U.S. DEPARTMENT OF ENERGY
Electricity Delivery & Energy Reliability
Advanced Grid Modeling 2014 Peer Review

A Lyapunov Function Based Remedial Action Screening Tool Using Real-Time Data

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Context/Vision

- Following a potentially destabilizing event, the grid can evolve along any of numerous possible trajectories. Appropriate operator action can stabilize the system.
- Most real-time tools today are based on steady state analysis. Transient stability analysis is computationally intensive, and emergency/remedial actions are prescribed using off-line studies.
- We are developing a screening tool that uses an approach based on Lyapunov functions to enable, without time-domain simulation, the selection of appropriate remedial actions that are most likely to result in stabilizing trajectories.
- Since the system evolves continuously, it is necessary to update the tool using real-time data from the SCADA/EMS.
- Our tool will screen contingencies for stability and prescribe remedial action at real-time speed.

Presentation Outline

- Project Vision
  - Significance and impact
  - Project components and deliverables
  - Project team
- Technical Approach
  - Lyapunov stability and screening; homotopy-based approach
  - System modeling and energy function
  - Polynomial Lyapunov function
  - Control actions
- Results and Technical Accomplishments
  - Screening by homotopy
  - Polynomial Lyapunov functions
  - Control actions
  - Real-time simulation status
  - Visualization
- Plans and Expectations
- Conclusion
- Acknowledgments/Contacts

Significance and Impact

- The past decade has witnessed a higher frequency of grid disruptions in the North American Grid than any other similar period in history.
- A key finding of NERC's *Technical Analysis of the August 14, 2003 Blackout* is that grid operators needed increased situational awareness, and improved understanding of remedial action alternatives.
- The need for better situational awareness fueled a multitude of activities that are part of various "smart grid" initiatives.
- The L-RAS will select appropriate remedial actions for the system operator to stabilize the system and represent a significant mathematical innovation toward enabling the understanding of catastrophic failure in power systems and the rapid and correct selection of remedial actions.
- The algorithms will be tested on a utility system (Southern California Edison) simulated on a real-time digital simulation cluster, and the software and interface will be vetted by utility (SCE) personnel.

Project Components/Tasks

1. Development of a methodology for contingency screening using a homotopy method based on Lyapunov functions and real-time data.
2. Development of a polynomial Lyapunov function that is capable of capturing a larger region of attraction than the energy functions that have been traditionally used in power systems.
3. Development of a methodology for recommending strategic and tactical remedial action recommendations based on the screening results.
4. Development of a visualization and operator interface tool.
5. Testing of screening tool, validation of control actions, and demonstration of project outcomes on a representative real system simulated on a Real-Time Digital Simulator (RTDS®) cluster.

Project Deliverables

1. A software prototype tested on a simulated system, vetted by utility personnel, and potentially ready for wider testing and commercialization
2. An RTDS-based test bed that can be used for future research in the field
3. A suite of breakthrough theoretical contributions to the field of power system stability and control
4. A new tool for visualization of power system stability margins

Project Team

Lead Institution: Michigan State University (MSU)

Principal Investigator: Prof. Joydeep Mitra, MSU

Partners: University of Illinois–Chicago (UIC), Los Alamos National Lab (LANL), Florida State University Center for Advanced Power Systems (FSU-CAPS), Southern California Edison (SCE), LCG Consulting (LCG)

Co-Investigators:

- Prof. Sudip K Mazumder, UIC
- Dr. Scott Backhaus, LANL
- Dr. Russell Bent, LANL
- Dr. Feng Pan, LANL
- Dr. Manuel Garcia, LANL
- Prof. Omar Faruque, FSU
- Dr. Mischa Steurer, FSU
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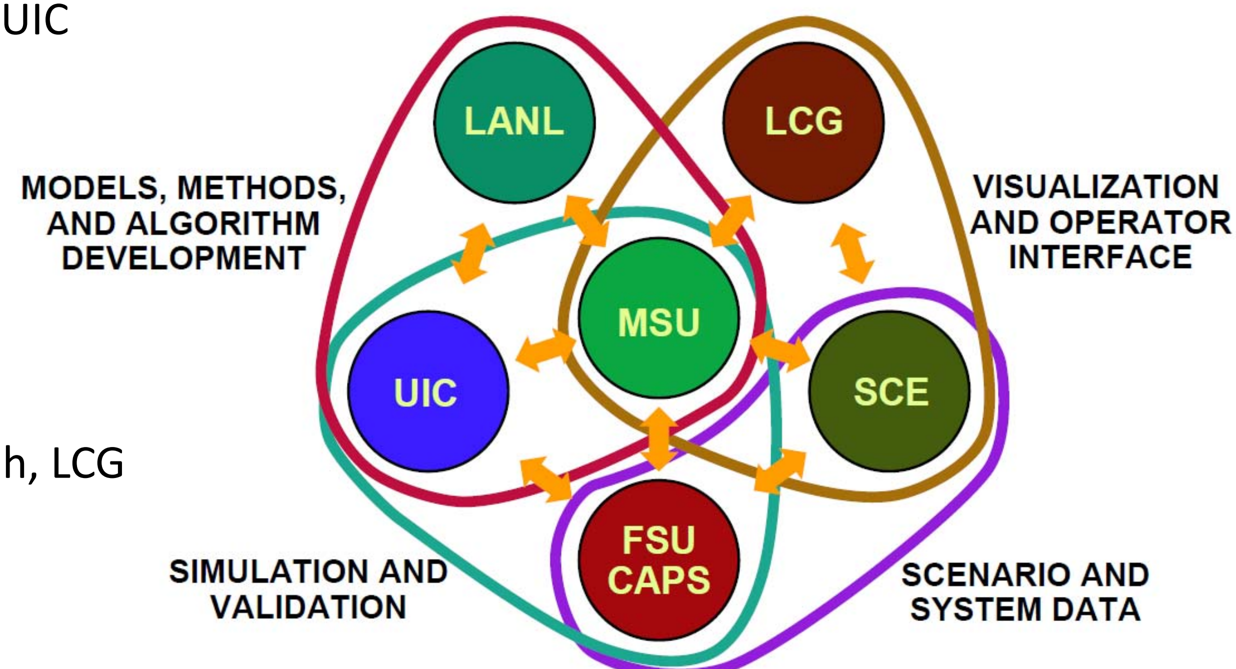
- Sidart Deb, LCG
- Dr. Nagy Abed, SCE
- Frank Ashrafi, SCE

