A (Smart) Real-time PMU-assisted Power Transfer Limitation Monitoring and Enhancement System

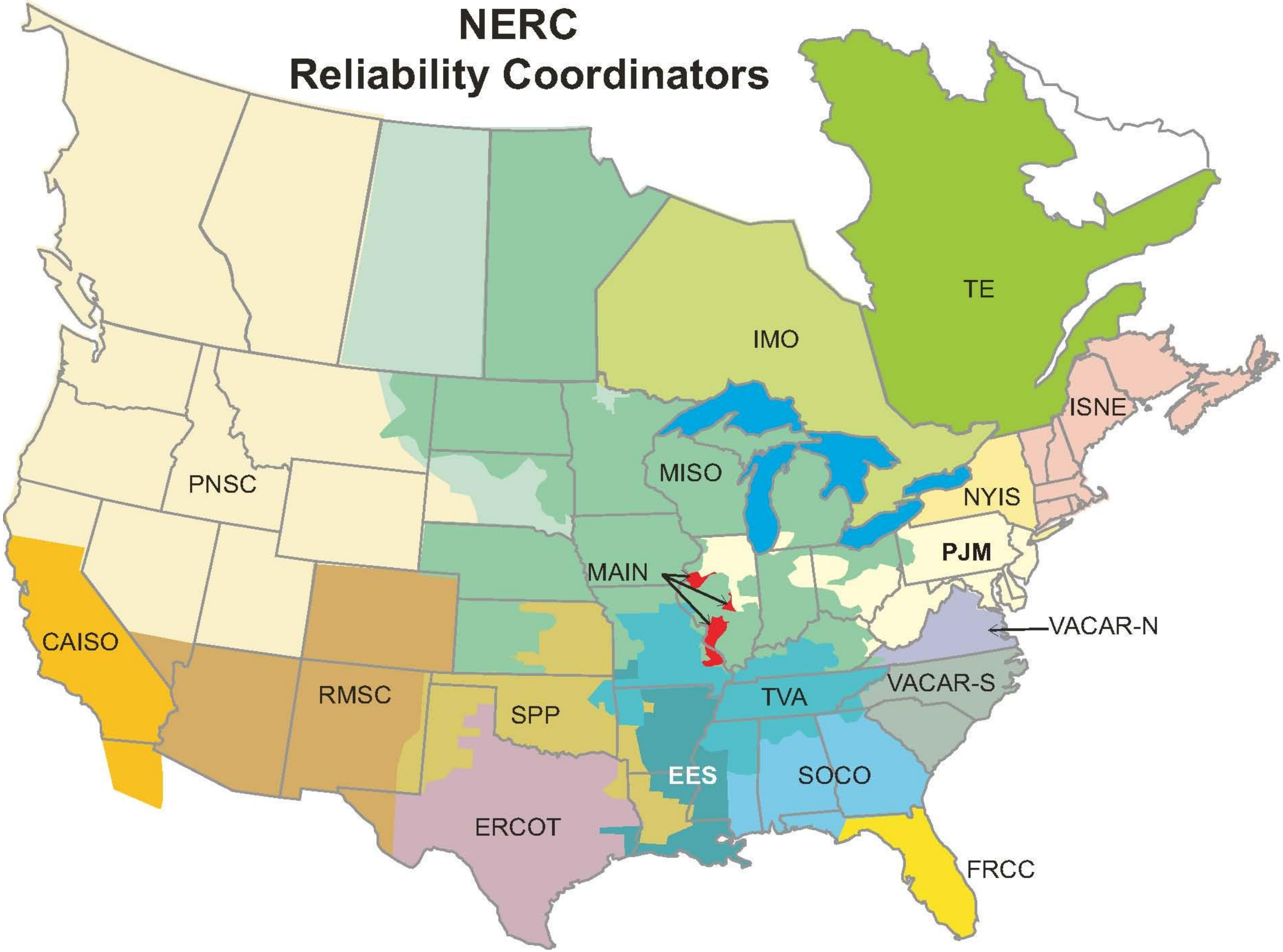
•Support Renewables on the Grid

• Exploring existing transmission infrastructure

•Enhance control room situational awareness and early warning system

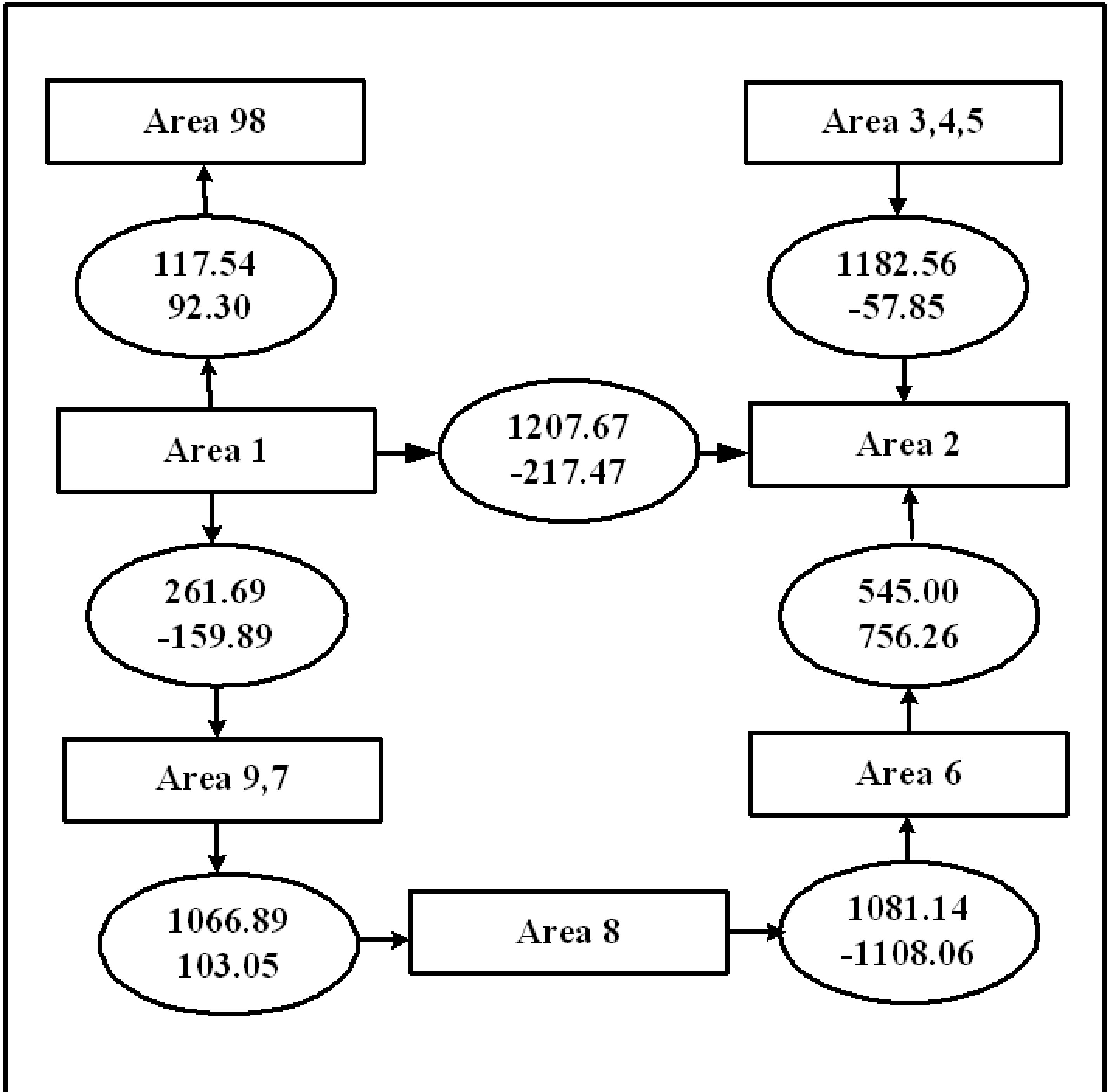
Dr. Hsiao-Dong Chiang

NERC Reliability Coordinators

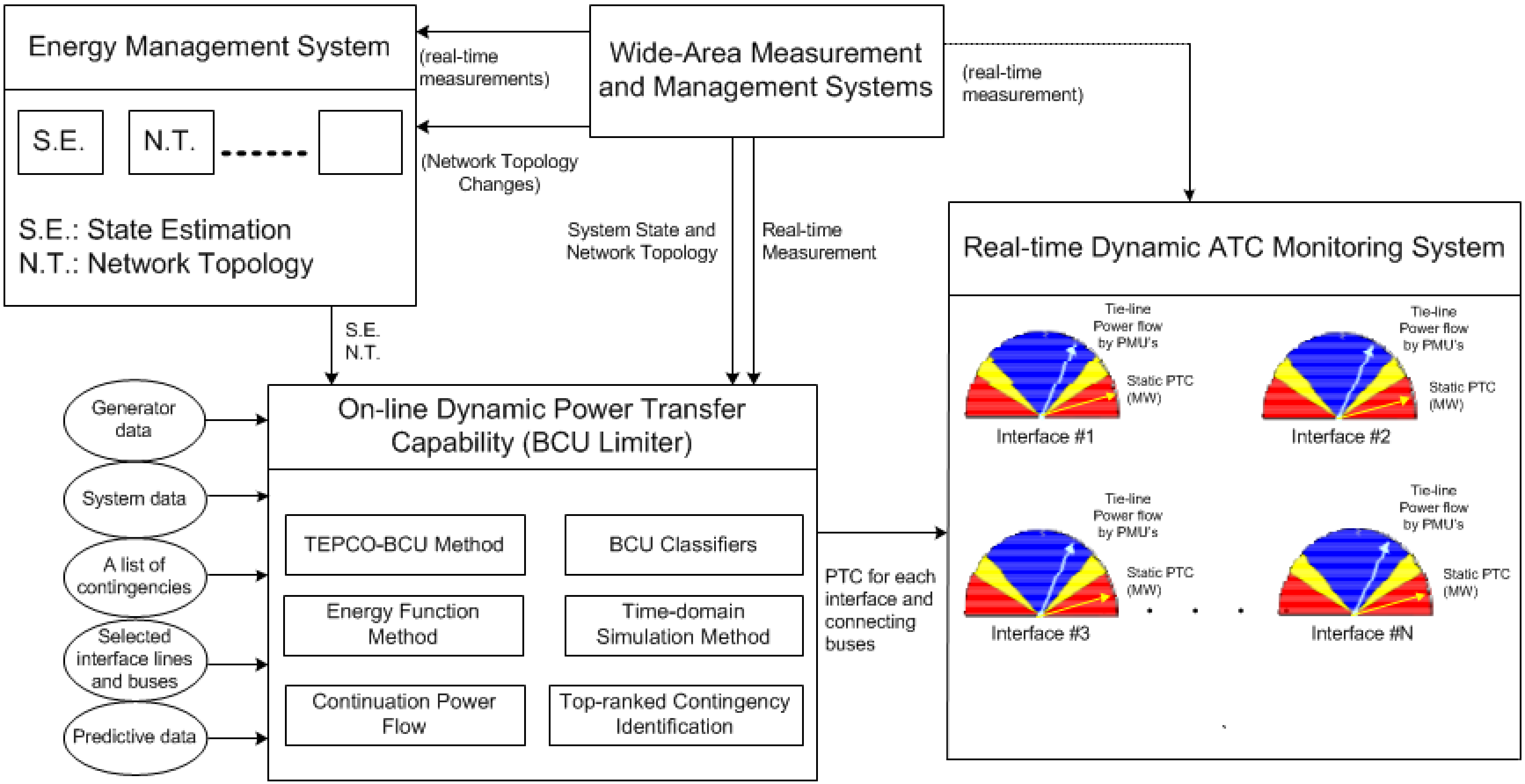


PJM System

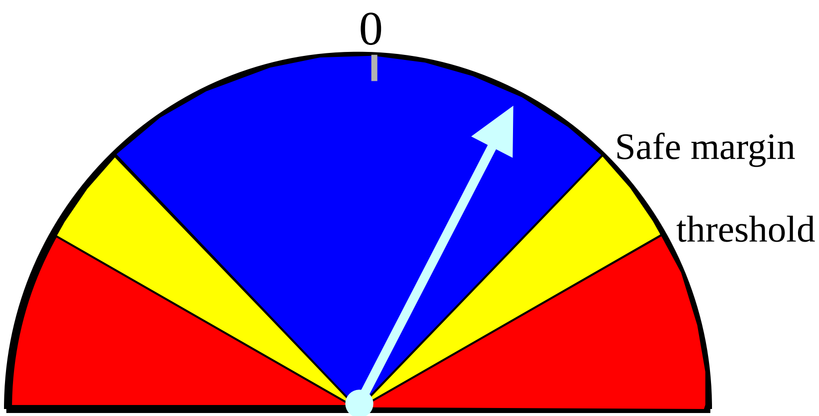
- PJM’s Base-case power system (State estimation EMS using CIM-compliance format or PSSE format)
- Look-ahead scenario (proposed power transfer, look-ahead loads, look-ahead generation dispatch scheme, planned outage schedule)
- PJM’s On-line Available transfer capability monitoring system and (smart) enhancements (i.e. increase ATC in a smart way)



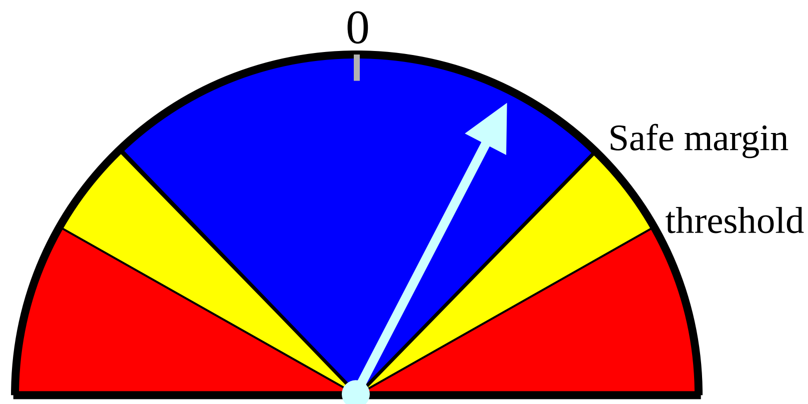
Area 98
Area 3,4,5
117.54
92.30
1182.56
-57.85
