NSF Workshop
Applied Mathematics for Deregulated Power Systems:
Optimization, Control and Computational Intelligence
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Power System Security

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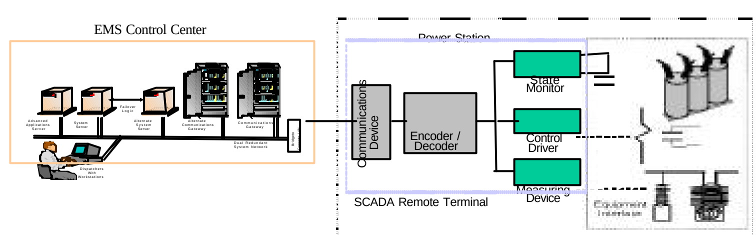
Outline

- Power system security
  - » Current practice
  - » Lesson from 2003 blackout
- A new approach to power system security analysis
  - » Security regions
- Challenges in power systems
  - » Mathematical theory
  - » Control-theoretic issues
  - » Information technology and enhanced intelligence
  - » Brain power shortage

Power System Reliability and Security

- Service reliability
  - » Continuity of service, without interruption
  - » In the face of constant disturbances or contingencies (generator and transmission outages)
- System security
  - » Ability to withstand contingencies
  - » Set requirement for generation reserve and limit to transmission loading
  - » Avoidance of cascading outages leading to blackout

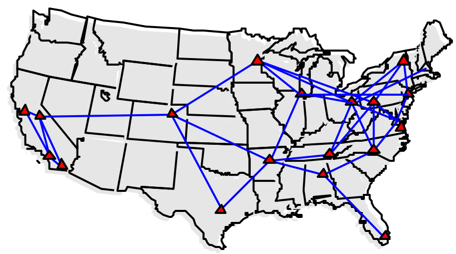
Control Centers

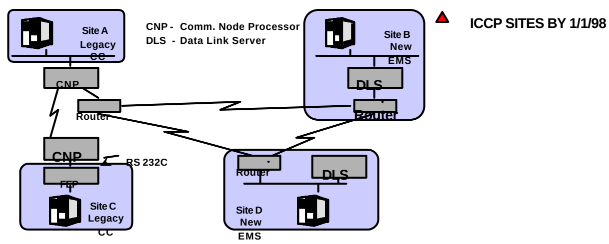


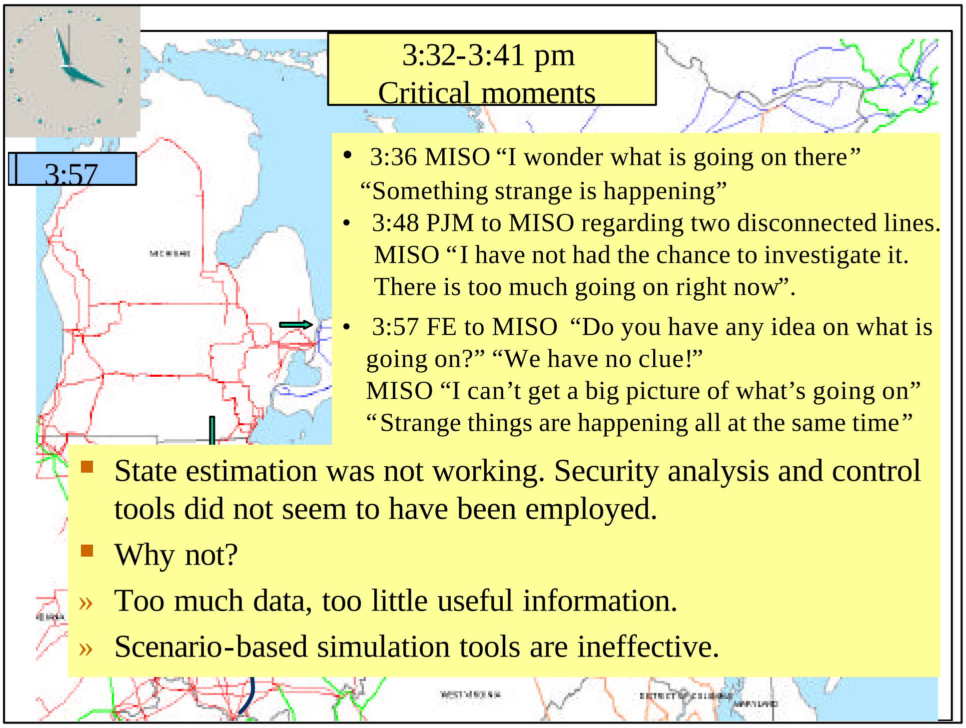
- Control center (energy management system)
  - » Real-time security monitoring and control (SCADA)
- Network security software
  - » State estimation
  - » Contingency analysis
  - » Security-constrained economic dispatch
  - » Security redispatch
- Remote control
  - » Automatic generation control
  - » Transmission switching
  - » Load shedding