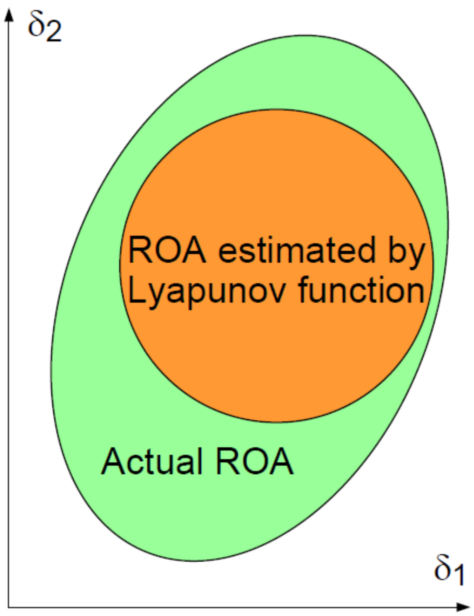


Technical Approach: Summary

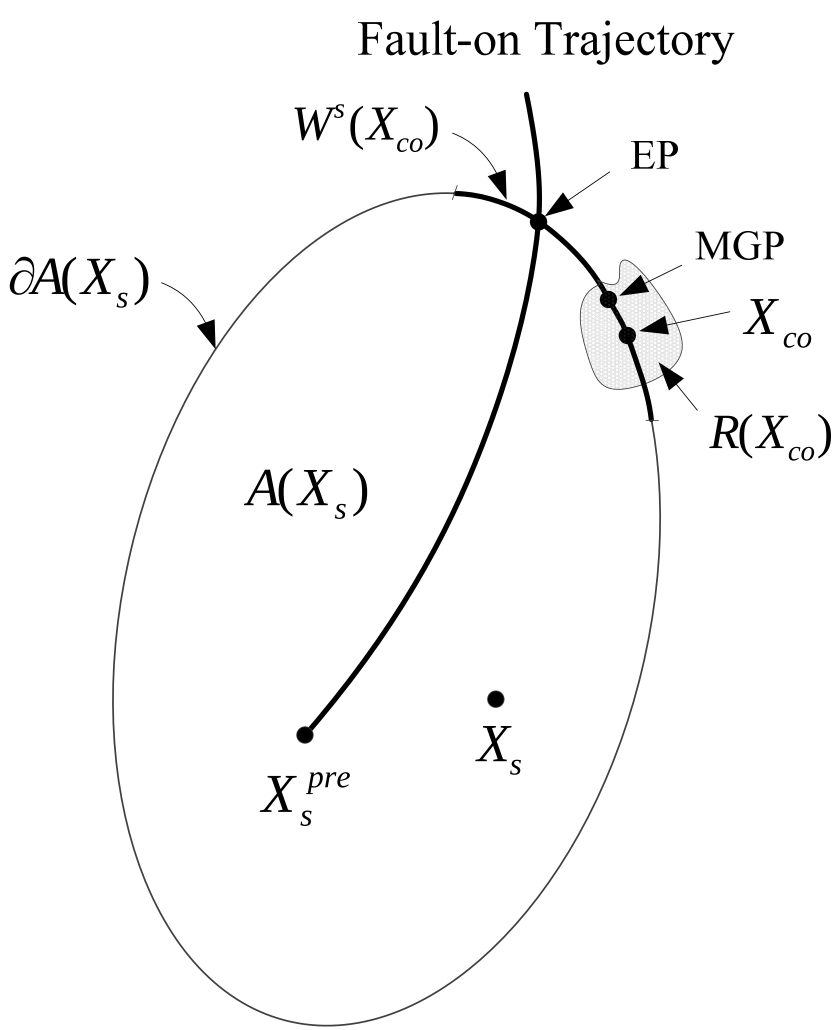
- This project will develop an advanced computational tool to assist system operators in making real-time redispatch decisions to preserve power grid stability.
- The tool will enable transient stability evaluation at real-time speed without the use of massively parallel computational resources.
- Traditional time domain simulation employed in transient stability analysis is computationally intensive. It is difficult to analyze a large number of trajectories to determine stability at real-time speed.
- To avoid time domain simulation, this project uses homotopy and Lyapunov functions to screen out stable trajectories. Only a small number of trajectories will be subjected to time domain simulation.
- The trajectories will be updated as necessary with real-time data.
- Based on the screening results, control actions will be developed to stabilize the system.

Lyapunov Function and Region of Attraction

- The Region of Attraction (ROA) of the post-fault SEP is characterized by the property that all trajectories inside this region will converge to the post-fault SEP.
- The "ideal" Lyapunov function would estimate the entire ROA; however, this is difficult to achieve in practice.
- Lyapunov functions tend to be conservative, in that they cover part of the ROA; hence, a trajectory not deemed stable by a Lyapunov function does not necessarily imply instability.
- The efficiency of the on-line transient stability screening tool depends strongly on the choice of the Lyapunov function.



Controlling Unstable Equilibrium Point



EP: Exit Point

MGP: Minimum Gradient Point

X_{co}: Controlling UEP

$R(X_{co})$: Region of Convergence of the controlling UEP

X_s: Post-Fault SEP

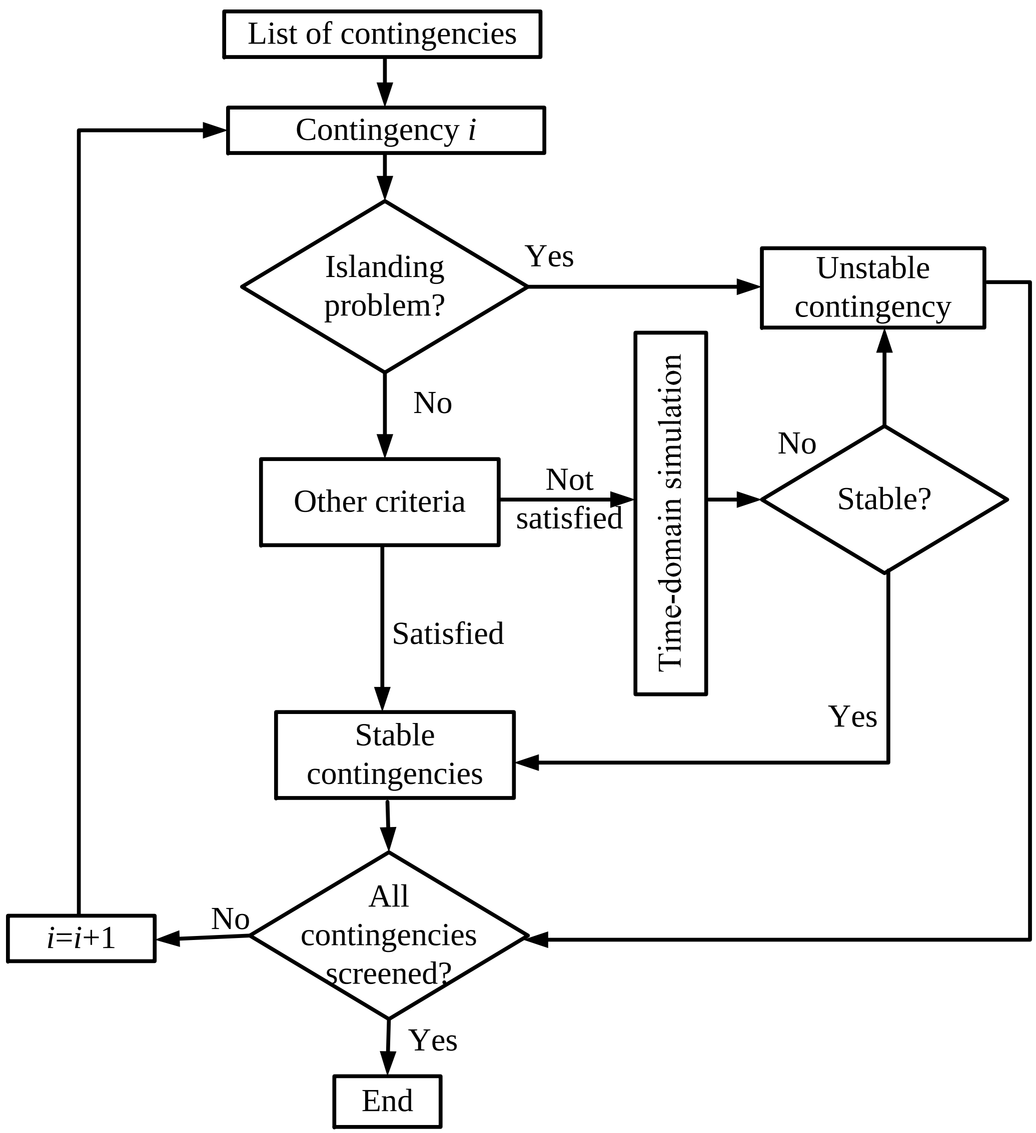
X_s^{pre} : Pre-Fault SEP

$A(X_s)$: Region of Attraction of Post-Fault SEP – ROA

$\partial A(X_s)$: Boundary of the Region of Attraction of Post-Fault SEP

$W^s(X_{co})$: Stable Manifold of the controlling UEP

Technical Approach: Screening



Other criteria include:

- No SEP convergence problem
- No Exit point problem
- Positive energy margin at exit point
- No ray adjustment problem
- Positive energy margin at MGP
- No controlling UEP convergence problem
- Positive energy margin at controlling UEP

Homotopy-based approaches

- Homotopy concept: we map the function

$$H(x,\lambda) = \lambda F(x) + (1-\lambda)G(x) = 0$$

where $G(x)$ is an arbitrary function with a known solution, $F(x)$ is the function that needs to be solved (i.e., the swing equations) and λ is the mapping or control parameter.