Area 1
1207.67
-217.47
Area 2
261.69
-159.89
545.00
756.26
Area 9,7
Area 6
1066.89
103.05
Area 8
1081.14
-1108.06



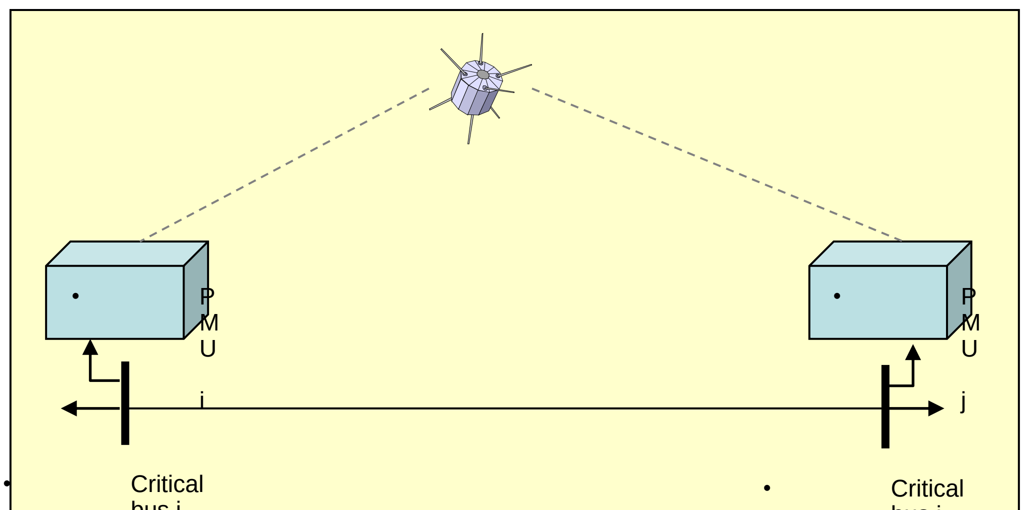
Energy Management System
S.E.
N.T.
S.E.: State Estimation
N.T.: Network Topology
(real-time measurements)
(Network Topology Changes)
Wide-Area Measurement and Management Systems
(real-time measurement)
System State and Network Topology
Real-time Measurement
S.E.
N.T.
Real-time Dynamic ATC Monitoring System
Tie-line Power flow by PMU's
Static PTC (MW)
Interface #1
Interface #2
Interface #3
Interface #N
Generator data
System data
A list of contingencies
Selected interface lines and buses
Predictive data
On-line Dynamic Power Transfer Capability (BCU Limiter)
TEPCO-BCU Method
BCU Classifiers
Energy Function Method
Time-domain Simulation Method
Continuation Power Flow
Top-ranked Contingency Identification
PTC for each interface and connecting buses