ICCP Network

- Inter-control center communication protocol (ICCP)
- TASE.2 (Technical Application Service Element)
  - » IEC standards





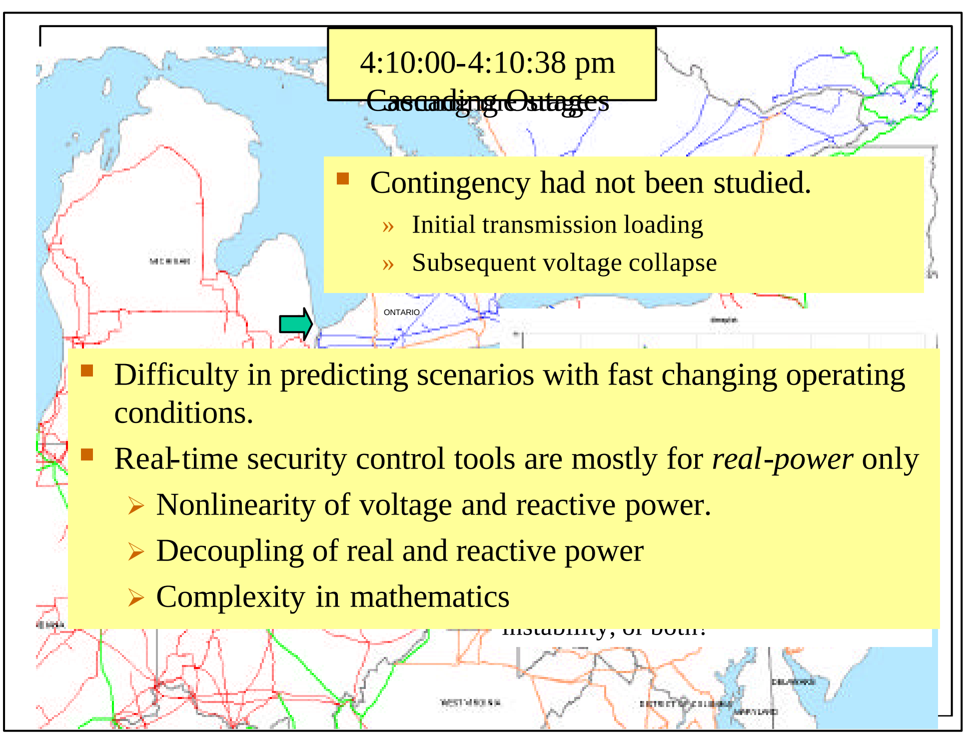


3:32-3:41 pm
Critical moments

3:57

- 3:36 MISO "I wonder what is going on there" "Something strange is happening"
- 3:48 PJM to MISO regarding two disconnected lines. MISO "I have not had the chance to investigate it. There is too much going on right now".
- 3:57 FE to MISO "Do you have any idea on what is going on?" "We have no clue!" MISO "I can't get a big picture of what's going on" "Strange things are happening all at the same time"

- State estimation was not working. Security analysis and control tools did not seem to have been employed.
- Why not?
  - » Too much data, too little useful information.
  - » Scenario-based simulation tools are ineffective.