- We have been using Newton Homotopy in the following form:

$$G(x) = F(x) - F(x_0)$$

The homotopy function then becomes

$$H(x,\lambda) = F(x) - (1-\lambda)F(x_0) = 0$$

Role of Homotopy in Screening

- Homotopy-based approaches map the trajectory of the solution (in this case the controlling UEP) from a known and easy to find solution (starting point). The starting points can be the exit points or the minimum gradient points (MGP) whichever is available.
- Homotopy-based approaches are used to avoid to the extent possible the use of time-domain simulations for the cases where numerical problems arise. Homotopy-based approaches are used in these scenarios:
  - Numerical problems in precise determination of the Exit Points or other uncertainty
  - The MGP cannot be detected
  - Iterative methods fail to calculate the controlling UEP

System Modeling I

We have initially implemented the energy function, which is the Lyapunov form traditionally used in power systems, and applied it to a reduced network model represented in the center of inertia (COI) angle coordinate.

$$\dot{\tilde{\delta}}_i = \tilde{\omega}_i$$

$$\tilde{\omega}_i = \frac{1}{M_i}(P_{mi} - P_{ei}) - \frac{1}{M_T} P_{COI} - \lambda \tilde{\omega}_i$$

where P_{mi} is the mechanical input of machine *i*, P_{ei} is the electrical power output of machine *i*, M_i is the inertia constant of machine *i*, $\dot{\tilde{\delta}}_i = \delta_i - \delta_0$

$\tilde{\omega}_i = \omega_i - \omega_0$, $\delta_0 = \frac{1}{M_T}\sum_{i=1}^{n} M_i \delta_i$, $\omega_0 = \frac{1}{M_T}\sum_{i=1}^{n} M_i \omega_i$, $M_T = \sum_{i=1}^{n} M_i$

and λ is the uniform damping constant.

System Modeling II

The electrical power of machine *i* is given as

$$P_{ei} = \sum_{j=1}^{n} E_i E_j \left[G_{ij} \cos(\tilde{\delta}_i - \tilde{\delta}_j) + B_{ij} \sin(\tilde{\delta}_i - \tilde{\delta}_j) \right]$$

The P_{COI} is computed as follows:

$$P_{COI} = \sum_{i=1}^{n} P_{mi} - \sum_{i=1}^{n} \sum_{j=1}^{n} E_i E_j \left[G_{ij} \cos(\tilde{\delta}_i - \tilde{\delta}_j) + B_{ij} \sin(\tilde{\delta}_i - \tilde{\delta}_j) \right]$$

where δ_i and ω_i are power angle and speed of machine *i* respectively, E_i is the constant voltage behind the stator reactance of the machine classical model and G_{ij} and B_{ij} are the conductance and susceptance of the admittance matrix of the reduced network model.

Energy Function

The transient energy function is expressed as

$$V = \frac{1}{2}\sum_{i=1}^{n} M_i \tilde{\omega}_i^2 - \sum_{i=1}^{n} P_i(\tilde{\delta}_i - \tilde{\delta}_i^s) - \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left[C_{ij}(\cos\tilde{\delta}_{ij} - \cos\tilde{\delta}_{ij}^s) - I_{ij}\right]$$

where $P_i = P_{mi} - E_i^2 G_{ii}$

I_{ij} is the energy dissipated in the network transfer conductances and can be expressed as

$$I_{ij} = \int_{\tilde{\delta}_i^s + \tilde{\delta}_j^s}^{\tilde{\delta}_i + \tilde{\delta}_j} D_{ij} \cos\tilde{\delta}_{ij} d\left(\tilde{\delta}_i + \tilde{\delta}_j\right)$$

This term is path dependent and can be calculated only if the system trajectory is known. It is common to use the following approximation:

$$I_{ij} = D_{ij} \frac{\tilde{\delta}_i + \tilde{\delta}_j - \tilde{\delta}_i^s - \tilde{\delta}_j^s}{\tilde{\delta}_i - \tilde{\delta}_j - \tilde{\delta}_i^s + \tilde{\delta}_j^s}\left[\sin\tilde{\delta}_{ij} - \sin\tilde{\delta}_{ij}^s\right]$$

Technical Approach: Polynomial Lyapunov Fn.

Purpose: To develop a polynomial Lyapunov function that can include losses, and potentially accommodate switching functions and other non-linearities .

1. Construct power system dynamical model: $\dot{x} = f(x)$
2. Determine equilibrium solution: $f(x) = 0$

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3. Determine a Lyapunov function that satisfies the following:

$$\begin{cases} V(x) > 0 \text{ for } \forall x \neq 0 \\ V(0) = 0 \end{cases} \quad \text{(3a)}$$

$$\dot{V}(x) = \nabla V(x) \cdot f(x) \leq 0 \text{ for } \forall x \quad \text{(3b)}$$

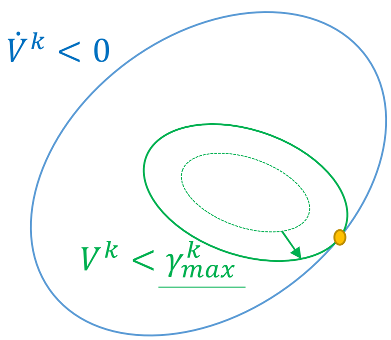
4. Determine the widest possible region in x for the equilibrium solution of $f(x) = 0$ that is constrained by an invariant subspace of $V(x)$ (i.e., $V(x) < \gamma$). In simple terms, this region is referred to as the region of attraction (ROA).

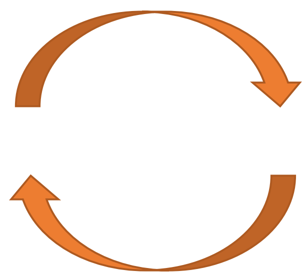
TDA

3. Choose a wide array of initial conditions in x.
4. For each of the initial conditions, determine if the corresponding trajectory in x converge to the nominal equilibrium solution given by $f(x) = 0$ (and never leaves the ROA).

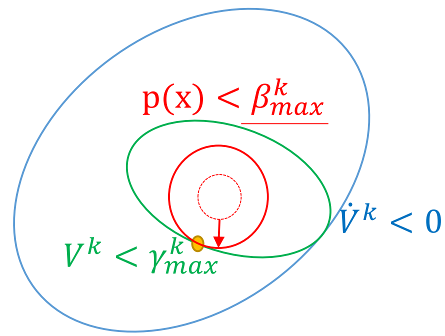
Algorithm for PLF

Step 1: Obtaining upper bound γ of V(x) such that
$V^k < \gamma^k_{max}$ included in $\dot{V}^k < 0$ such that
$-[\nabla V(x) \cdot F(x) + L_2(x) + s_2(x) \cdot (\gamma - V(x))]$ is SOS

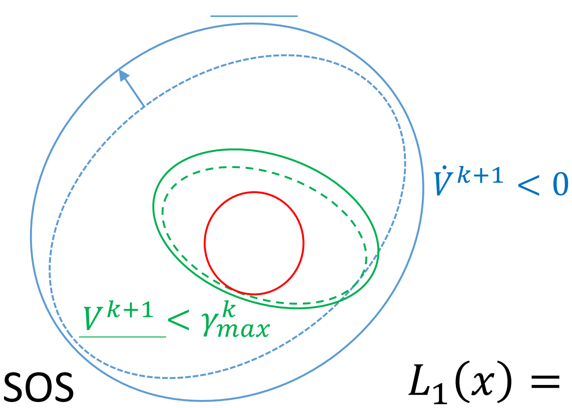




Step 2: Determining the largest β such that:
$\mathrm{p(x)} < \beta^k_{max}$ included in $V^k < \gamma^k_{max}$
$-[(V(x) - \gamma) + s_1(x) \cdot (\beta - p(x))]$ is SOS



Step 3: Determining a V(x) such that
$V^{k+1} < \gamma^k_{max}$ included between $\dot{V}^k < 0$
and $\mathrm{p(x)} < \beta^k_{max}$
$V(x) - L_1(x)$ is SOS
$-[\nabla V(x) \cdot F(x) + L_2(x) + s_2(x) \cdot (\gamma - V(x))]$ is SOS
$-[(V(x) - \gamma) + s_1(x) \cdot (\beta - p(x))]$ is SOS



$L_1(x) = \epsilon_1 x^T x$
$L_2(x) = \epsilon_2 x^T x$

Technical Approach: Control Actions

System Model

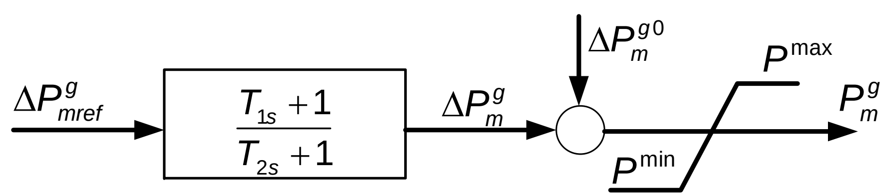
- Fourth order synchronous three phase generator model
  - State variables:
    - d and q-axis voltage magnitudes
    - rotor angle
    - rotor frequency
- First order turbine governor model
  - Custom Controller
- Third order exciter model
  - AVR: proportional control on local voltage magnitude
- Constant Impedance Loads