Monitoring of critical angle difference



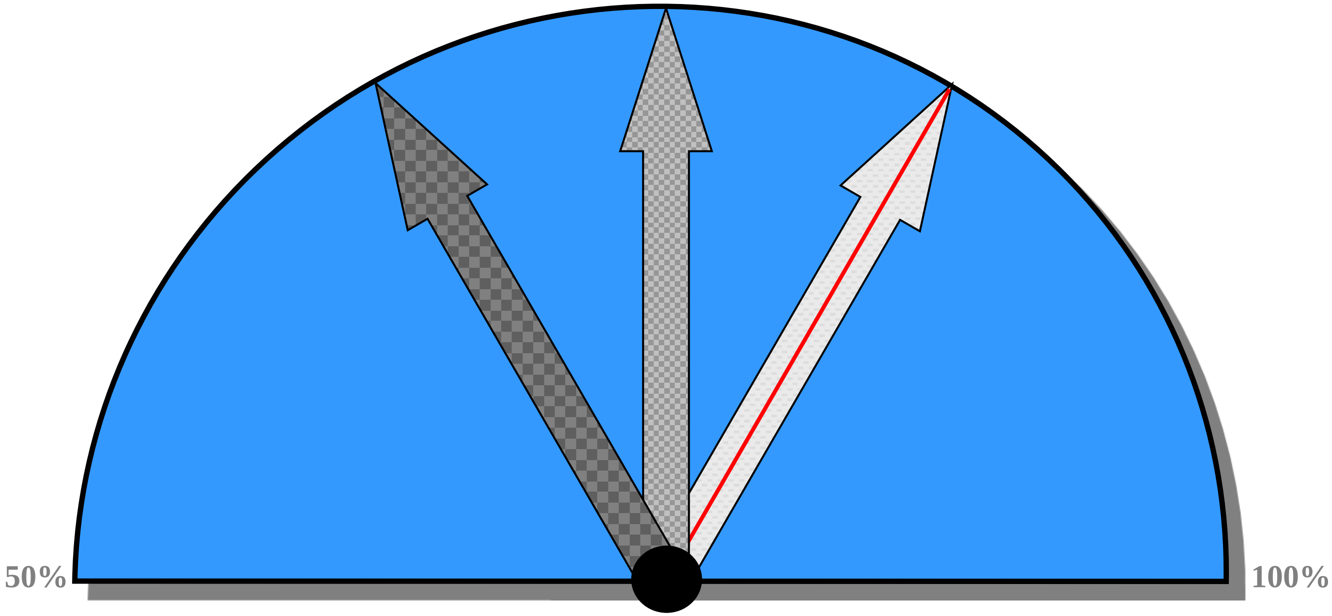
Monitoring of critical power transfer



critical bus #i angle

critical bus #j angle

Monitoring & Analysis
Graphical Scheme



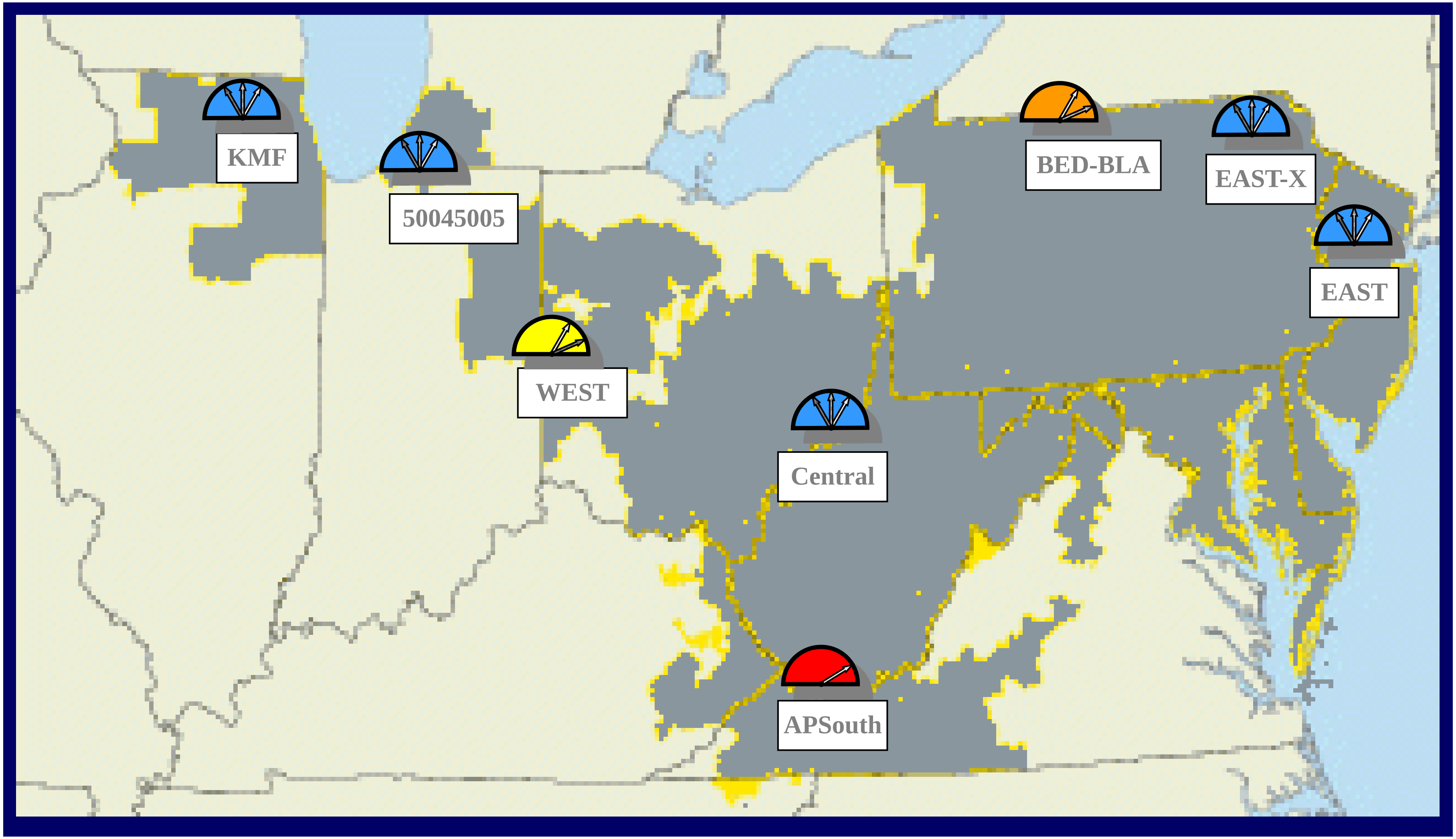
Voltage Security Threat Key

Red	Danger of Voltage Collapse
Orange	Danger of Thermal Limit
Yellow	Danger of Voltage Violation
Blue	Safe

Voltage Violation Type Key

	Voltage Collapse
	Thermal Limit
	Voltage Violation

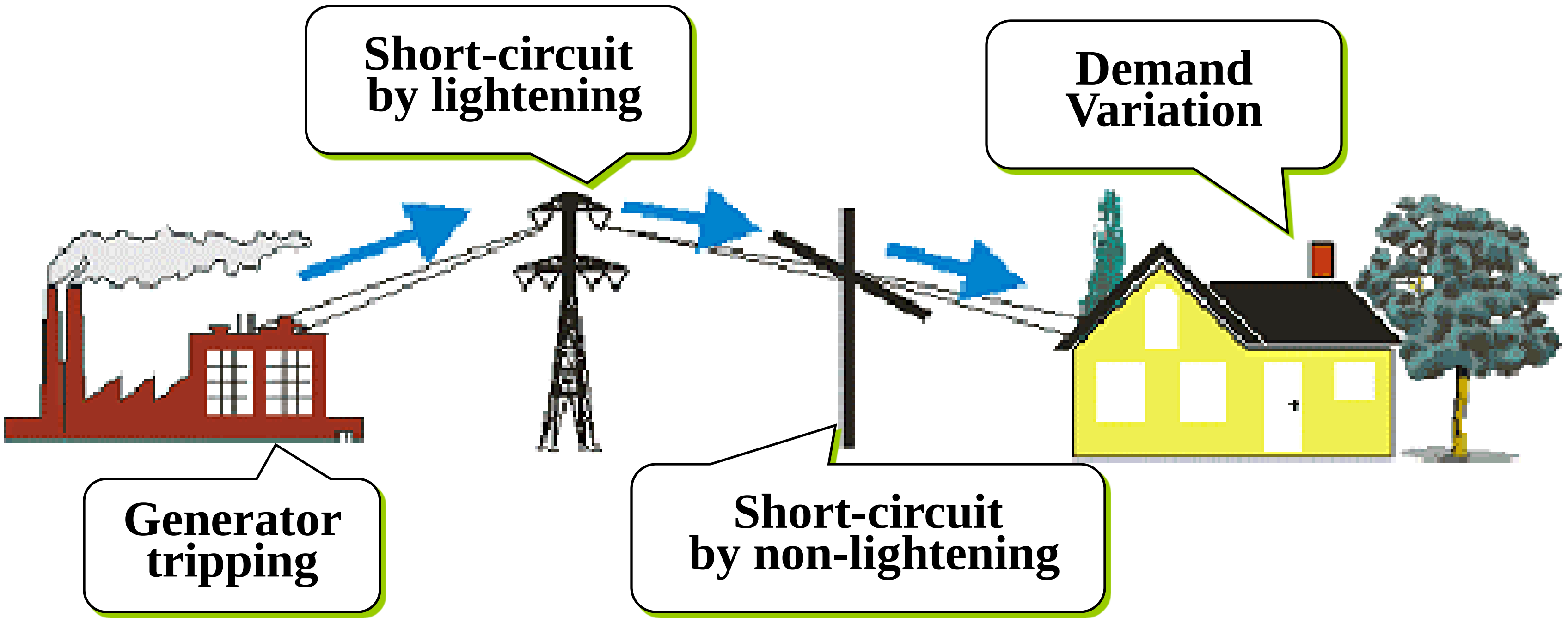
Monitoring & Analysis (Base-Case) Main Window



Contingencies

Power System Outage
and Blackout

Contingencies



Contingencies cause limits on power systems

<u>Hard Limits</u>

Transient (angle) instability

Voltage instability

Small Signal Stability

Contingencies cause limits on power systems

Soft Limits

Voltage limit

Thermal limit

Challenges and Opportunities

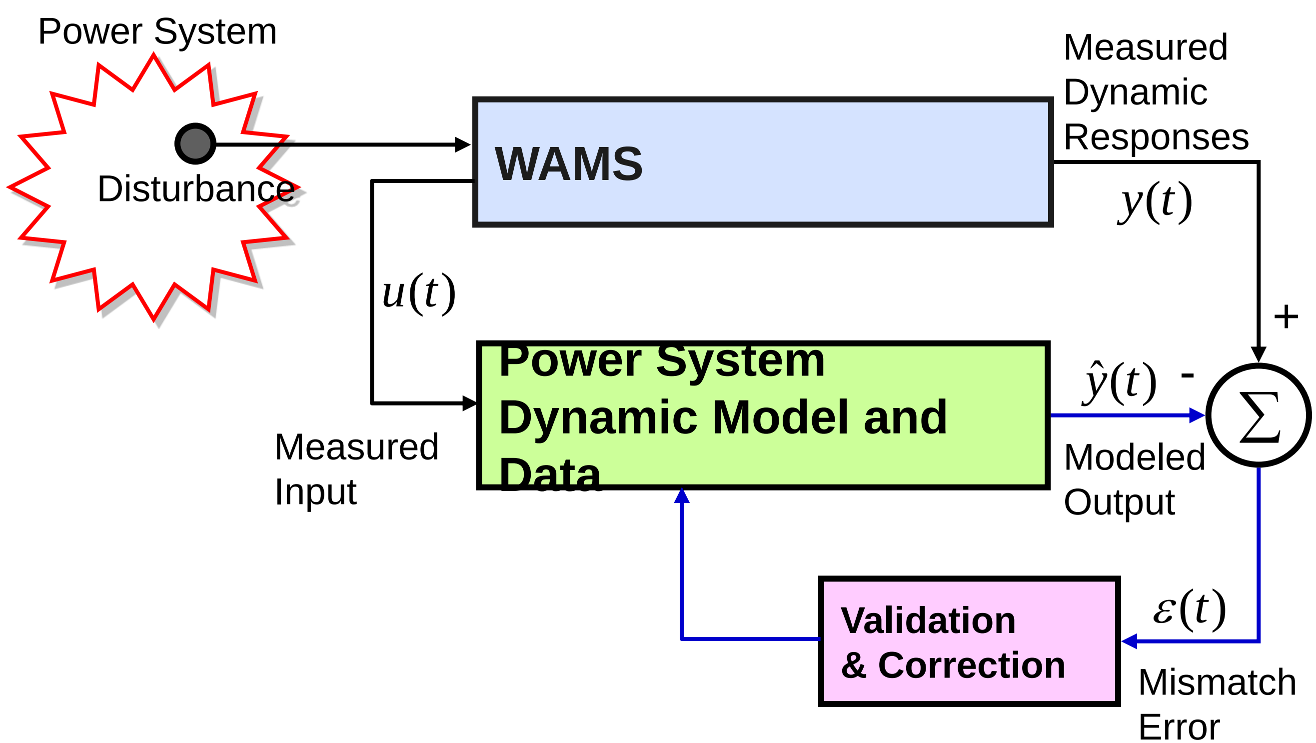
ATC Monitoring and Enhancement

Data issues

- Real-time network model of 13,000-bus, 18168 braches
- Real-time data
- Verification of model and data

Model Validation & Correction

- Identify critical component and parameters.
- Validate and correct model structure and parameters using measurement-based (mismatch-based) approach.