4:10:00-4:10:38 pm
Cascading Outages

- Contingency had not been studied.
  - » Initial transmission loading
  - » Subsequent voltage collapse

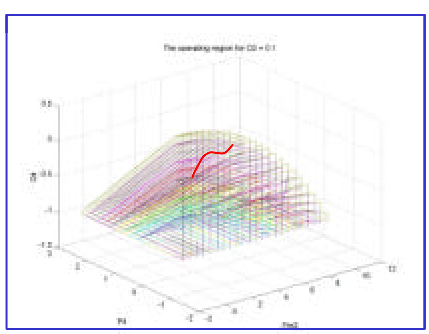
- Difficulty in predicting scenarios with fast changing operating conditions.
- Real-time security control tools are mostly for *real-power* only
  - ➢ Nonlinearity of voltage and reactive power.
  - ➢ Decoupling of real and reactive power
  - ➢ Complexity in mathematics

A New Approach

- A new approach
  - » To address the shortcomings of existing methods
- An interdisciplinary team
  - » Electrical engineering, applied mathematics, computer sciences, …
  - » HK: Univ. of Hong Kong; China: Tsinghua U., Tianjin U., Academy of Science, etc.

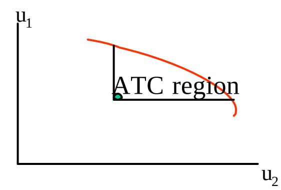
Security Regions

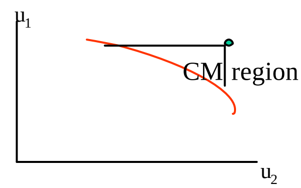
- Security region is defined in the space of controllable market variables
- It is the operating region in which the power system is secure.
- Change in configurations changes the shape of the region.
- Changing operating state (due to contracts, …) moves the point around.
- Boundary of security region gives the limitation imposed by the security constraints.



ATC and CM

- Space of controllable market variables
  - » Manageable dimension
  - » Provides useful information
- A unified approach
  - » Steady-state (real power and voltages)
  - » Small-disturbance (voltage stability)
  - » Transient stability
- Region-wise vs point-wise
  - » Available transfer capability
  - » Congestion management





- Provides feasible region in which to overlay objective functions for decision-making

Steady-State Security Regions

- Power system in steady-state

$$f(x,u)=0$$
$$g(x,u)\le 0$$

x: state variables.
u: controllable market variables
(quantities that are controllable by market participants and grid operator)

- Steady-state security region

$$\Omega_s=\{u: f(x,u)=0, g(x,u)\le 0\}$$

- Boundary of steady-state security region $\partial\Omega_s$

Small Disturbance Security Region

- Birfurcation and voltage instability
  - Saddle node
  - Hopf
- Small disturbance security region

$$\Omega_{sd} = \{u : F_x(x,u) \ \text{nonsingular} \ \}$$

- Boundary of small disturbance security region $\partial\Omega_{sd}$

Dynamic Security Region

Pre fault	*Fault-on*	*Post-fault*
$0 = F(x,u)$	$\dot{y} = F_1(y,u)$	$\dot{z} = F_2(z,u)$
(x,u)	$y(t) = f(t,x,u)$	$sep : z_s(u)$
	$y(t_F) = f(t_F, x, u)$	$SR(z_s(u))$

- Dynamic security region

$$\Omega_d = \{u : f(u) \in SR(z_s(u)\}$$

- Boundary of dynamic security region $\partial\Omega_d$

Research Issues

- Characterize boundary of security regions.
- Determine whether the changed state is inside or outside the security region (security assessment).
- If it is inside the security region, what is the range in which market participants can engage in further trades (available transfer capability)
- If it is outside the security region, what are ways to bring it to the boundary of the security region (congestion management).
- Computational algorithms.