Turbine-Governor Model/Control

- Power Flow term can exhibit step changes (quick response)
- Distributed measurements and control
- Special behavior of grid (robust)

Turbine Governor

$$\Delta P_{mref}^{g} = C_g(\omega_g(t) - \omega_0) + \sum C_j (P_j(t) - P_j(0))$$



ΔP_m^g is the input we control

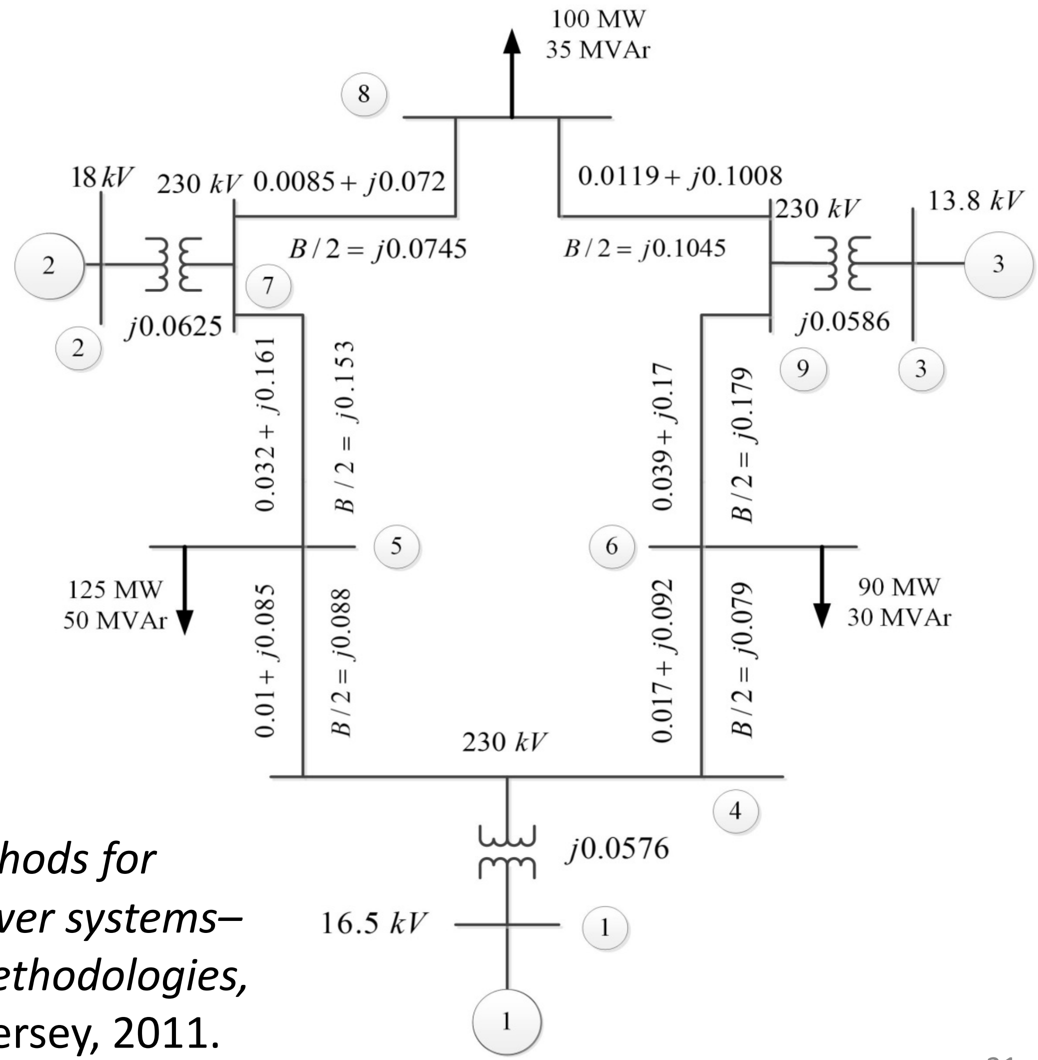
ΔP_{mref}^{g} is the mechanical power output

Results and Technical Accomplishments

1. The fundamental theoretical development of homotopy-based screening tool has been completed using traditional energy functions, and tested in the IEEE 39-bus test system.
2. The fundamental theoretical development of a polynomial Lyapunov function suitable for power system stability analysis has been completed and tested on several small test systems.
3. A methodology for evaluation of trajectory stability, and control strategies for stabilization of sets of potentially unstable trajectories, have been developed and are being tested.
4. A preliminary version of a visualization tool had been developed.
5. The IEEE 39-bus test case has been implemented on an RTDS cluster. Several PMU cards have been procured and installed on the cluster, and streaming of PMU data from CAPS and acquisition at MSU had been tested.

Test Systems Used

- Most of the results reported here are from the 9-bus test system used in several references, including [1], and shown alongside.
- However, the homotopy method and screening algorithm have also been demonstrated on the IEEE 39-bus test system shown later in this presentation.



[1] Hsiao-Dong Chiang, *Direct methods for stability analysis of electric power systems– theoretical foundation, BCU methodologies, and applications*, Wiley, New Jersey, 2011.

Results: Screening by Homotopy Method

Table 1: Contingency list and the exit point of each contingency

Contingency number	Fault at Bus	Line Trip		Exit points ($\delta 1$, $\delta 2$, $\delta 3$) (rad)
		From	To	
1	4	4	5	[−0.8316,2.0522,2.1675]
2	5	4	5	[−0.8560,2.2447,1.9505]
3	4	4	6	[−0.8298,2.0463,2.1662]
4	6	4	6	[−0.8296,2.0153,2.2308]
5	5	5	7	[−0.7785,2.0851,1.6806]
6	7	5	7	[−0.8387,2.6561,0.9392]
7	6	6	9	[−0.7584,1.8363,2.0522]
8	9	6	9	[−0.5084,0.5168,2.8945]
9	7	7	8	[−0.7694,2.4080,0.9225]
10	8	7	8	[−0.7730,1.7539,2.3416]
11	8	8	9	[−0.7753,1.7588,2.3490]
12	9	8	9	[−0.4687,0.4965,2.6252]

Results: Screening by Homotopy II

Table 2: Controlling UEP obtained by homotopy method

Contingency number	CUEP from homotopy	CUEP from [1]
1	[−0.8323, 2.0742, 2.1447]	[−0.8364, 2.0797, 2.1466]
2	[−0.8323, 2.0742, 2.1447]	[−0.8364, 2.0797, 2.1466]
3	[−0.8266, 2.0821, 2.0540]	[−0.8256, 2.0830, 2.0549]
4	[−0.8266, 2.0821, 2.0540]	[−0.8256, 2.0830, 2.0549]
5	[−0.7598, 1.9521, 1.8071]	[−0.7589, 1.9528, 1.8079]
6	[−0.7598, 1.9521, 1.8071]	[−0.7589, 1.9528, 1.8079]
7	[−0.7586, 1.8576, 1.9979]	[−0.7576, 1.8583, 1.9986]
8	[−0.7586, 1.8576, 1.9979]	[−0.7576, 1.8583, 1.9986]
9	[−0.5430, 2.1797, −0.3764]	[−0.5424, 2.1802, −0.3755]
10	[−0.3500, 0.0738, 2.5861]	[−0.3495, 0.0745, 2.5864]
11	[−0.2915, −0.1017, 2.5004]	[−0.2910, −0.1011, 2.5008]
12	[−0.2915, −0.1017, 2.5004]	[−0.2910, −0.1011, 2.5008]

[1] Hsiao-Dong Chiang, *Direct methods for stability analysis of electric power systems–theoretical foundation, BCU methodologies, and applications*, Wiley, New Jersey, 2011.