Challenges and Opportunities

ATC Monitoring and Enhancement

Computation Challenges

- On-line computation capability
- N-1 Criteria

Challenges and Opportunities

ATC Monitoring and Enhancement

Control Challenges

- Optimal control design

(priority-based, minimum number of control actions and minimum amount of control actions)

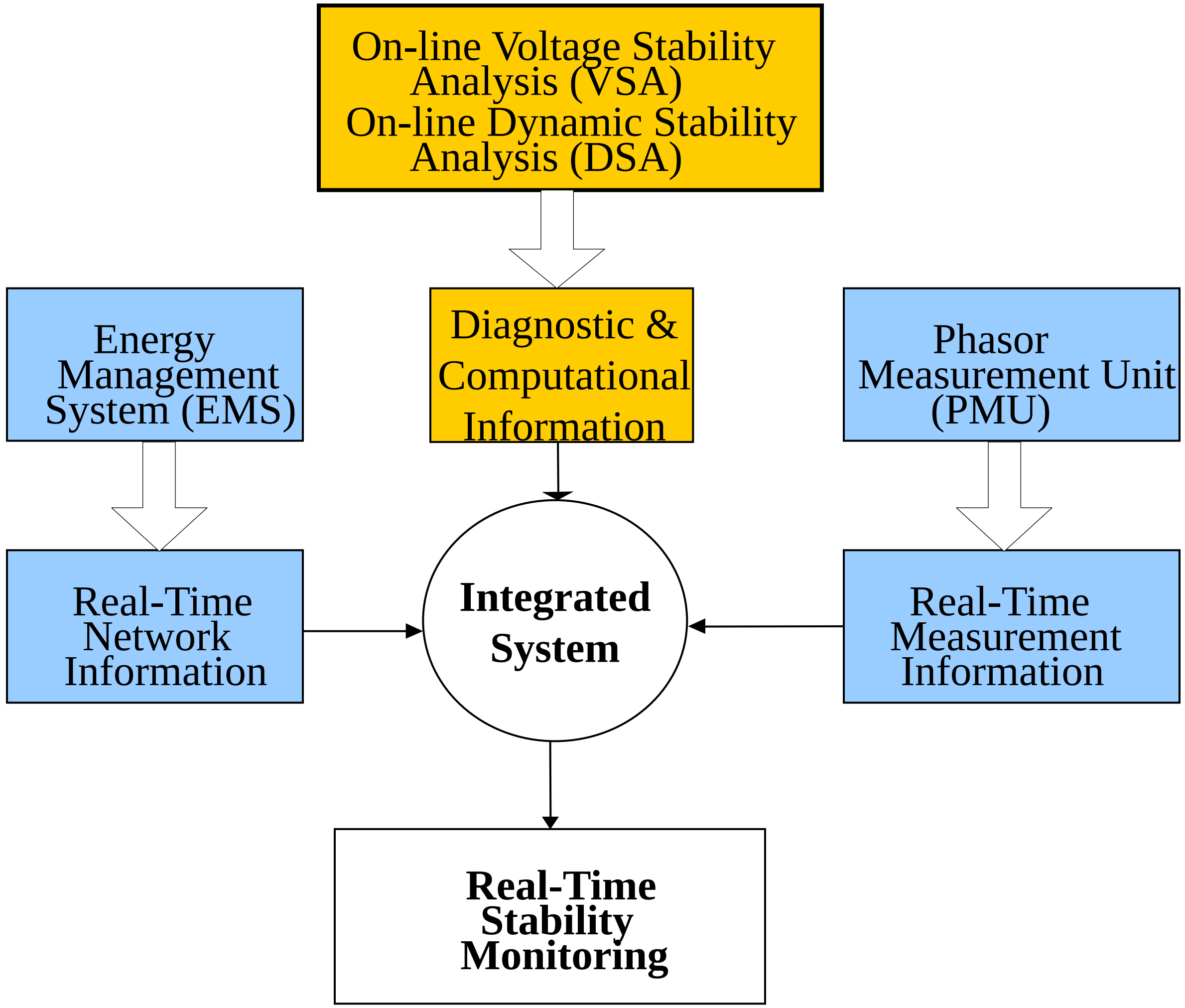
- On-line optimization technologies

Problem statements

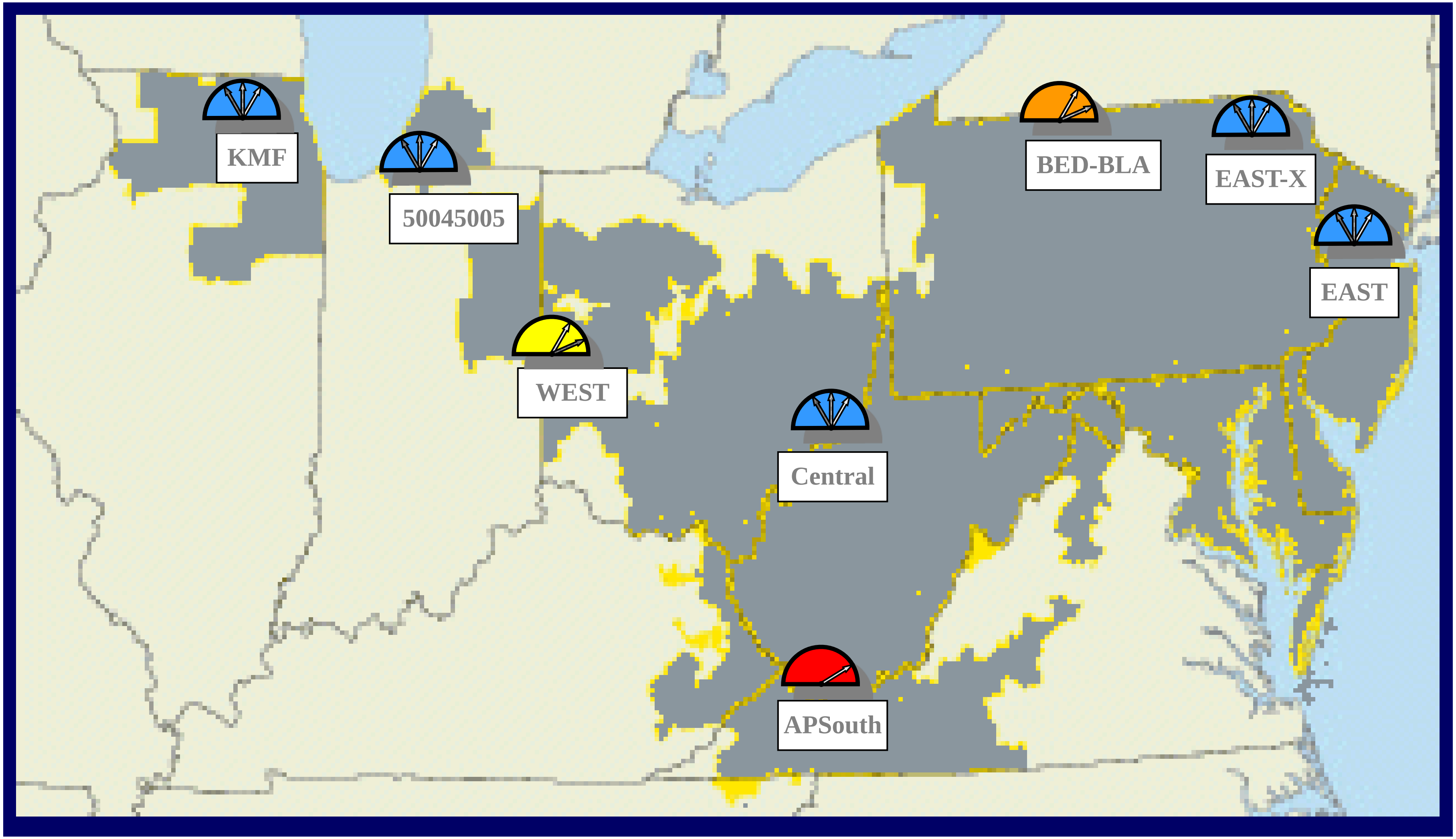
Considerations (ATC monitoring systems)

1. ATC of the base-case power system
2. ATC of base-case + contingencies
3. Which ones will cause ATC's limitation ? (insecure contingencies)
4. Which ones will push the system near its limitations ? (critical contingencies)
5. Where are the weak buses, weak areas ?

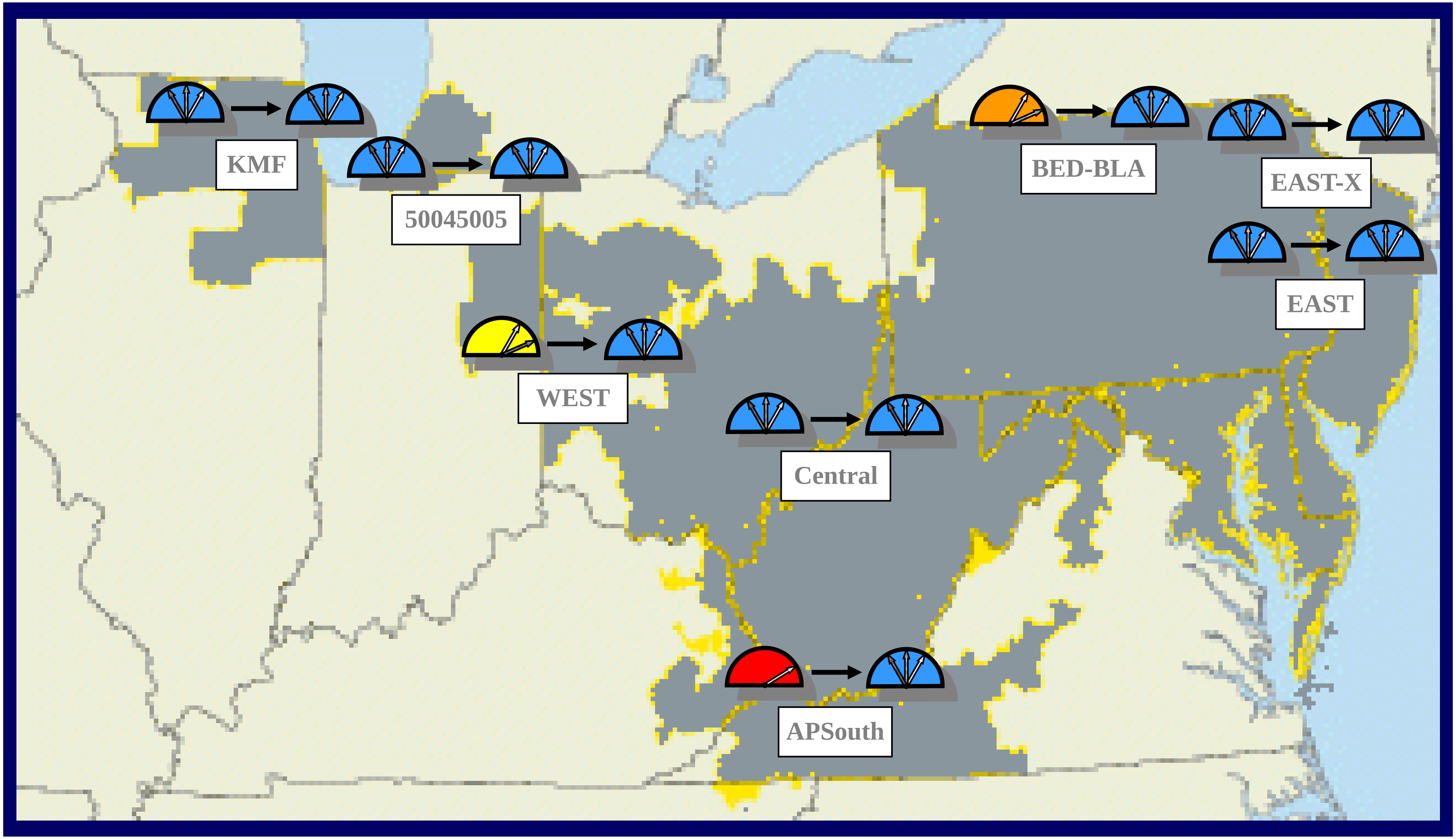
Architecture of Real-Time Stability Monitoring Systems