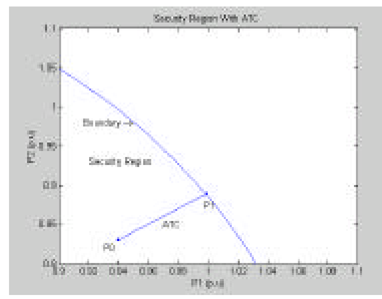
Approach

- Solve one-dimensional u sub problem first.
  - » Applications: fixed allocation ATC and CM.
- For multi-dimensional u
  - » Patching up local boundary segments from one-dimensional solutions.
- Computational efforts
  - » Off-line: one-dimensional problems
  - » On-line: decision-making in the space of multi-dimensional u.

Steady-state ATC

- For one-dimensional u, the problem is how far λ is the boundary from the current state u_0

$$f(x, u_0 + \lambda u) = 0$$
$$g(x, u_0 + \lambda u) \le 0$$



- Which inequality constraint $g_i(x, u_0 + \lambda u) = 0$ to hit first?
- Reformulate the problem using the pointwise maximum function

$$F(x, \lambda) = \begin{Bmatrix} f(x, \lambda) \\ \max_i \{g_i(x, \lambda)\} \end{Bmatrix} = 0$$

- F(x, λ) is a semi-smooth function.

Smoothing Function

- The semi-smooth function can be solved by semi-smooth Newton method. However, global convergence is difficult to obtain.
- An approach using the following smoothing function is taken:

$$g_s(t, y) = \{ \begin{array}{ll} t \ln(\sum e^{g_i(y)/t}), & if \;\; t \ne 0 \\ \max\{g_i(y)\}, & if \;\; t = 0 \end{array}$$

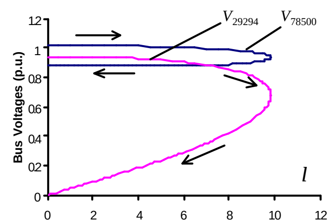
$$where \quad y = (x, \lambda)$$

- Efficient algorithms have been developed and global convergence proved.

ATC Limited by Saddle Node Bifurcation

- Moore-Spence

$$F(x, l) = 0$$
$$F_x(x, l)y = 0$$
$$l^T y = 1$$



- Algorithmic improvement with decomposition-coordination.

Boundary of Stability Region

- Post-fault system dynamics

$$\dot{z} = F(z)$$

- Boundary of stability region

$$\partial SR(z_s) = \bigcup_{z_e^1 \in \partial AR} W^s(z_e^1)$$

- Local characterization

$$W^s(z_e^1) = \{h(z) = 0 \mid L_F h = m \cdot h,, h(z_e^1) = 0\}$$

where $L_F h =< F(z), h_z(z) >$

m is theunstableeigenvalueat z_e^1

Boundary of Dynamic Security Region

- Dynamic security region

$$\Omega_d = \{u : f(u) \in SR(z_s(u)\}$$

- Boundary of dynamic security region

$$\partial\Omega_d = \{u : f(u) \in \partial SR(z_s(u))\}$$

- Local boundary of dynamic security region

$$\{u : h(f(u), u) = 0\}$$

Boundary Approximation

- Quadric approximation

$$h_Q(z, u_0) = [z - z_u(u_0)]^T h(u_0) + [z - z_u(u_0)]^T Q(u_0)[z - z_u(u_0)]/2$$

where h is left unstable eigenvector of the Jacobian at z_e

Q is the solution of $CQ + QC^T = H$, $C = (mI/2 - J^T)$ and $H = \sum h_i Hess(F_i)$