Results: Screening by Homotopy III

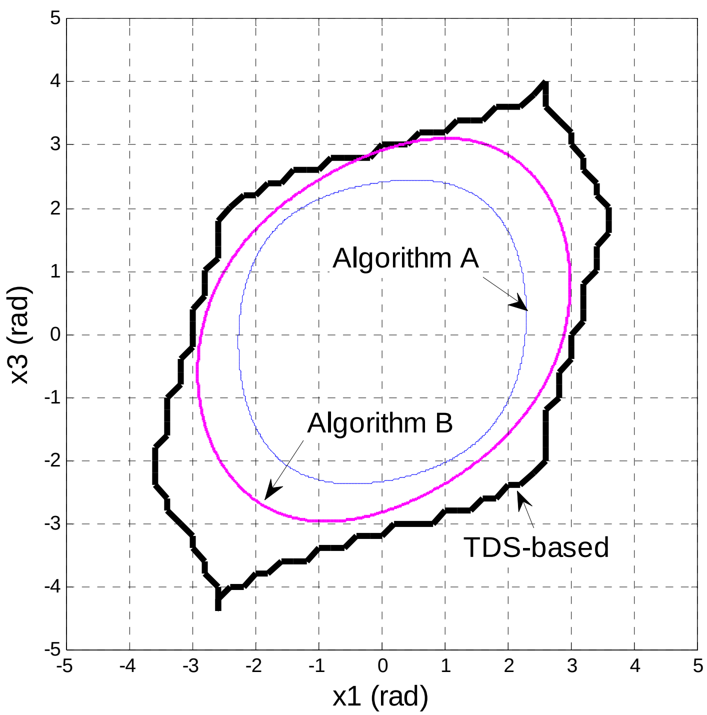
Table 3: The use of program components in the screening process in case of disturbing the exit points

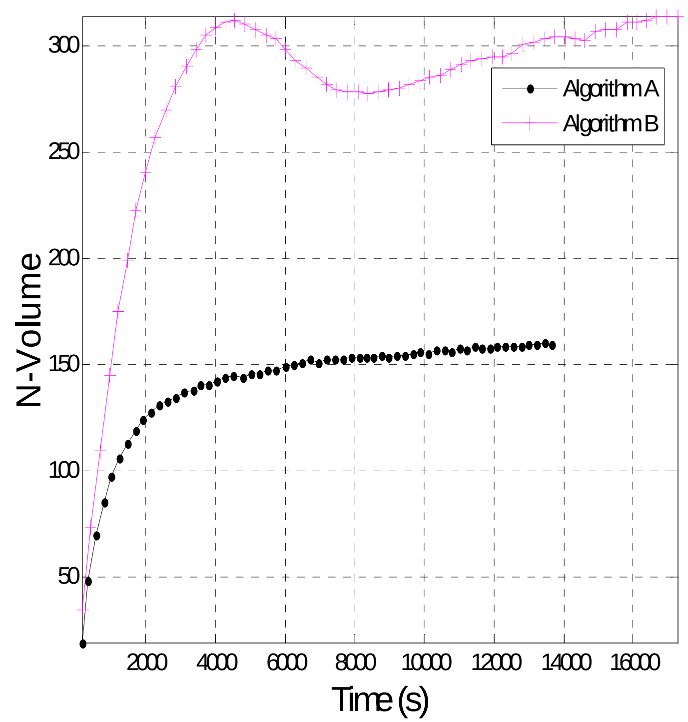
Contingency number	Stable/ Unstable	Use of program components		
		Iterative methods	Homotopy	Time-domain
1	stable	✗	✓	–
2	stable	✗	✓	–
3	stable	✗	✓	–
4	stable	✗	✓	–
5	–	✗	✗	stable
6	unstable	✗	✓	–
7	stable	✗	✓	–
8	unstable	✗	✓	–
9	–	✗	✗	unstable
10	stable	✗	✓	–
11	stable	✗	✓	–
12	unstable	✗	✓	–

Results: PLF for Lossless System

This uses the same 9-bus test system, with machine 3 as reference.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\sin(x_1) - 0.5\sin(x_1 - x_3) - 0.4x_2 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = -0.5\sin(x_3) - 0.5\sin(x_3 - x_1) - 0.4x_4 + 0.05 \end{cases}$$

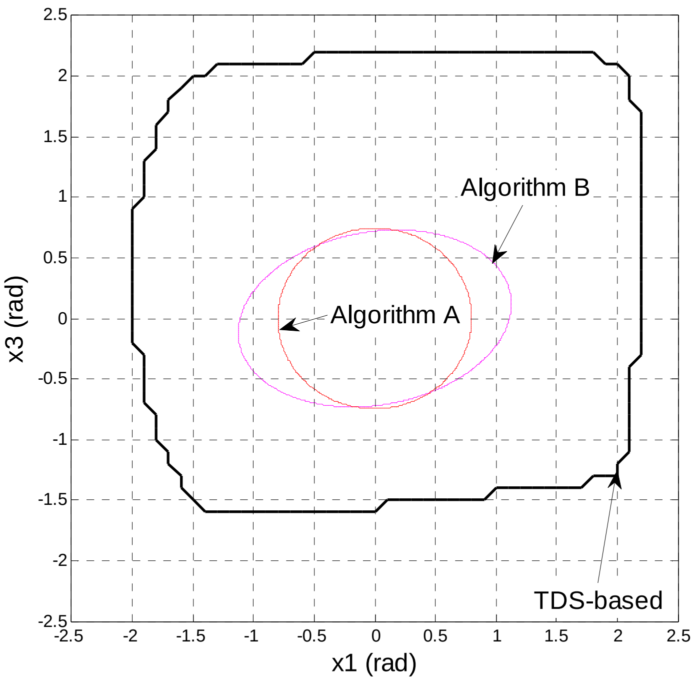


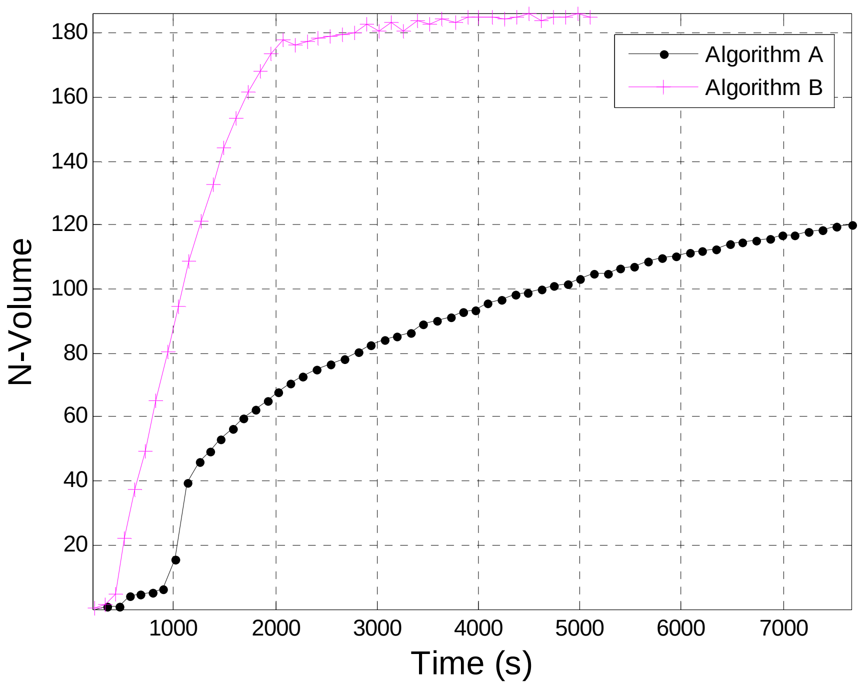


Algorithms A and B differ in the manner in which the shaping parameter *p*(*x*) is updated.

Results: PLF for Lossy System

$$
\begin{cases}
\dot{x}_1 = x_2 \\
\dot{x}_2 = 33.5849 - 1.8868\cos(x_{13}) - 5.283\cos(x_1) \\
-16.9811\sin(x_{13}) - 59.6226\sin(x_1) - 1.8868\, x_2 \\
\dot{x}_3 = x_4 \\
\dot{x}_4 = 48.4810 + 11.3924\sin(x_{13}) - 1.2658\cos(x_{13}) \\
-3.2278\cos(x_3) - 99.3671\sin(x_3) - 1.2658 x_4
\end{cases}
$$





Results: Optimized Control Actions

Penalty Terms:

- Frequency dispersion among generators. $\bar{\omega}(t)$ is the instantaneous average generator frequency.
- Voltage deviation on every bus.