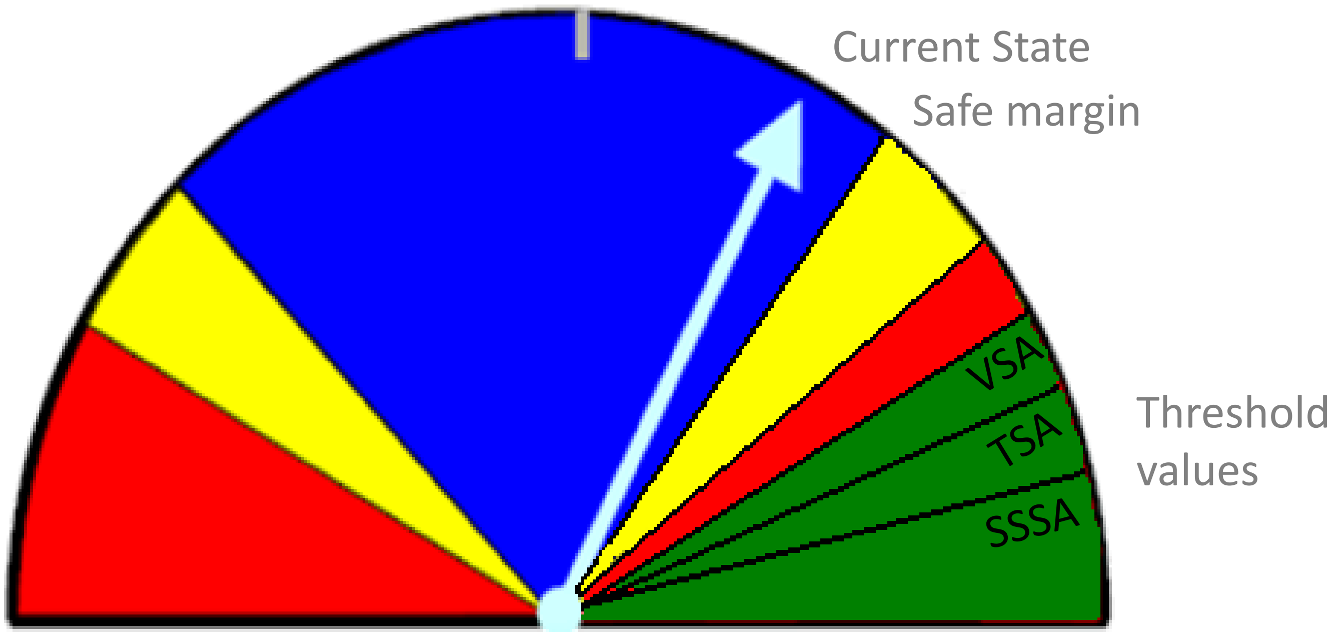
Monitoring & Analysis (Base-Case) Main Window



Preventive & Enhancement Control Main Window



Real-Time ATC Monitoring System



On-line TSA (Transient Stability Assessment)

- 12,000 plus buses in system model
- 1,300 generators
- 3000 contingencies

- 15-minute cycle for real-time EMS data
- 5 minutes in cycle allocated for contingency screening
- target is 1.5 seconds to 2 seconds per contingency

Model for each contingency

Differential equations

$$\dot{x}_1 = f_1(x, y)$$
$$\dot{x}_2 = f_2(x, y)$$
$$\vdots$$
$$\vdots$$
$$\vdots$$
$$\dot{x}_{15,000} = f_{15,000}(x, y)$$

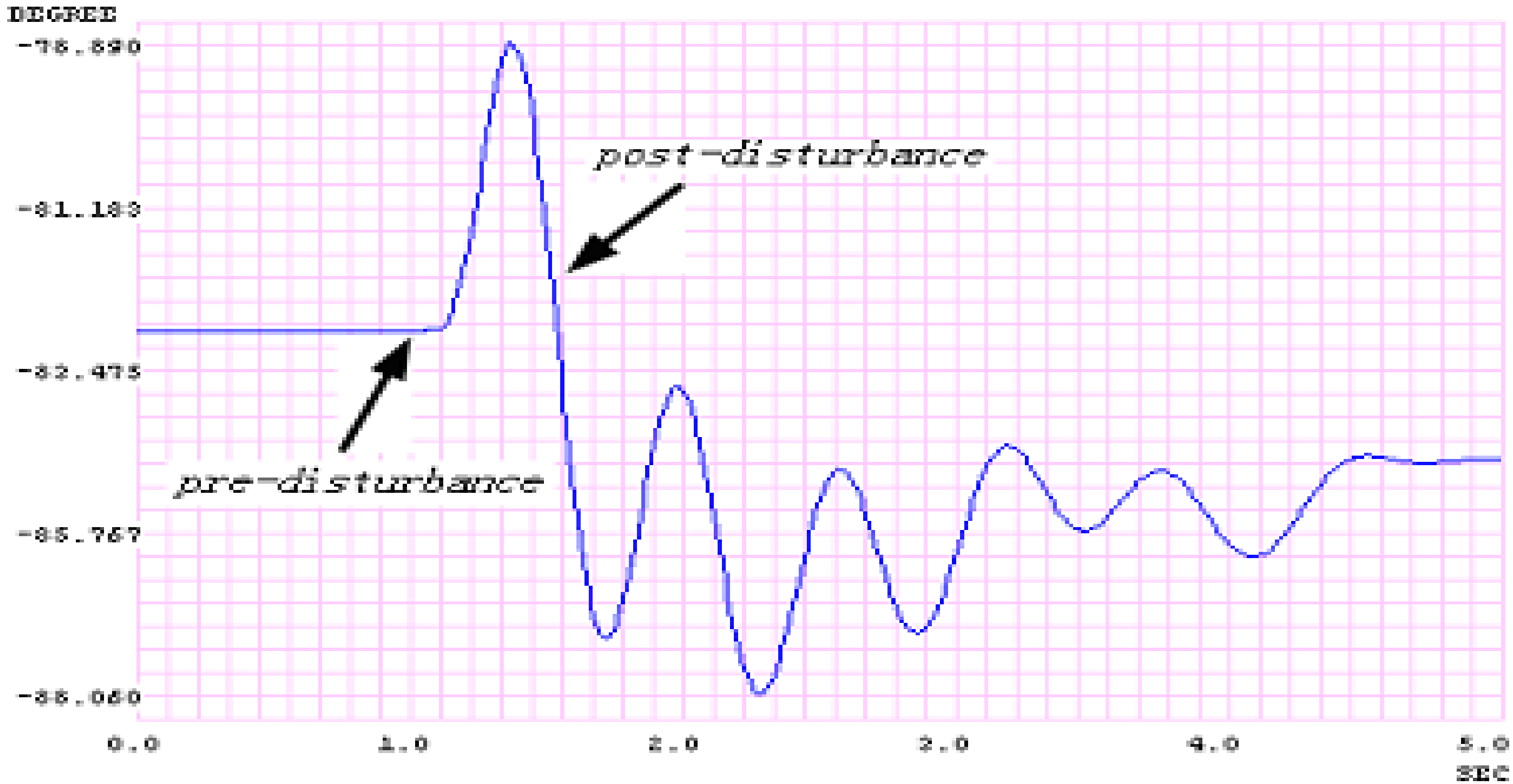
Nonlinear algebraic equations

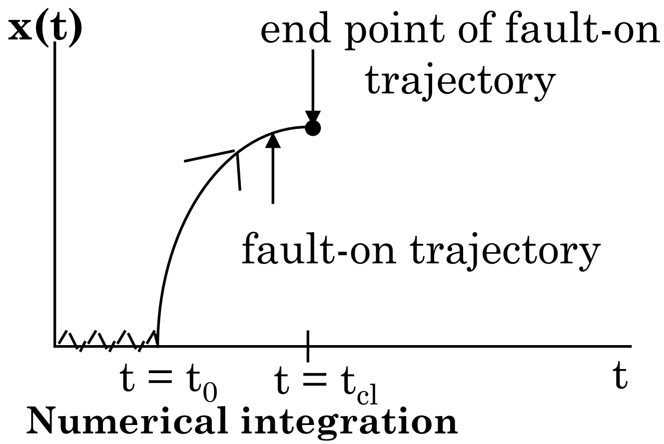
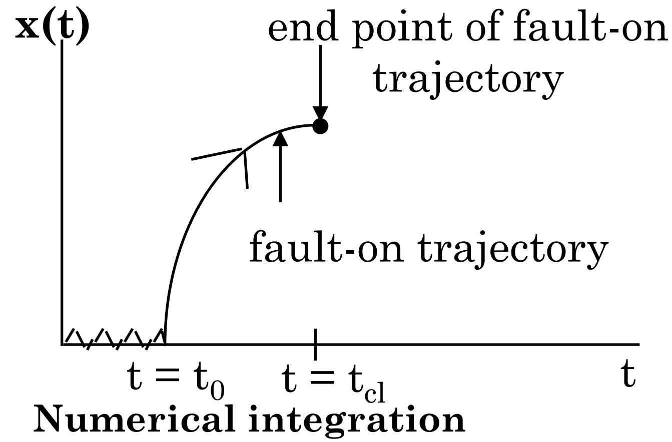
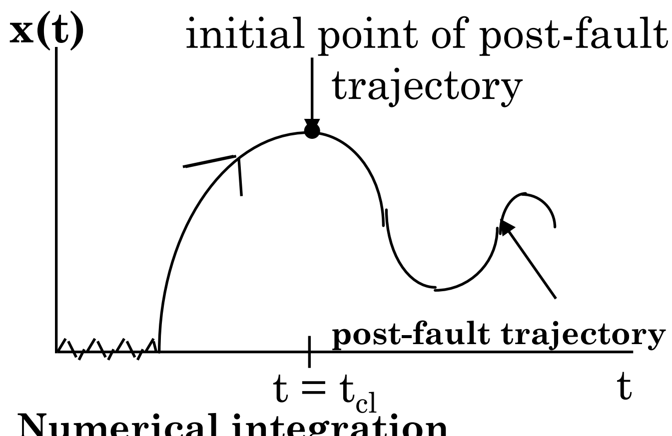
$$0 = g_1(x, y)$$
$$0 = g_2(x, y)$$
$$\vdots$$
$$\vdots$$
$$\vdots$$
$$\vdots$$
$$0 = g_{40,000}(x, y)$$

