Measurement-based Voltage Stability Assessment for Load Areas

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Content

- Background on measurement-based voltage stability assessment (VSA)

- MBVSA Methods:
  - Using a Thevenin (1+1 buses)equivalent
  - Using an N+1 buses equivalent

- Hybrid VSA approach and demonstrations

Simulation/model based Voltage Stability Assessment

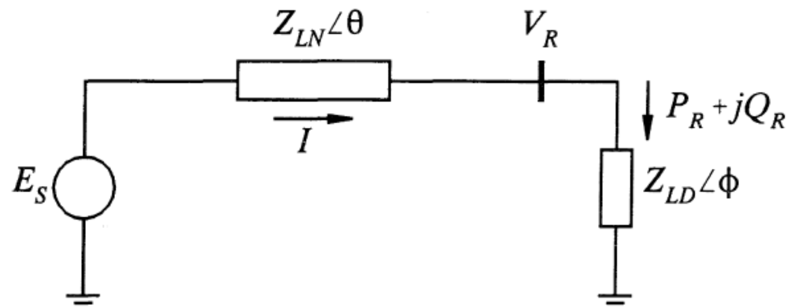
- Strengths
  - Look-ahead capabilities in stability prediction and control for “what-if” scenarios
  - Lots of commercial software tools.

- Limitations in Online Application
  - **Model-dependent**: the accuracy depends on how accurate the power system models is
  - **Contingency-dependent**: only applied to selected critical contingencies
  - **Requiring a steady-state powerflow solution**: the state estimator may fail to converge under stressed operating conditions.
  - **Computationally intensive**: especially for dynamic simulations

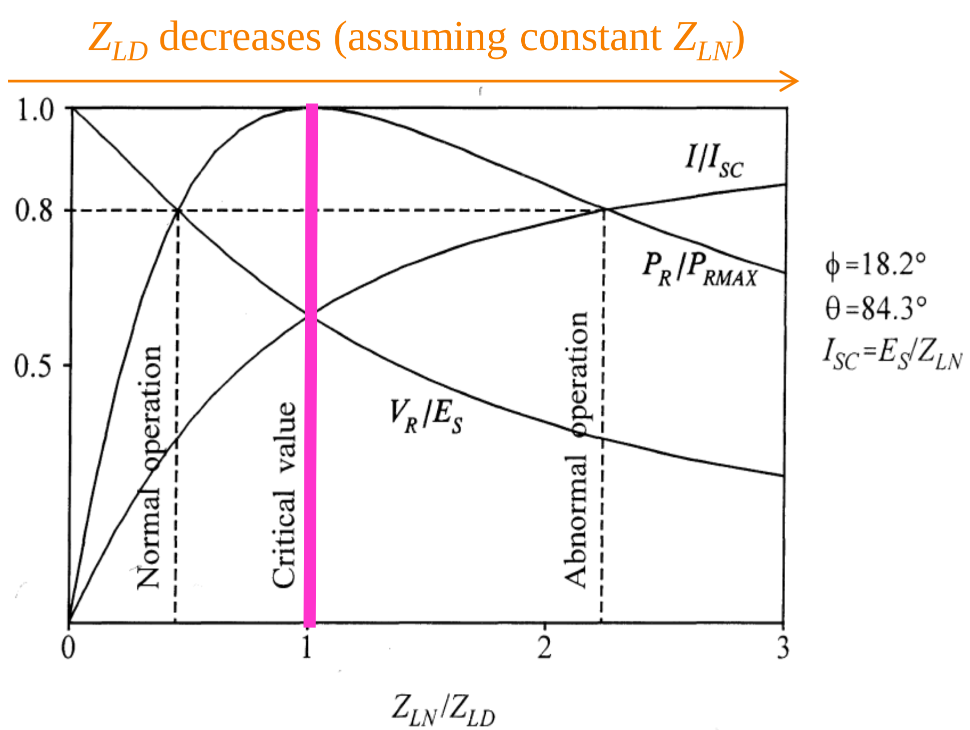
- An alternative approach is Measurement-based VSA

