CONVENTIONAL PRACTICE FOR TRANSIENT STABILITY ANALYSIS

- **Time Domain Simulation (TDS)** has long been the common practice for transient stability assessment

\[
\dot{x} = f(x, y) \\
0 = g(x, y)
\]
However, there are 3 major problems with Time Domain Simulation:

1. **Accuracy and Speed:** Slower in computation speed ≈ minutes per contingency
   - Can only handle small contingency lists in online operation (e.g. RTO runs 3,000 contingencies for VSA but can only run 70 contingencies for TSA because of the limited time-domain approach)

2. **Cannot differentiate** between critical and non-critical contingencies and provide degree of stability (Energy margin, CCT)

3. **Little (or No effective) control actions** can be determined from Time Domain simulation to mitigate critical contingencies
Bigwood Systems, Inc. (NY, USA) and Tokyo Electric Power Company (Tokyo, Japan) presents:

**TEPCO-BCU for Transient Stability**

- Co-developed the TEPCO-BCU approach with Tokyo Electric Power Company (TEPCO) providing financial resources since 1997 (1997-2008).
- Boundary of Stability-Region-based Controlling Unstable Equilibrium Point Method (BCU method)

The **only direct method** that:
- Has a solid theoretical foundation and practical online applications
- Develops both enhancement control and preventive control.
Benefits

• **Enhance the current practice (supporting the time-domain simulation approach):**

1. **Fast dynamic contingency analysis screening and ranking**
   • > 1 second per contingency
   • Allows for real-time transient stability analysis of a practical contingency list

2. Differentiate between **critical** and **non-critical contingencies, and provide degree of stability** (Energy margin, CCT)

3. Determines effective **control actions** to mitigate critical contingencies
THEORETICAL FOUNDATION

Theoretical foundations of TEPCO-BCU span a wide range of analytical developments of the following:

1. Theory of Stability Regions
2. Theory of Energy Functions
3. Controlling UEP Method: Theoretical function and computation
4. BCU Methods: Methodologies and Theoretical Foundations
5. BCU-Exit Methods: Methodologies and Theoretical Foundations
6. BCU-CUEP Methods: Methodologies and Theoretical Foundations
7. Group-based BCU Methods: Group Properties and Methodologies
Bigwood Systems, Inc. SecureSuite Control Center

SCREEN AND RANK

(1) SCREENING
(2) RANKING
(3) DETAILED ANALYSIS

Methodology:

BCU Classifier

Time-domain Analysis

Function:

BCU Method

(1) SCREENING
(2) RANKING
(3) DETAILED ANALYSIS

20 contingencies remain for Time-Domain simulation vs. initial 3000 contingencies
• Early termination scheme (runs for 3 second for each contingency, accuracy??)
• Large integration step-size (in order to speed up however, accuracy??)
• Operator/engineer screening
TEPCO-BCU method for fast screening, ranking, and detailed analysis
- Time-Domain Simulation
Available Power Transfer capability at key flow gates and corresponding limiting contingencies
Insecure and critical contingencies provided
On-line control recommendation engine
PJM EVALUATION

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

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\[ \begin{align*}
\dot{x}_1 &= f_1(x, y) \\
\dot{x}_2 &= f_2(x, y) \\
\vdots \\
\dot{x}_{15,000} &= f_{15,000}(x, y) \\
0 &= g_1(x, y) \\
0 &= g_2(x, y) \\
\vdots \\
0 &= g_{40,000}(x, y)
\end{align*} \]
High-level Overview Solution for PJM online Transient Stability Assessments

Data Bridge contains common fixed data for both TEPCO-BCU/TSAT and local data required only by TEPCO-BCU or TSAT
SPEED (PJM’s goal: 1.5 second)

- For a total of 5.29 million contingencies, TEPCO-BCU consumed a total of 717,575 CPU seconds.
- Computation time: **1.3556 second for each contingency** (average) on a regular desktop computer

Table 2. Speed Assessment

<table>
<thead>
<tr>
<th>Total No. of contingency</th>
<th>Computation Time</th>
<th>Time/per contingency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5293691</td>
<td>717575 seconds</td>
<td><strong>1.3556 second</strong></td>
</tr>
</tbody>
</table>
SCREENING MEASURE

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

• In other words, only 0.5% to 8% of the contingency list will have to go through further analysis

Table 3. Screening Percentage Assessment

<table>
<thead>
<tr>
<th>Total No. of contingency</th>
<th>Percentage Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>5293691</td>
<td>92% to 99.5 %</td>
</tr>
</tbody>
</table>
RELIABILITY MEASURE

• PJM ran TEPCO-BCU over the span of a full year
• Ran on a total of 5.29 million contingencies
• RESULTS: TEPCO-BCU captures all the unstable contingencies (100%).