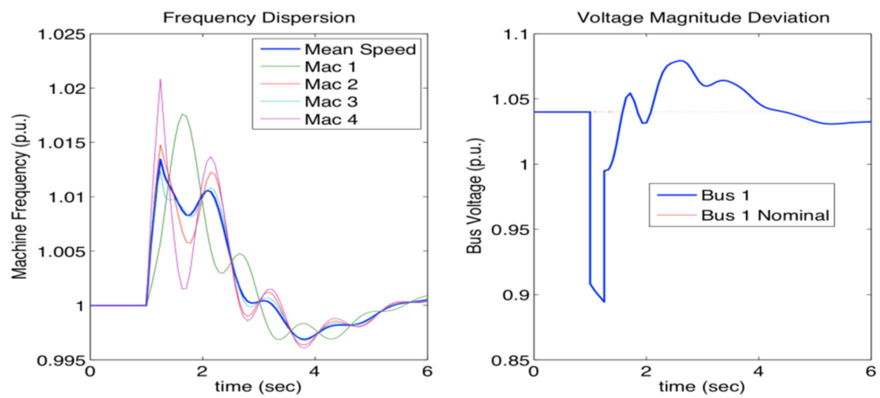


Figure: Illustration of penalty terms

$$P = \frac{1}{T}\int_{t_0}^{t_f}\left[\alpha\sum_{i\in G}\left(\frac{\omega_i(t)-\bar{\omega}(t)}{\omega_0}\right)^2+\sum_{i\in N}\left(\frac{V_i(t)-V_i(t_0)}{V_i(t_0)}\right)^2\right]a(t)dt$$

Optimization

- Choose Threshold *P* using Penalty vs Duration curve
- Determine unstable faults *U*
- Solve using gradient method

$$\min_{C_j} P_{mult} = \min_{C_j}\sum_{i\in U}\max(P_i-\bar{P}_i,0)$$

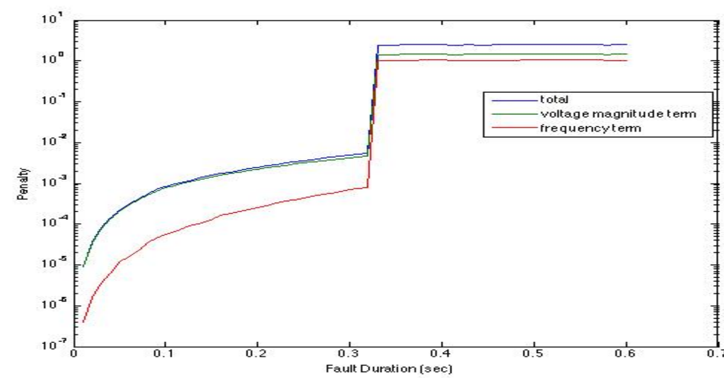


Figure : Penalty vs Duration Curve

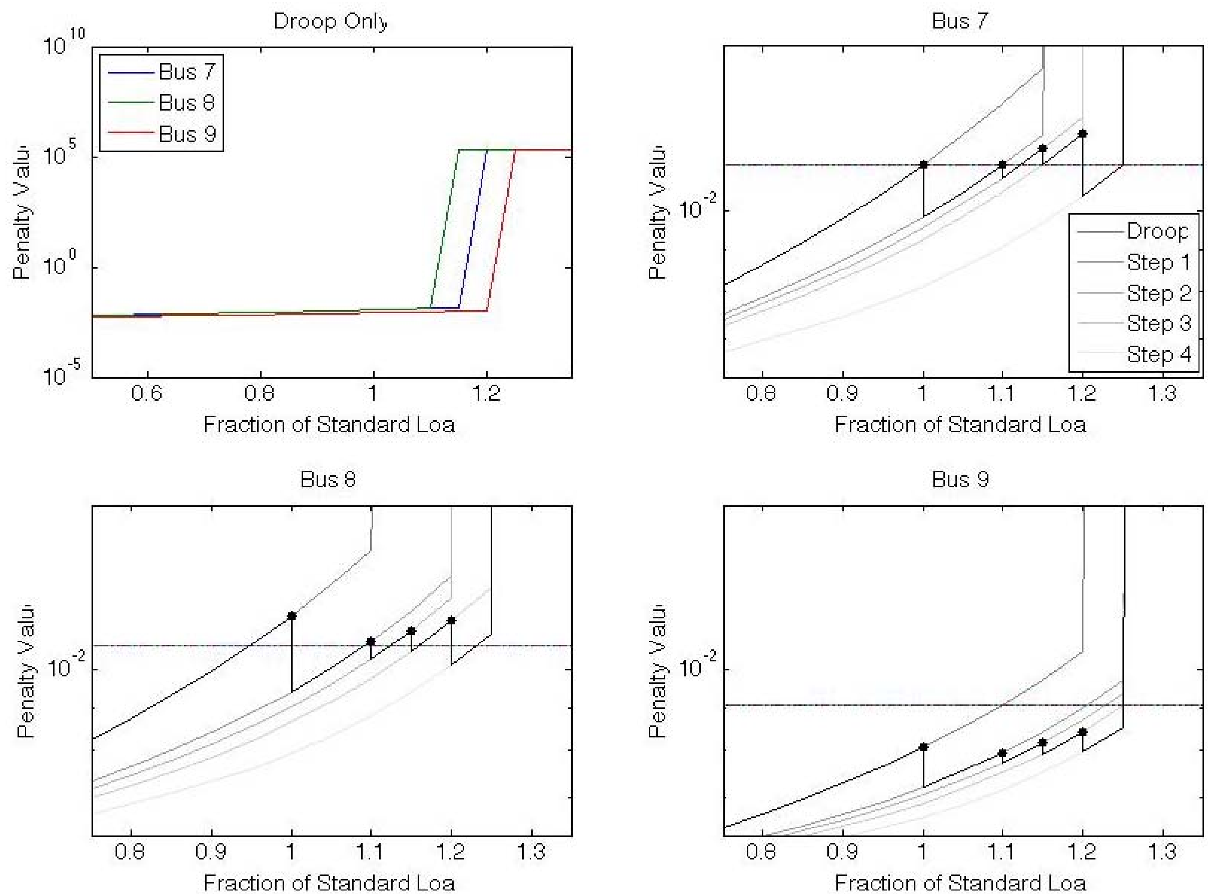
Results: Increasing System Load

Penalty will increase as system load increases. Assume load increases uniformly.

- Top Left: Droop control curves for faults at bus 7, 8 and 9
- Other Three: Evolution of curve as control is updated

Interpreting Plots:

- begin by traversing droop control curve
- perform update when penalty at bus 8 crosses threshold
- traverse step 1 curve until another fault crosses its threshold



Real-Time Digital Simulation

The 14-rack RTDS system at FSU-CAPS is being used as a surrogate for a real system to achieve the following:

- Validate the accuracy and effectiveness of the proposed Lyapunov function based algorithm by mimicking the dynamic behavior of power system using real-time simulation.
- Demonstration of the robustness of the algorithm for contingency analysis.

Validation Strategy: Summary

1. Real-time Simulation Model Development

Model conversion from PSSE to RTDS and Validation using IEEE 39 Test Bus	Model conversion/development and validation of actual SCE System

Status: Developed and validated the IEEE 39 BUS test system in RTDS. Next step is to develop the model of actual SCE system. Waiting on SCE data and LRAS tool development

2. Hardware and software installation for PMU streaming

Installation of PMU hardware and firmware on RTDS Platform for streaming phasor data from the real-time simulation using the standard IEEE C37.118 protocol

Status: Installation and testing is complete. Capable of streaming 96 PMU data from different location of the network.

3. PMU measurement data streaming through the Internet

Using Internet as the communication media	Bi-directional data communication between MSU and FSU using VPN or secured networking

Status: One way data communication between FSU and MSU and testing is complete; working on making it bi-directional

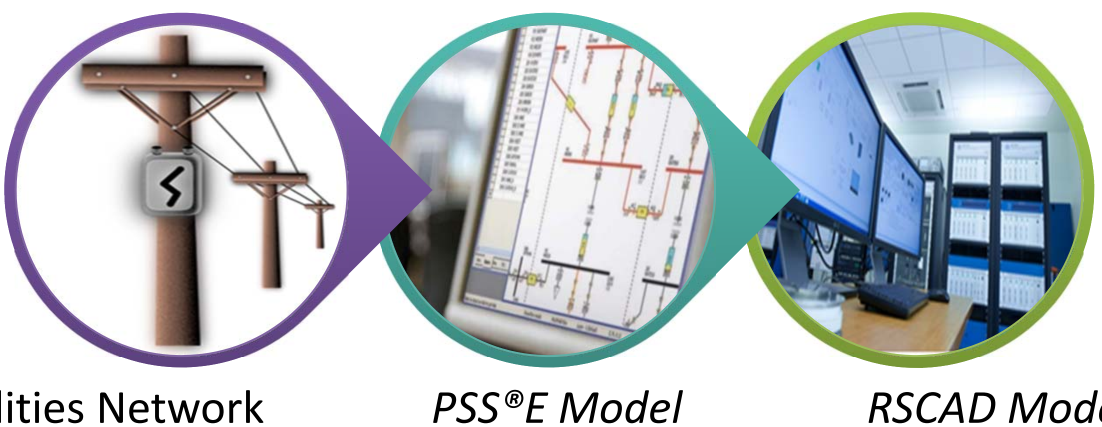
4. Overall performance validation and evaluation

Comprehensive testing using LRAS tool and PMU data streaming in real-time over the Internet	Demonstration of the algorithm in contingency analysis by feeding real-time data from PMU streaming

Status: In progress.