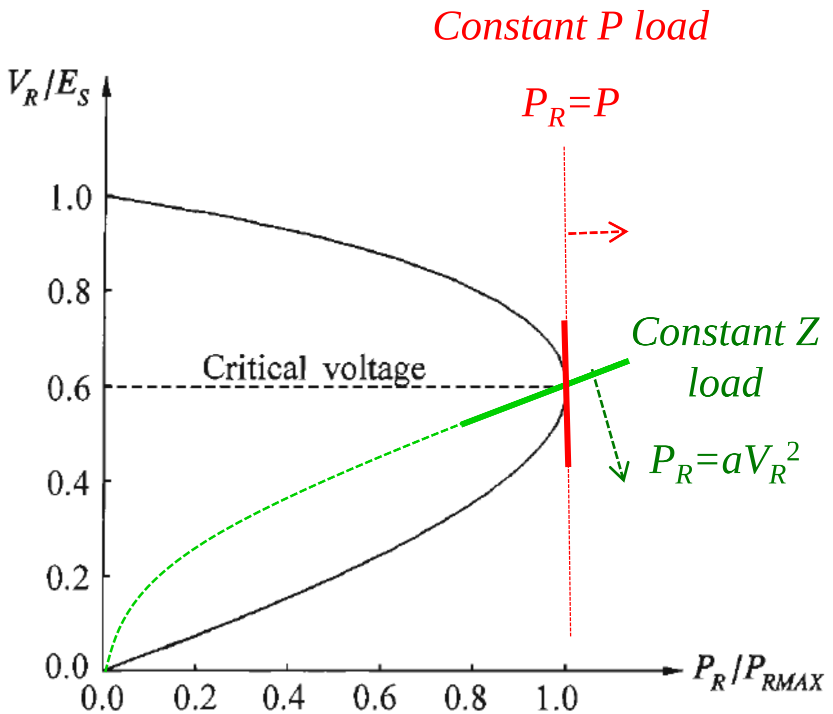
A simple radial system

- How does V_R change as P_R increases? (example from Kundur's book)



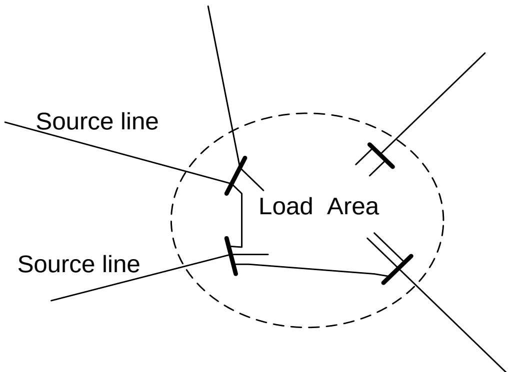
$P_R = P_{RMAX}$ when $Z_{LN} = Z_{LD}$





Methods on Measurement-based VSA

For a load pocket area

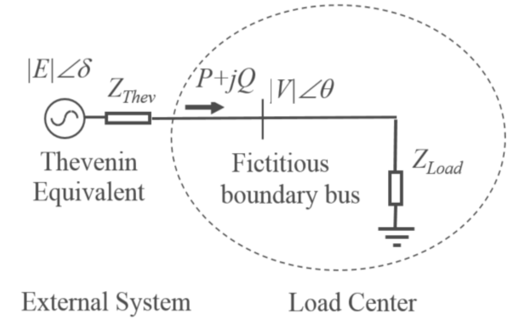


Measuring synchronized voltages V_i and currents I_i at all boundary buses

Thevenin equivalent (1+1 buses) [1]-[5]

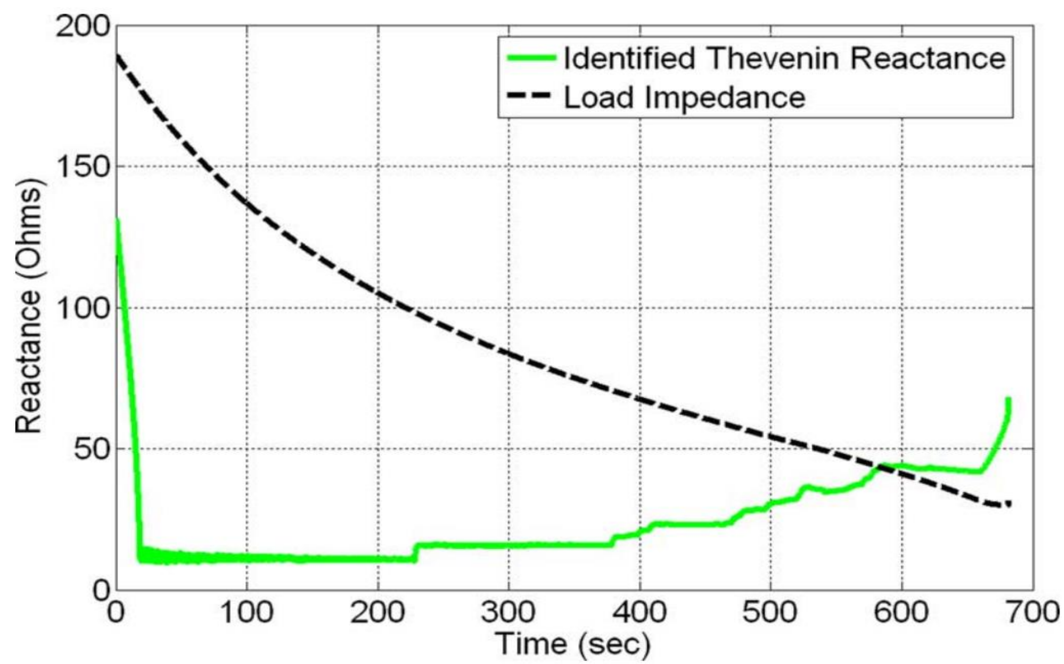
1. Merge all lines to be one

$$V = \sum_{i=1}^{N} V_i I_i^* \Big/ \sum_{i=1}^{N} I_i^* \ , \quad S = P + jQ = \sum_{i=1}^{N} V_i I_i^*$$