Time-Domain Approach

- Speed: too slow for on-line applications
- Degree of Stability: no knowledge of degree of stability (critical contingencies vs highly stable contingencies)
- Control : do not provide information regarding how to derive effective control

Dynamical behavior, a generator's angle



	Time-Domain Approach	**Direct Methods (Energy Function)**
Pre-Fault System	• (Pre-fault s.e.p.)	• (Pre-fault s.e.p.)
Fault-On System $\dot{\mathbf{x}} = \mathbf{f_F}(x,y)$ $\mathbf{t_0 < t < t_{cl}}$		
Post-Fault System $\dot{\mathbf{x}} = \mathbf{f}(x,y)$ $\mathbf{t_{cl} < t < t_\infty}$		1. The post-fault trajectory x(t) is not required 2. If $v(x(t_{cl})) < v_{cr}$, x(t) is stable. Otherwise, x(t) may be unstable. Direct stability assessment is based on an energy function and the associated critical energy

History of Direct Methods

- R&D between 1950s and 1980s were based on heuristics and did not work.
- Theoretical foundations were developed in 1987 by Chiang, Wu and Varaiya (Berkeley)
- Practical methods, Controlling UEP method + BCU method, were developed in the 1990s.

History of Direct Methods

- MOD (mode of disturbance) method (1970-1980s)
- PEBS method (by Kakimoto etc.)
- Acceleration machine method (Pavella etc.)
- Extended Equal Area Criteria (EEAC)
- Single-Machine-Equivalent-Bus (SIME)
- BCU method
- TEPCO-BCU method

Key developments

- Theoretical Foundation
- Design of Solution Algorithm
- Numerical Methods
- Implementations (Computer Programs)
- Industrial User Interactions
- Practical system installations

Key developments

1. Theoretical Foundation (gain insights and build <u>belief</u>)

- Theory of stability boundary
- Energy Function Theory (extension of Lyapunov function function)
- Energy Functions for Transient Stability Models (non-existence of analytical energy function)

Key developments

1. Theoretical Foundation (gain insights and build belief)

- Theoretical Foundations of Direct Methods
- CUEP method and Theoretical foundation
- Theoretical Foundation of BCU method

Important Implications

- *CUEP method is the key direct method*

- To directly compute CUEP of the original power system model, the time-domain approach seems to be the only approach

- *These results serve to explain why previous direct methods did not work (motivation of developing BCU method)*

Fundamentals of BCU Method

What: a boundary of stability region based controlling unstable equilibrium point method to compute the critical energy

Why: an effective method to compute CUEP.

Static and Dynamic Relationships

$$
\begin{aligned}
0 &= -\frac{\partial}{\partial u}U(u,w,x,y) + g_1(u,w,x,y) \\
0 &= -\frac{\partial}{\partial w}U(u,w,x,y) + g_2(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) + g_3(u,w,x,y) \\
\dot{y} &= z \\
M\dot{z} &= -Dz - \frac{\partial}{\partial y}U(u,w,x,y) + g_4(u,w,x,y)
\end{aligned}
$$

?

$$
\begin{aligned}
0 &= -\frac{\partial}{\partial u}U(u,w,x,y) + g_1(u,w,x,y) \\
0 &= -\frac{\partial}{\partial w}U(u,w,x,y) + g_2(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) + g_3(u,w,x,y) \\
\dot{y} &= -\frac{\partial}{\partial y}U(u,w,x,y) + g_4(u,w,x,y)
\end{aligned}
$$

(Step 7)

(Step 1)

$$
\begin{aligned}
\varepsilon_1\dot{u} &= -\frac{\partial}{\partial u}U(u,w,x,y) + g_1(u,w,x,y) \\
\varepsilon_2\dot{w} &= -\frac{\partial}{\partial w}U(u,w,x,y) + g_2(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) + g_3(u,w,x,y) \\
\dot{y} &= z \\
M\dot{z} &= -Dz - \frac{\partial}{\partial y}U(u,w,x,y) + g_4(u,w,x,y)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_1\dot{u} &= -\frac{\partial}{\partial u}U(u,w,x,y) + g_1(u,w,x,y) \\
\varepsilon_2\dot{w} &= -\frac{\partial}{\partial w}U(u,w,x,y) + g_2(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) + g_3(u,w,x,y) \\
\dot{y} &= -\frac{\partial}{\partial y}U(u,w,x,y) + g_4(u,w,x,y)
\end{aligned}
$$

(Step 6)

(Step 2)

$$
\begin{aligned}
\varepsilon_1\dot{u} &= -\frac{\partial}{\partial u}U(u,w,x,y) \\
\varepsilon_2\dot{w} &= -\frac{\partial}{\partial w}U(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) \\
\dot{y} &= z \\
M\dot{z} &= -Dz - \frac{\partial}{\partial y}U(u,w,x,y)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_1\dot{u} &= -\frac{\partial}{\partial u}U(u,w,x,y) \\
\varepsilon_2\dot{w} &= -\frac{\partial}{\partial w}U(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) \\
\dot{y} &= -\frac{\partial}{\partial y}U(u,w,x,y)
\end{aligned}
$$

(Step 5)

(Step 3)

$$
\begin{aligned}
\varepsilon_1\dot{u} &= -\frac{\partial}{\partial u}U(u,w,x,y) \\
\varepsilon_2\dot{w} &= -\frac{\partial}{\partial w}U(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) \\
\dot{y} &= (1-\lambda)z - \lambda\frac{\partial}{\partial y}U(u,w,x,y) \\
M\dot{z} &= -Dz - (1-\lambda)z - \lambda\frac{\partial}{\partial y}U(u,w,x,y)
\end{aligned}
$$

(Step 4)

$$
\begin{aligned}
\varepsilon_1\dot{u} &= -\frac{\partial}{\partial u}U(u,w,x,y) \\
\varepsilon_2\dot{w} &= -\frac{\partial}{\partial w}U(u,w,x,y) \\
T\dot{x} &= -\frac{\partial}{\partial x}U(u,w,x,y) \\
\dot{y} &= -\frac{\partial}{\partial y}U(u,w,x,y) \\
M\dot{z} &= -Dz
\end{aligned}
$$

Fundamentals of BCU Method

Basic Ideas: Given a power system stability model (which admits an energy function), the BCU method computes the controlling u.e.p. of the original model via the controlling u.e.p. of a dimension-reduction system whose controlling u.e.p. can be easily, reliabily computed.

Fundamentals of the BCU Method

Step 1: *define an artificial, dimension-reduction system satisfying the static as well as dynamic properties.*

(***how ?***) *explores special properties of the underlying original model*

Step 2: *find the controlling u.e.p. of the dimension-reduction system*

(***how?***) *explores the special structure of the stability boundary and the energy function of the dimension-reduction system*.

Fundamentals of the BCU Method

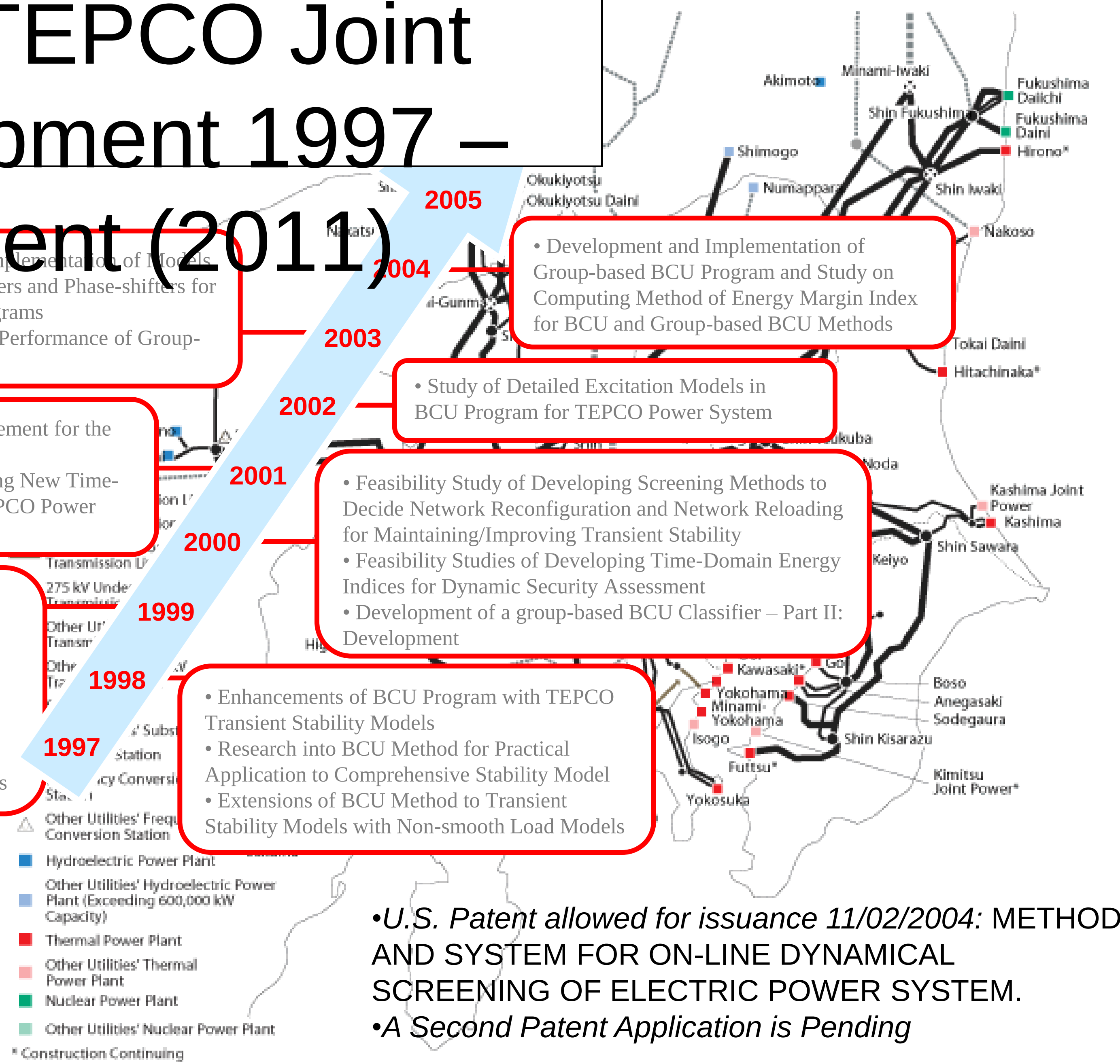
Step 3: *find the controlling u.e.p. of the original system.*