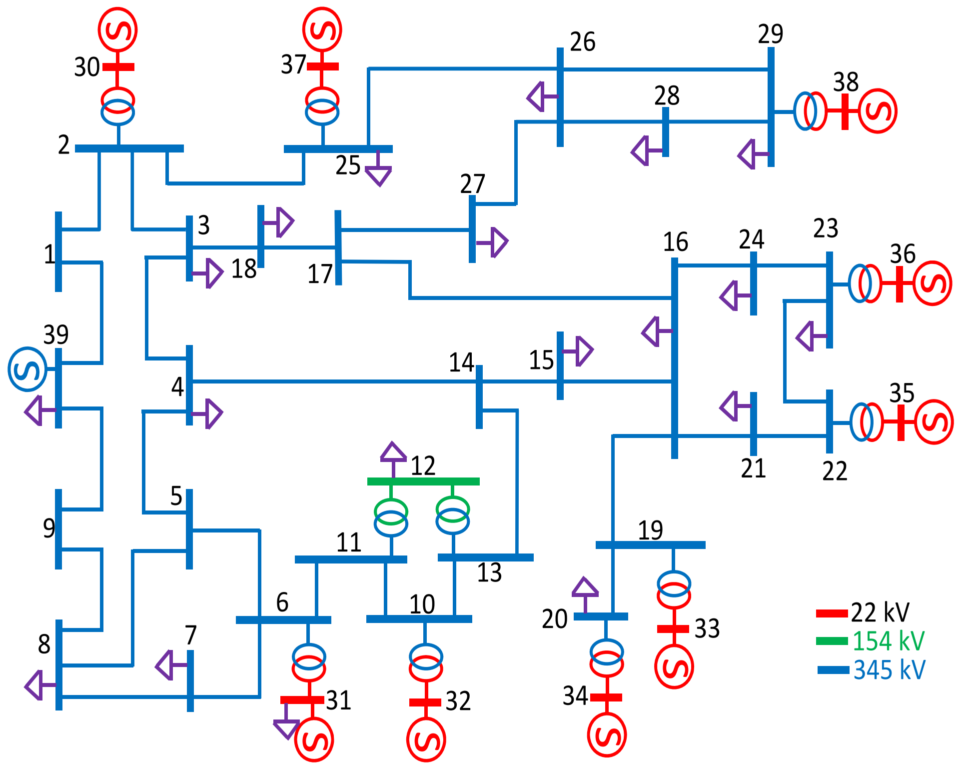
Progress on Demonstration I

1. **Real Utility Distribution System Conversion to Simulation Model:**
   - Since Utility Models are available in PSS®E format, we need to convert this model into real-time model (RSCAD format).
   - To validate the conversion process, FSU converted IEEE 39 Test bus system from PSS®E model to RSCAD model
   - Several steady state and transient case studies are performed to evaluate the accuracy and effectiveness of the conversion process
   - A paper entitled "Conversion of PSS®E Models into RSCAD Models: Lessons Learned" has been submitted based on the experience of model conversion.

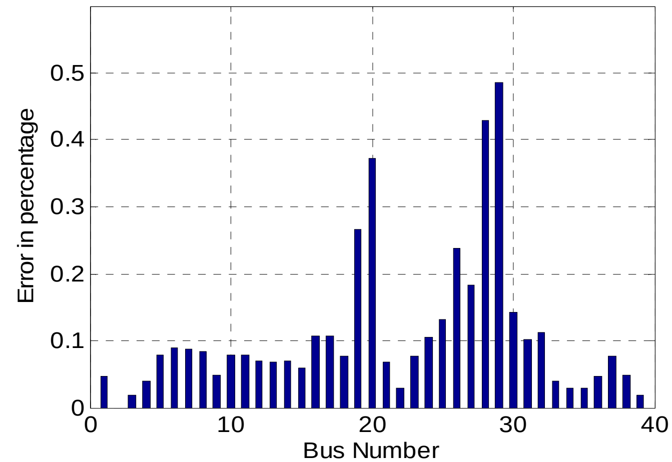


Progress on Demonstration II

Validation of the conversion process using IEEE 39 Bus Test System:



IEEE 39 Bus System

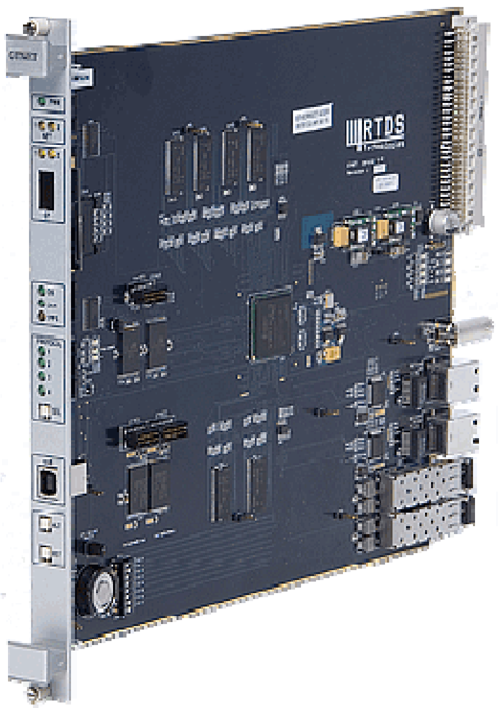


A comparison between the voltages of solutions obtained by PSS®E and RTDS reveals that the percentage of error between the two is minimal. Highest error is 0.5% and the mean error is less than 0.03%

Progress on Demonstration III

***2.* Hardware and software Capacity up-gradation to perform PMU data streaming**

- New hardware was acquired for the CAPS RTDS simulator in support of the project. Four Giga-Transceiver Network Communication Cards (GTNET), with Phasor Measurement Unit firmware (PMU) were installed.
- Firmware of the PMU hardware was upgraded that increased the PMU data streaming channels from 24 to 96.



GTNET PMUs (courtesy of RTDS)

RTDS simulators at CAPS

Progress on Demonstration IV

3. PMU measurement data streaming through Internet

- Test cases were executed using the IEEE 39 Bus system.
- Four fault cases were created and PMU measurement of Voltage and Current data for 32 Buses were streamed through the Internet.
- FSU has streamed the data over the Internet to MSU who received those PMU data remotely using open source software named “PMU connection tester” and saved the data for further analysis.