- Changing u, $u = u_0 + l\Delta u$

$$h_Q(z, u) = [z - z_u(u)]^T h(u) + [z - z_u(u)]^T Q(u)[z - z_u(u)]/2$$

- Approximation

$$h_{AQ}(z, u_0 + l\Delta u) = [z - (z_u(u_0) + \frac{\partial Z_u}{\partial u} l\Delta u)]^T (h(u_0) + h_u l\Delta u)$$
$$+ [z - (z_u(u_0) + \frac{\partial Z_u}{\partial u} l\Delta u)]^T [Q(u_0) + Q_u l\Delta u][z - (z_u(u_0) + \frac{\partial Z_u}{\partial u} l\Delta u)]$$

Dynamic ATC

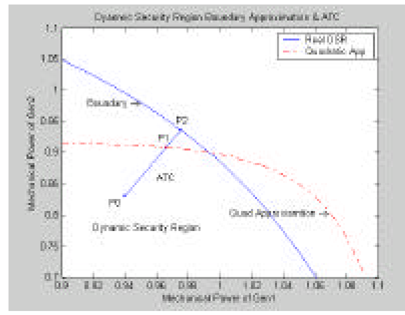
- Fault-on trajectory

$$f(u) \simeq f(u_0) + \frac{\partial f}{\partial u} l \Delta u$$

- Approximate boundary of dynamic security region

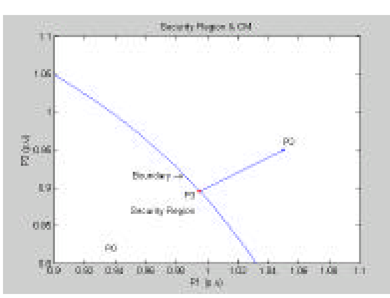
$$h_{AQ}(f(u_0) + \frac{\partial f}{\partial u} l \Delta u, u_0 + l \Delta u) = 0$$

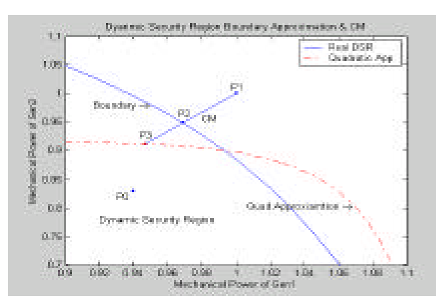
- Quadratic function of λ that can readily be solved.



Congestion Management

- Dual problem of ATC





Broader Issues

- The research effort reported here is only a small part of what is needed.
- Root causes of blackout
  - » Lack of basic understanding of power systems
  - » Mismatch of analysis tools in the new environment
  - » Slow progress in automation and intelligence
  - » Shortage of brain power

Challenges: Mathematical Theory

- The 2003 North America blackout exposed the inadequacy of tools for power system security
  - » Too much data, not enough useful information
  - » Scenario-based simulation is ineffective
  - » Theoretical understanding of nonlinear power system dynamics is inadequate
- It is time for more theoretical research to develop alternatives to complement scenario-based simulation paradigm: mathematical theory to understand the complex dynamic behavior of large-scale interconnected power systems utilizing modern nonlinear mathematics.

Challenges: Control-theoretic Issues

- We are using tools not designed for the (restructured) system to deal with problems arising from our using the system not the way it was designed.
  - » Fundamental conflict between centralized optimization and decentralized competitive market
- It is time to free ourselves from centralized optimization paradigm and for innovative research in various dimensions of control-theoretic issues of:
  - » information structure
  - » decision making
  - » Coordination

Challenges: Enhancing Intelligence

- We are not using the best available technologies to manage the system.
  - » Slow progress in automation and intelligentization
- It is time for more research in effective utilization of modern computer, communication and control technologies to make the system highly intelligent.

Challenges: Brain Power Shortage

- We are not attracting the best talents to the profession
  - » Many major US engineering schools do not have a power program any more (MIT, Stanford, Berkeley…)
  - » Power engineers salary is lower than the average engineer.
    - – Median: $73,625 vs. $82,000 (-10%)
      Highest 10%: $107,000 vs. $132,000 (-19%)
- It is time for government to provide significant funding to universities to conduct innovative research that would attract creative-minded faculty and students, and for industry to change employment attitude.