Table 1. Reliability Measure

<table>
<thead>
<tr>
<th>Total No. of contingency</th>
<th>Percentage of capturing unstable contingencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>5293691</td>
<td>100%</td>
</tr>
</tbody>
</table>
• Published Results of PJM Evaluation over one-year on a 16,000-bus Network

<table>
<thead>
<tr>
<th>Contingencies</th>
<th>Reliability</th>
<th>Speed</th>
<th>Screening</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of contingencies</td>
<td>100%</td>
<td>1.35 seconds</td>
<td>Percentage of stable contingencies screened out</td>
<td>Online</td>
</tr>
<tr>
<td>5,293,691</td>
<td></td>
<td></td>
<td>92% to 99.5%</td>
<td></td>
</tr>
</tbody>
</table>
If the fault is cleared before the fault-on trajectory reaches the exit point, say at $x(t_{cl})$, then the fault-clearing point must lie inside the stability region of the post-fault SEP. Hence, the post-fault trajectory starting from the fault-clearing point must converge to the post-fault SEP $x_s$. 
THE CONTROLLING UEP METHOD

- **Determination of the Critical Energy**
  
  **Step 1.1.** Find the controlling UEP, $X_{co}$, for a given fault-on trajectory, $X_f(t)$.

  **Step 1.2.** The critical energy, $v_{cr}$, is the value of the energy function $V(\cdot)$ at the controlling UEP; that is,

  $$ v_{cr} = V(X_{co}) $$

- **Direct Stability Assessment**
  
  **Step 2.1.** Calculate the value of the energy function $V(\cdot)$ at the time of fault clearance (say, at time $t_{cl}$):

  $$ v_f = V(X_f(t_{cl})) $$

  **Step 2.2.** If $v_f < v_{cr}$, then the post-fault system is stable. Otherwise, it may be unstable.

The controlling UEP method approximates the relevant stability boundary, the stable manifold of the controlling UEP, by the constant energy surface, passing through the controlling UEP.
Consider a general postfault system that has an energy function $V(\cdot): R^n \to R$. Let $X_{co}$ be an equilibrium point on the stability boundary $\partial A(X_s)$ of a SEP $X_s$ of this system. Then, the following results hold:

- The connected constant energy surface $\partial S(V(X_{co}))$ intersects with the stable manifold $W^s(X_{co})$ only at point $X_{co}$; moreover, the set $S(V(X_{co}))$ has an empty intersection with the stable manifold $W^s(X_{co})$.

- Any connected path starting from a point $P \in \{S(V(X_{co})) \cap A(X_s)\}$ and intersecting with $W^s(X_{co})$ must also intersect with $\partial S(V(X_{co}))$.
Consider a general post-fault system that has an energy function $V(\cdot): \mathbb{R}^n \rightarrow \mathbb{R}$. Let $X_{co}$ be an equilibrium point on the stability boundary $\partial A(X_s)$ of a SEP $X_s$ of this system.

Then, the following results hold:

- If $X^u$ is a UEP and $V(X^u) > V(X_{co})$, then $S(V(X^u)) \cap W^s(X_{co}) \neq \phi$
- If $X^u$ is a UEP and $V(X^u) < V(X_{co})$, then $S(V(X^u)) \cap W^s(X_{co}) = \phi$
- If $X$ is a state vector on the stability boundary but is not the closest UEP, then the constant energy surface passing through $X$ has a nonempty intersection with the complement of the closure of the stability region; that is, $\partial S(V(\bar{X})) \cap (\bar{A}(X_s))^c \neq \phi$
TSA Control produces actionable control recommendations to mitigate both insecure and critical contingencies

- Preventive Control (Insecure Contingencies)
- Enhancement Control (Critical Contingencies)
- Controls include:
  - Real power rescheduling
  - Phase-shifter adjustments
  - Load shedding

Minimum COST
Minimum number of control ADJUSTMENTS
Minimum load shedding
Contingency Number 17 is assessed as unstable (see time-domain simulation)

- At time 0”, 3-phase short circuit at PEACHBOT 500KV bus.
- The fault is cleared after 5 cycle by tripping the transformer PEACHBOT1KV 1-P
CONTROL USE CASE

• Implement control and run with a targeted Critical Clearing Time (CCT) at 0.1 seconds (or a target available power transfer capability)
• Control adjustment recommendations increase CCT from 0.0 seconds to 0.1 seconds

Increase outputs of top-ranked 9 generators and decrease outputs of bottom-ranked 3 generators
CONTROL RESULTS

Before

After
Theoretical Basis for Control:
Enlarge relevant stability region
2018 TEPCO-BCU Installation

Bigwood Systems will be installing production-grade TEPCO-BCU packages at:

• #4 largest transmission utility in the US
• A large transmission owner in the Midwest
FOR MORE INFO

Hsiao-Dong Chiang, Luís F. C. Alberto

Cambridge University Press, 2015
THANK YOU!
Please contact us for more information

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