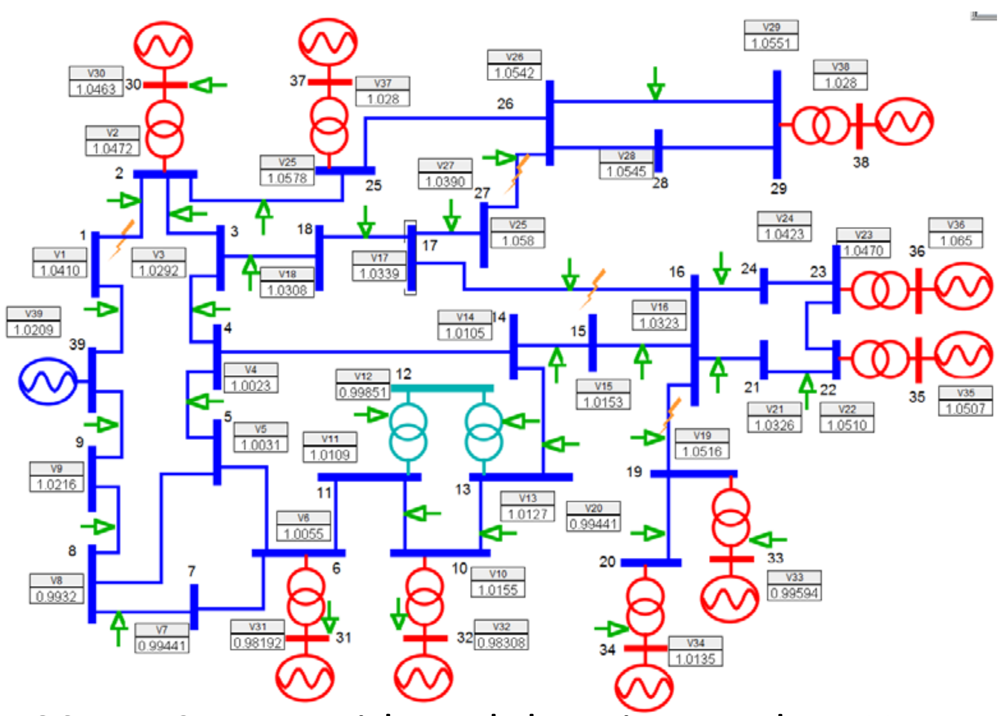


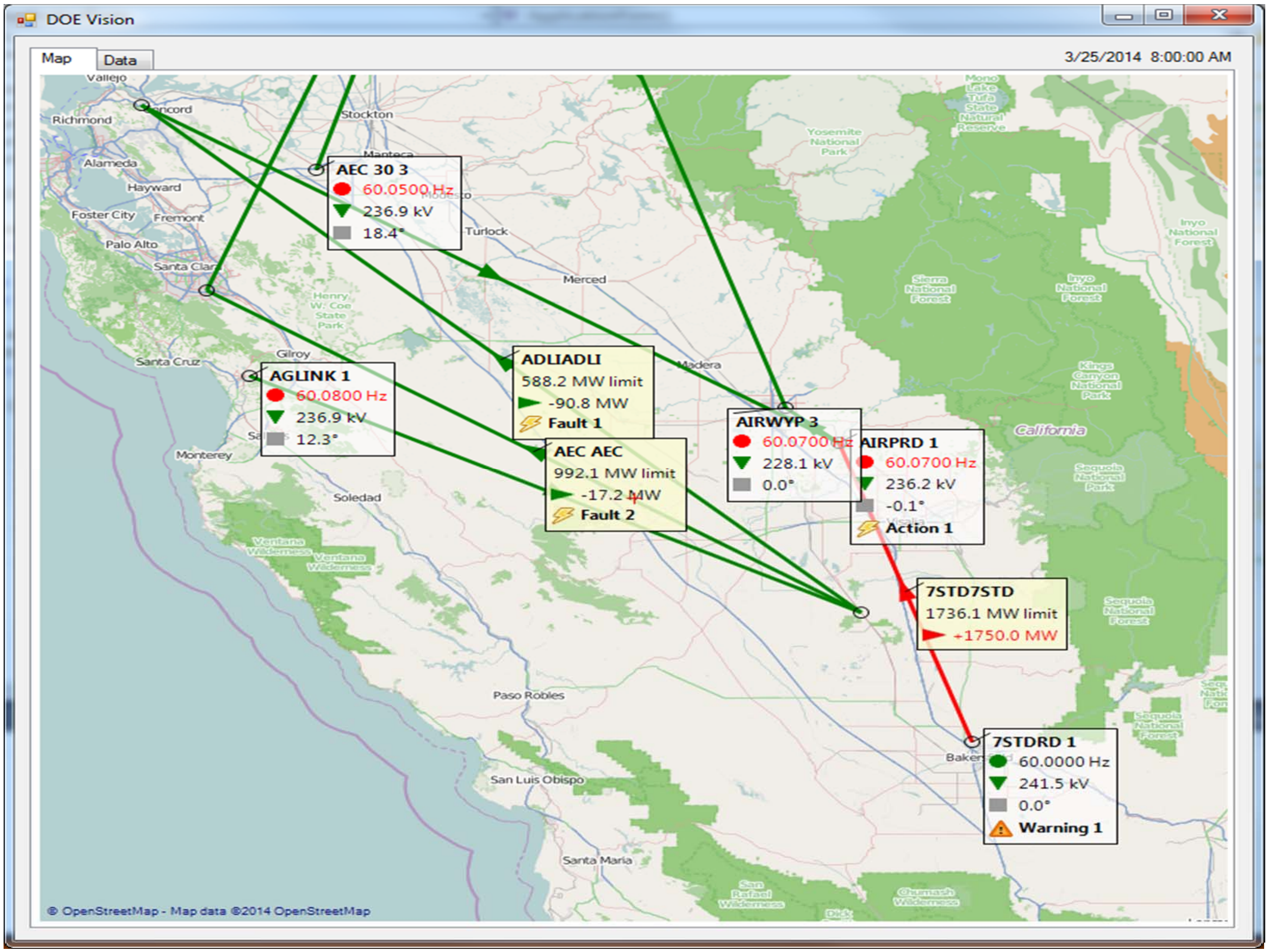
Fig. IEEE 39 Bus System with Fault locations and PMU connections

Visualization Scheme

The following data is communicated and updated every 4 seconds

- **Bus data**: Bus ID, Name, Latitude, Longitude, Nominal Voltage, Real Power Load, Reactive Power Load, Angle, Voltage, Frequency
- **Generator data**: Generator ID, Generator Name, Bus ID, Pmin, Pmax, Qmin, Qmax, Real Power, Reactive Power
- **Lines data**: Line ID, Name, From Bus ID, To Bus ID, Limit, Active Power Flow, Reactive Power Flow
- **Interfaces**: Interface ID, Interface Name, Forward Limit, Reverse Limit, Flow
- **Interface lines**: Interface ID, Line, Coefficient
- **Bus warning**: Bus ID, Warning
- **Line warning**: Line ID, Description
- **Bus fault**: Bus ID, Description
- **Line fault**: Line ID, Description

Visualization: Illustration



Plans and Expectations

The near-term plans and next steps for the project components are as follows.

1. The homotopy-based method is being developed into a multi-parameter, variable-gain form for increased computational efficiency. This will then be tested on several large test systems.
2. After testing the polynomial Lyapunov method and the control strategies on larger systems, these will be integrated with the homotopy-based screening algorithm.
3. The screening algorithm will be modified to accept and use real-time data streamed from the RTDS cluster at FSU-CAPS. The control algorithm will be sent to CAPS for testing on the RTDS.
4. SCE is developing a reduced model of their system for implementation on the RTDS cluster.
5. LCG is developing a user interface to integrate with the visualization tool. This visualization and user-interface tool will be integrated with the screening and control algorithm for final testing, demonstration, and vetting by the team, including utility personnel.

Conclusion

- This project has many components under development in parallel and these have progressed well.
- New theoretical contributions that were anticipated have also produced promising results:
  - Homotopy method
  - Polynomial Lyapunov function
  - Distributed control actions
- A preliminary visualization tool has also been developed.
- The work performed has been kept in alignment with input from industry partners.
- Integration and demonstration tasks that remain are expected to be completed by September 2015.
- We are excited about this project and look forward to producing an integrated and potentially commercializable product.

Acknowledgements/Contacts

- ❑ Financial support is acknowledged from the US Department of Energy.
- ❑ Technical contributions from the following are appreciated:
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    - Prof. Sudip K. Mazumder, mazumder@uic.edu
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    - Dr. Benyamin Moradzadeh, moradzadeh@energyonline.com
  - And my graduate students:
    - Mohammed Benidris
    - Niannian Cai
    - Nga Nguyen
- ❑ Principal Investigator: Prof. Joydeep Mitra, mitraj@msu.edu

A Lyapunov Function Based Remedial Action Screening Tool Using Real-Time Data

Key Personnel: *Joydeep Mitra* (Michigan State University), *Sudip K. Mazumder* (University of Illinois–Chicago), *Scott N. Backhaus* (Los Alamos National Lab), *Omar Faruque* (Florida State University), *Sidart Deb* (LCG Consulting), *Nagy Abed* (Southern California Edison)

Purpose of Project: *To develop an advanced computational tool that is will assist system operators in making real-time redispatch decisions to preserve power grid stability. The tool relies on screening contingencies using a homotopy method based on Lyapunov functions to avoid, to the extent possible, the use of time domain simulations. This enables transient stability evaluation at real-time speed without the use of massively parallel computational resources. The tool is updated with real-time data as the contingency evolves.*

Key Innovations:

- A new methodology for contingency screening using a homotopy approach based on Lyapunov functions and real-time data.
- A polynomial Lyapunov function capable of capturing a larger region of attraction than energy functions.
- A methodology for recommending strategic and tactical remedial action recommendations based on the screening results.
- A novel visualization and operator interface tool.

Deliverables:

- A software prototype ready for commercialization
- A real-time digital simulation test-bed
- A suite of breakthrough theoretical contributions on grid stability and control
- A new visualization tool for grid stability

Budget:

DOE: $1,500,000

Cost-share: $375,000

Total: $1,875,000