*(***How ?***) relates the controlling u.e.p. of the artificial system to the controlling u.e.p. of the original system with theoretical supports.*

BCU Method

- Explores the special structure of the underlying model so as to define an artificial, reduced-state model which captures all the equilibrium points on the stability boundary of the original model, and then
- Computes the controlling u.e.p. of the original model via computing the controlling u.e.p. of the reduced-state, which can be efficiently computed without

BSI &TEPCO Joint Development 1997 – Present (2011)



1997

- Development of a Group-based BCU Method – Part I: Research
- Development of Improved BCU Classifier for TEPCO Incorporated Analytical System
- Study of the Applicability of Improved BCU Classifiers for Multi-swing Stability Analysis
- Continual Development of BCU Classifiers (Version 2)

1998

- Enhancements of BCU Program with TEPCO Transient Stability Models
- Research into BCU Method for Practical Application to Comprehensive Stability Model
- Extensions of BCU Method to Transient Stability Models with Non-smooth Load Models

1999

2000

- Feasibility Study of Developing Screening Methods to Decide Network Reconfiguration and Network Reloading for Maintaining/Improving Transient Stability
- Feasibility Studies of Developing Time-Domain Energy Indices for Dynamic Security Assessment
- Development of a group-based BCU Classifier – Part II: Development

2001

- Study of the precision improvement for the Group-based BCU Method
- Feasibility Study of Developing New Time-Domain Energy Indices for TEPCO Power System

2002

- Study of Detailed Excitation Models in BCU Program for TEPCO Power System

2003

- Development and Implementation of Models of Generator Controllers and Phase-shifters for BCU and GBCU Programs
- Improvement in the Performance of Group-based BCU Programs

2004

- Development and Implementation of Group-based BCU Program and Study on Computing Method of Energy Margin Index for BCU and Group-based BCU Methods

2005

- *U.S. Patent allowed for issuance 11/02/2004:* METHOD AND SYSTEM FOR ON-LINE DYNAMICAL SCREENING OF ELECTRIC POWER SYSTEM.
- *A Second Patent Application is Pending*

TEPCO-BCU

- TEPCO-BCU is developed under this direction by integrating BCU method, improved BCU classifiers, and BCU-guide time domain method. The evaluation results indicate that TEPCO-BCU works well on several study power systems including a 15,000-bus test system.

LEARN HOW TO IMPLEMENT BCU METHODS FOR FAST DIRECT STABILITY ASSESSMENTS OF ELECTRIC POWER SYSTEMS

Electric power providers around the world rely on stability analysis programs to help ensure uninterrupted service to their customers. These programs are typically based on step-by-step numerical integrations of power system stability models to simulate system dynamic behaviors. Unfortunately, this off-line practice is inadequate to deal with current operating environments. For years, direct methods have held the promise of providing real-time stability assessments; however, these methods have presented several challenges and limitations.

This book addresses these challenges and limitations with the BCU methods developed by author Hsiao-Dong Chiang. To date, BCU methods have been adopted by twelve major utility companies in Asia and North America. In addition, BCU methods are the only direct methods adopted by the Electric Power Research Institute in its latest version of DIRECT 4.0.

Everything you need to take full advantage of BCU methods is provided, including:

- Theoretical foundations of direct methods
- Theoretical foundations of energy functions
- BCU methods and their theoretical foundations
- Group-based BCU method and its applications
- Numerical studies on industrial models and data

Armed with a solid foundation in the underlying theory of direct methods, energy functions, and BCU methods, you'll discover how to efficiently solve complex practical problems in stability analysis. Most chapters begin with an introduction and end with concluding remarks, making it easy for you to implement these tested and proven methods that will help you avoid costly and dangerous power outages.

HSIAO-DONG CHIANG, PhD, a Fellow of IEEE, is Professor of Electrical and Computer Engineering at Cornell University. Dr. Chiang is the Founder of Bigwood Systems, Inc. and Global Optimal Technology, Inc. as well as the Co-founder of Intelicis Corporation. Dr. Chiang's research and development activities range from fundamental theory development to practical system installations. He and his group at Cornell have published more than 300 refereed journal and conference papers. Professor Chiang's research focuses on nonlinear system theory and nonlinear computations and their practical applications to electric circuits, systems, signals, and images. He was awarded ten US patents and four patents from overseas countries.

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Direct Methods for Stability Analysis of Electric Power Systems

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Theoretical Foundation, BCU Methodologies and Applications

HSIAO-DONG CHIANG

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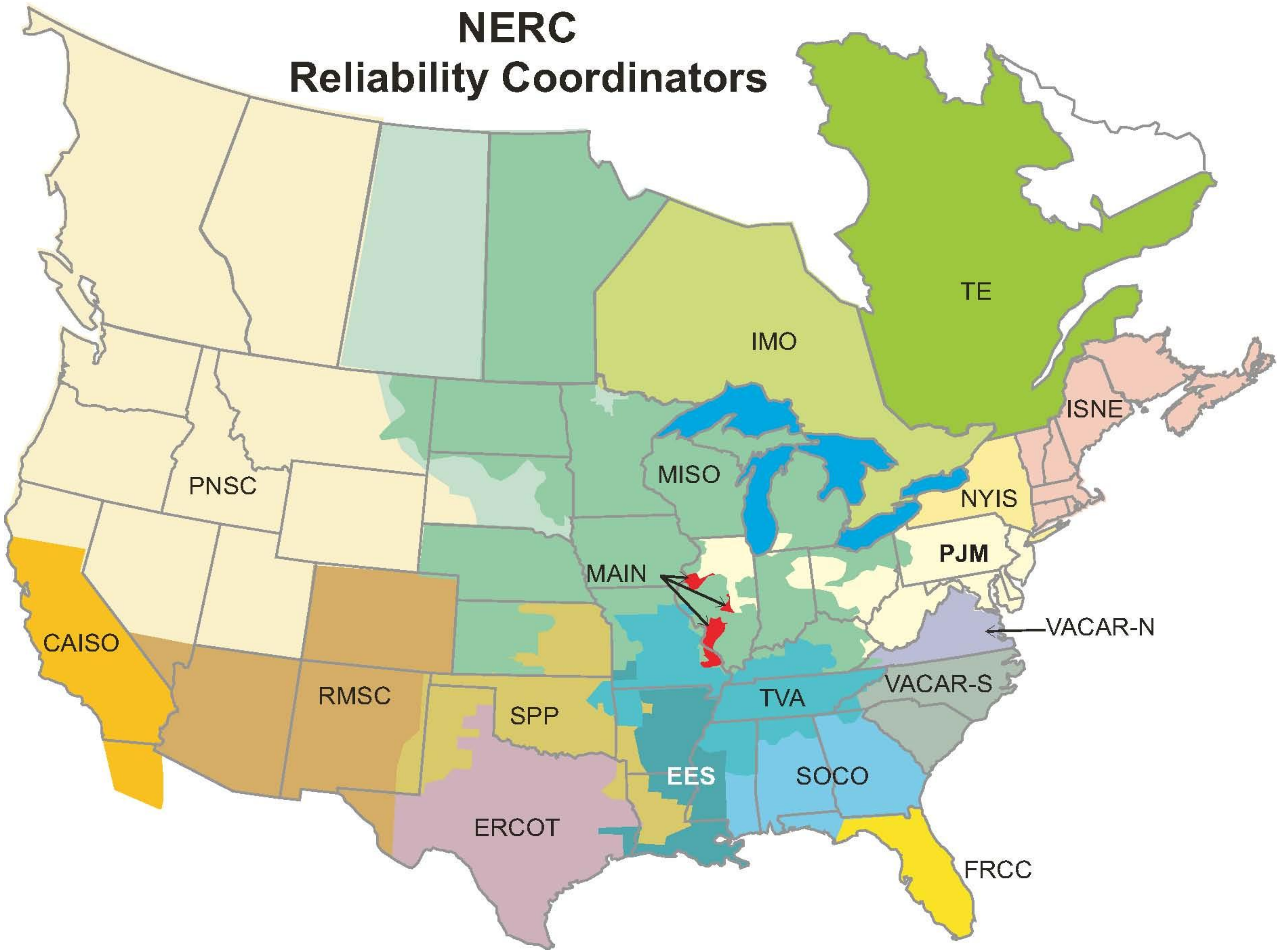
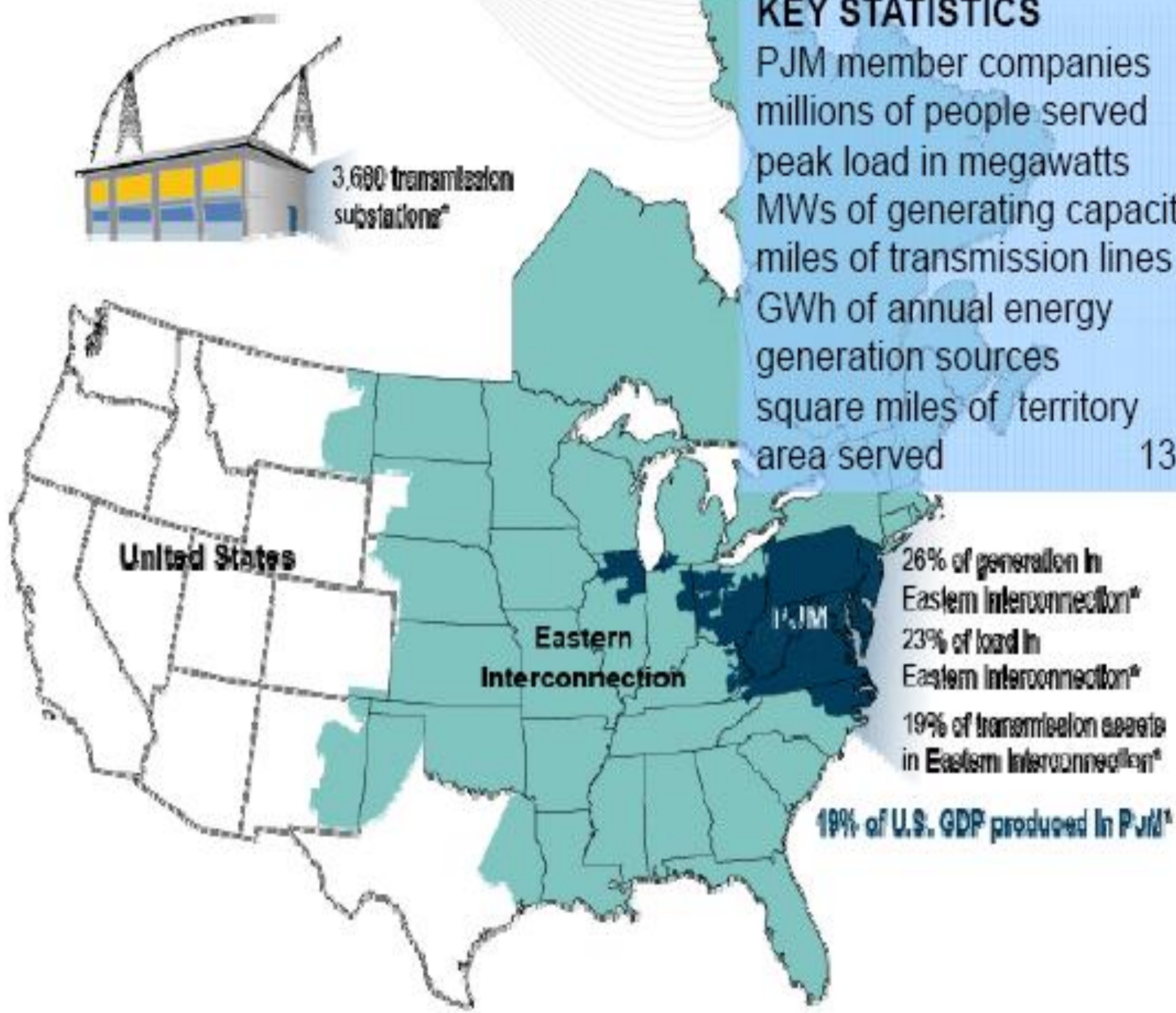
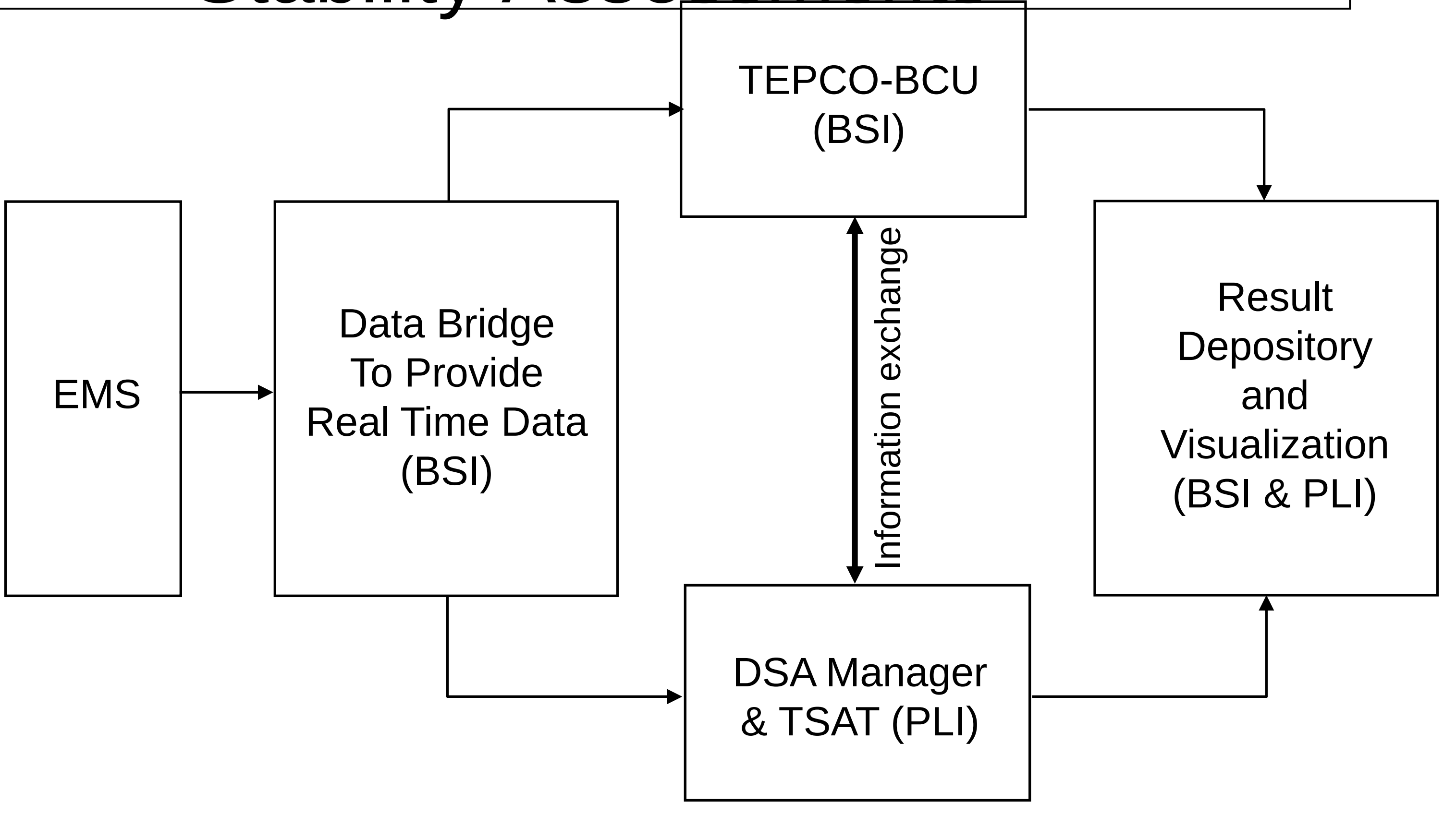

