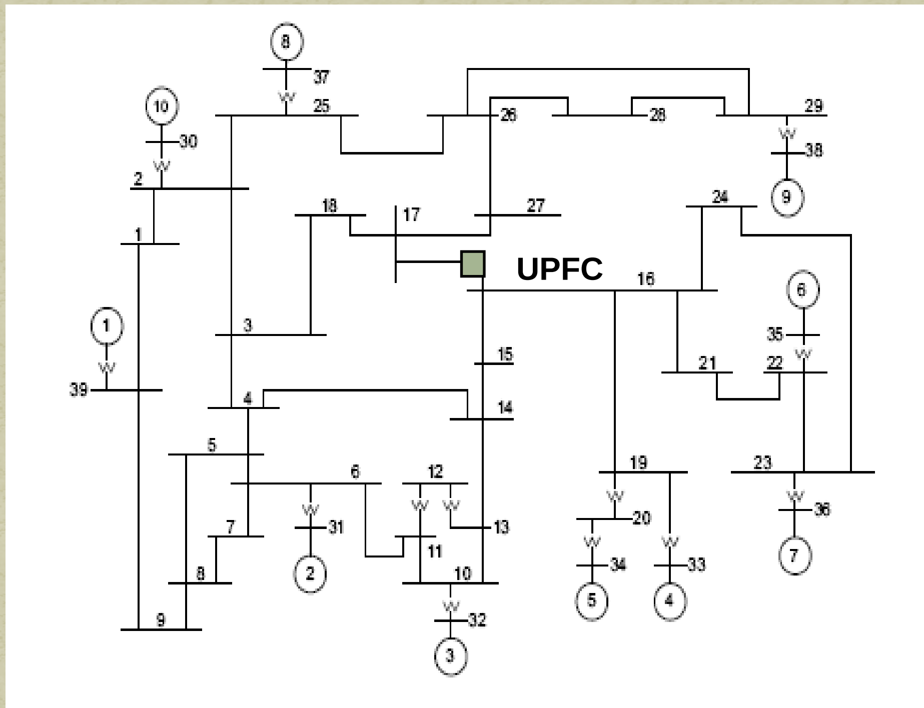
An Adaptive Distance Relaying Scheme in Presence Of UPFC

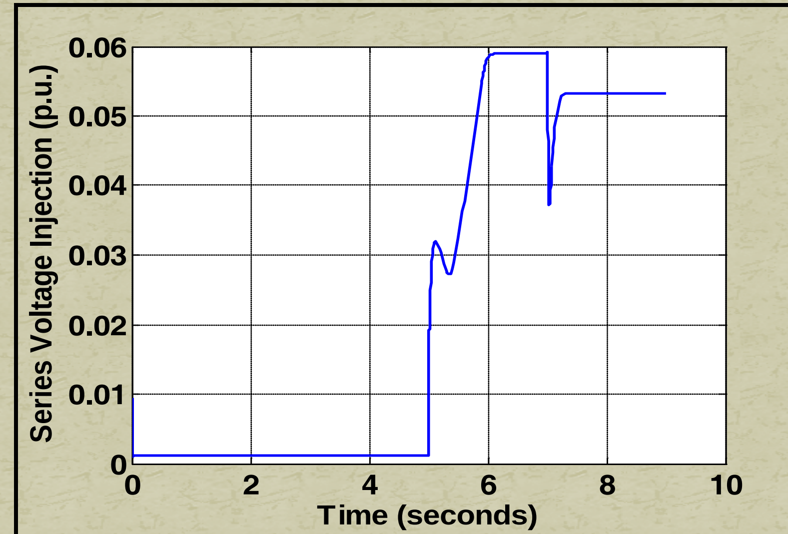
1. Proposed scheme assumes that PMUs are available at the two ends of a line having UPFC. Line flow and voltage data are available. UPFC is located near relay point. A Generalized Regression Neural Network (GRNN) ,a type of RBFN, is used to generate trip boundaries in presence of UPFC.