NERC
Reliability Coordinators
TE
IMO
ISNE
MISO
NYIS
PNSC
PJM
MAIN
VACAR-N
CAISO
VACAR-S
TVA
RMSC
SPP
EES
SOCO
ERCOT
FRCC

PJM as Part of the Eastern Interconnection

KEY STATISTICS	
PJM member companies	400+
millions of people served	51
peak load in megawatts	145,000
MWs of generating capacity	165,738
miles of transmission lines	56,070
GWh of annual energy	700,000
generation sources	1,082
square miles of territory	164,260
area served	13 states + DC



High-level Overview
Solution for PJM on-line Transient Stability Assessments



Data Bridge contains common fixed data for both TEPCO-BCU/TSAT and local data required only by TEPCO-BCU or TSAT

PJM Evaluation Results

- (1) **Reliability measure**: TEPCO-BCU consistently gave conservative stability assessments for each contingency during the three-month evaluation time. TEPCO-BCU did not give over-estimated stability assessment for any contingency.

PJM Evaluation Results

- For a total of 5.29 million contingencies, TEPCO-BCU captures all the unstable contingencies.

Table 1.Reliability Measure

Total No. of contingency	Percentage of capturing unstable contingencies
5293691	100%

Speed:

- TEPCO-BCU consumes a total of 717575 CPU seconds. Hence, on average, TEPCO-BCU consumes about 1.3556 second for each contingency.

Table 2. Speed Assessment

Total No. of contingency	Computation Time	Time/per contingency
5293691	717575 seconds	**1.3556 second**

Screening measure:

- Depending on the loading conditions and network topologies, the screening rate ranges from 92% to 99.5%

Table 3. Screening Percentage Assessment

Total No. of contingency	Percentage Range
5293691	92% to 99.5 %

A summary

- The overall performance indicates that TEPCO-BCU is an excellent screening tool These unstable contingencies exhibit first-swing instability as well as multi-swing instability.

Table 4. Overall performance of TEPCO-BCU for on-line dynamic contingency screening

Reliability measure	Screening measurement	Computation speed	on-line computation
100%	**92% to 99.5%**	1.3 second	Yes

Proposed PJM Implementation

20 Processors

3000 Contingencies

TEPCO-BCU

Contingency Ranking 1 to 3000

3.75 to 5 Min.

Remarks

This evaluation study represents the largest practical application of the stability region theory and its estimation of relevant stability region behind the BCU methodology in terms of the size of the study system which is a 14,000-bus power system dynamic model with a total of 5.3 million contingencies.

Control Developments

1. Preventive control (against all insecure contingencies)
2. Enhancement control (to increase load margins for critical contingencies)

Example of Enhancement Control

_Buildin_EAST
Enhancement Control Table

Session: buildin.ses Conting. List: buildin.ses Run Date: 6/9/06 10:00

Enhancement Control

Specific Contingency Name	Steele-Vienna & Ind River- Milford
Margin for Pre-control System (MW)	2710.52002
Margin for Post-control System (MW)	2917.33008
Required Margin Increase (MW)	200.00000
Real Margin Increase (MW)	206.81000

Num	Location		Area	Type	Original Amount	Control Amount	Final Amount	Upper Limit	Lower Limit
1	1927 EDGEMOOR 21926 EDGEMOOR 138.0kV	1	DPL	LTC	1.00000	-0.05000	0.95000	1.05000	0.95000
2	1993 MILFORD 2301992 MILFORD 138.0kV	1	DPL	LTC	1.00000	-0.03750	0.96250	1.50000	0.51000
3	2046 REDLION 5002044 REDLION 230.0kV	1	DPL	LTC	1.03120	-0.00625	1.02495	1.10000	0.90000
4	1923 EDGEMOOR 19.0kV	1	DPL	Gen_Q	1.00180	0.01494	1.01674	1.05072	0.94928

Enhancement control results on Structure-Preserving Models (DAE)

Contingency #	Fault- bus: fault-line	Original CCT	Maximum CCT after enhancement controls	% Improvement
1	7: 7, 6	0.1539	0.5211	238.5965 %
2	59: 59, 72	0.2633	0.4592	74.40182 %
3	112: 112, 69	0.2631	8.3104	3058.647 %
4	91: 91, 75	0.301	0.6271	108.3389 %
5	6: 6, 1	0.1667	4.4899	2593.401 %
6	12: 12, 14	0.3209	0.5936	84.97974 %
7	6: 6, 10	0.2713	4.296	1483.487 %
8	33: 33, 49	0.2007	0.4371	117.7877 %
9	69: 69, 32	0.1408	0.3532	150.8523 %
10	105: 105, 73	0.2021	0.2935	45.22514 %
11	59: 59, 103	0.2442	5.798	2274.283 %
12	66: 66, 8	0.3135	2.4021	666.2201 %

The enhancement control scheme is also effective on SP model

My Belief

solving practical problems efficiently and reliably can be accomplished through

- a thorough understanding of the underlying theory, in conjunction with
- exploring the features of the practical problem under study