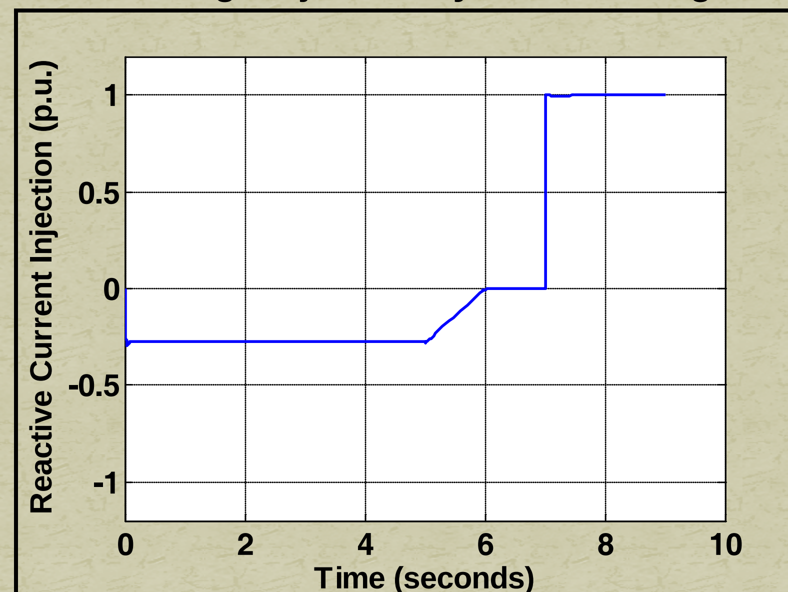
2. Relay receives local and remote PMU data and status signal from UPFC
   - **1- UPFC in Automatic power flow control mode**
   - **0- UPFC in Bypass mode (Self protection Mode)**
3. UPFC's pre-fault control settings (E_{se} and I_{sh}) are computed from basic power flow equations. Trip boundaries, generated under different **Pre-Controlled Power Flow (PCPF)** and **fault locations** with varying **fault impedances**, are used for training the GRNN.
4. Inputs to the GRNN are the UPFC control mode, its pre-fault control settings , end bus voltages and measured fault impedance.

Simulation Results: NE 39 Bus System





Series voltage injection by UPFC during fault



Reactive current injection by UPFC during fault

Sample Training Cases

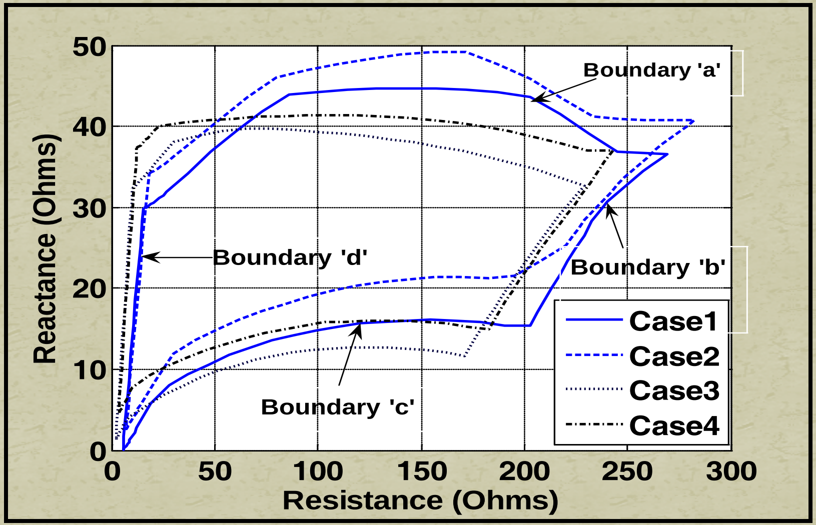
Cases	PCPF (MVA)
Case 1	28-j62
Case 2	28+j0
Case 3	80-j62
Case4	80+j0

Power control mode

Cases	PCPF (MVA)
Case A	28-j62
Case B	28+j0
Case C	28-j27

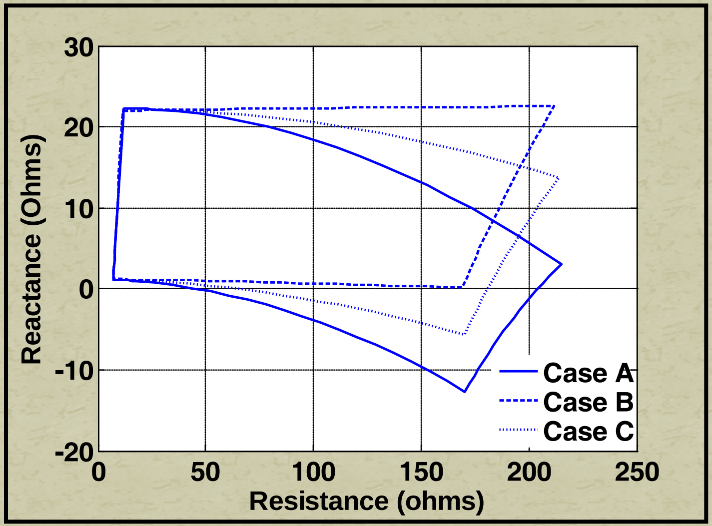
Bypass Mode

Trip Boundaries with UPFC

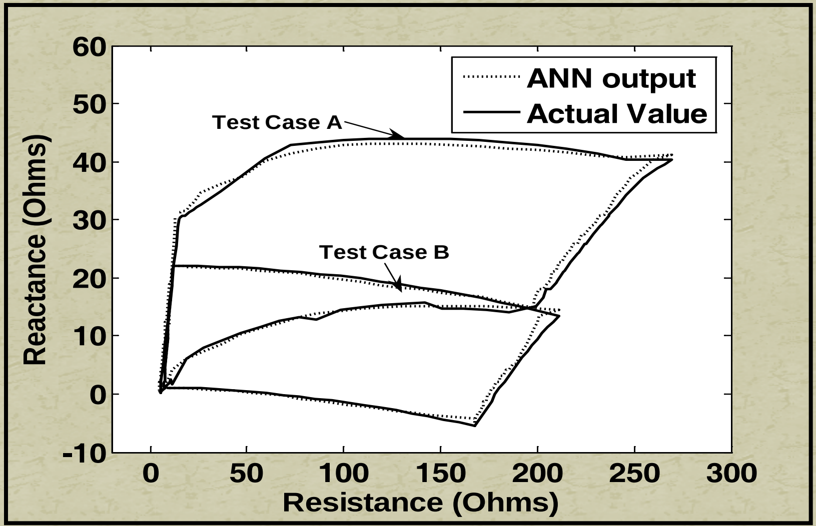


UPFC in power flow control mode

TRAINING CASES



UPFC in bypass mode



GRNN output comparison

TEST CASES

Case	PCPF (MVA)	V_{se} (p.u.)	φ_{se} (deg)	Control Mode
A	20-j63	0.054	1.1	0
B	20-j27	0.031	10.1	1

Future Research Activities

- **Development of hybrid state estimator considering SCADA and PMU data.**
- **Developing new algorithms for estimating phasors under dynamic conditions.**
- **Development of faster methods for Voltage and Oscillatory Angle Stability Prediction and deciding control actions using PMU data on Indian power system networks.**
- **Development of methodology for frequency and voltage stability based load shedding scheme.**
- **Application of synchrophasor measurements on adaptive relay and controller coordination.**
- **Development of a lab scale WAMS model (currently planned using NI hardware and labview environment) for testing some of the algorithms.**

Thank You !