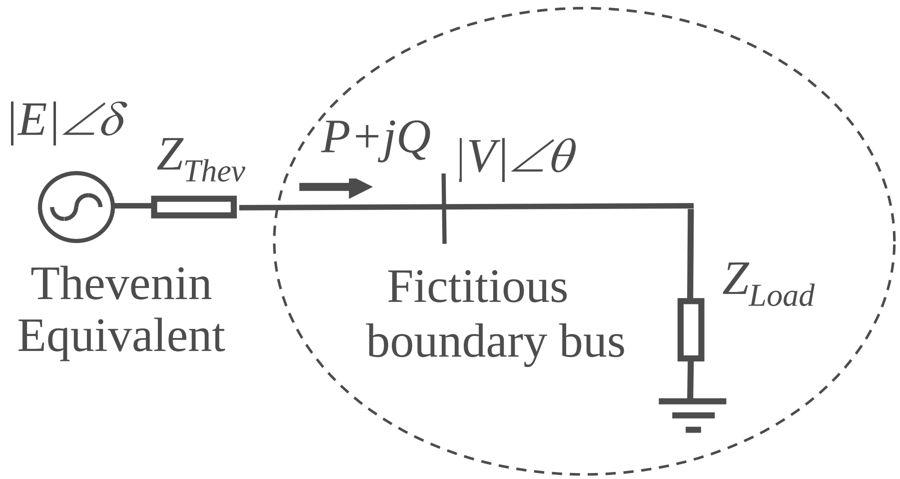


2. Estimate E and Z_{Thev} by, e.g., least squares

3. Transfer limit P_{max} is met when $|Z_{Load}| = |Z_{Thev}|$



Using a Thevenin equivalent [1]-[5]



External System   Load Center

$$V = \sum_{i=1}^{N} V_i I_i^* \Big/ \sum_{i=1}^{N} I_i^*, \quad S = P + jQ = \sum_{i=1}^{N} V_i I_i^*$$

$$I = \frac{E - V}{Z_{Thev}} = \left(\frac{S}{V}\right)^* = \left(\frac{P + jQ}{|V| \angle \theta}\right)^*$$

To be solved by, e.g., a least square approach

Phasor measurements

Measure **voltage and current waveforms** at the boundary buses (key substations) of the load center using synchrophasors

↓

Calculate $V\angle\theta$, P and Q at the fictitious bus using **voltage and current waveforms**

↓

Calculate the external system's Thevenin Equivalent parameters:
$|V|\angle\theta$, P, and Q → $|E|\angle\delta$ and Z_{Thev}

↓

Calculate power transfer limits:
$|E|\angle\delta$ and Z_{Thev} → P_{max} and Q_{max}

↓

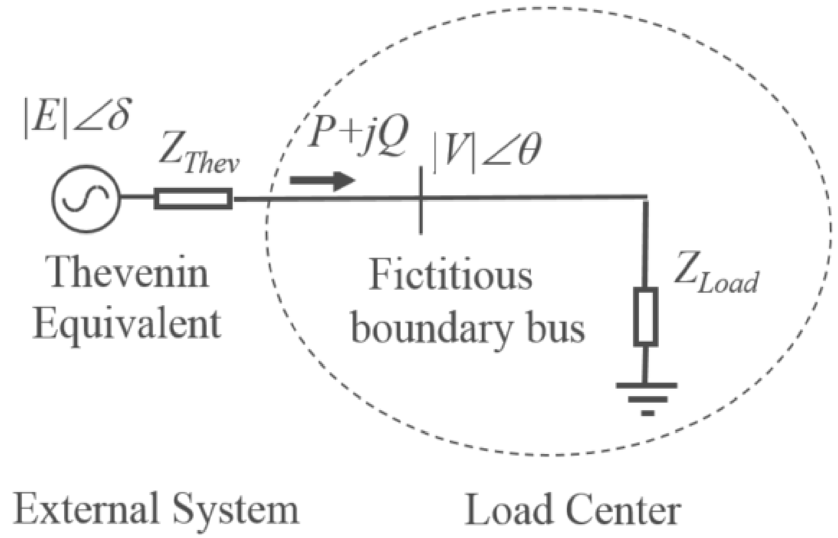
Calculate voltage stability margin:
$P_{margin} = P_{max} - P$ and $Q_{margin} = | Q_{max} - Q |$

Thevenin (1+1-bus) equivalent based method [1]-[3]

$$\begin{cases} P = |EVY|\cos(\theta-\delta-\beta) - |V|^2|Y|\cos\beta \\ Q = |EVY|\sin(\theta-\delta-\beta) + |V|^2|Y|\sin\beta \end{cases}$$

where $|Y|\angle\beta = 1/Z_{Thev}$

- Assume constant power fact ϕ



$$V_{\text{critical}} = \frac{|E|}{\sqrt{2[1+\cos(\phi+\beta)]}}$$

$$P_{\max} \overset{\Delta}{=} P|_{V=V_{critical}} = \frac{|E|^2 |Y| \cos\phi}{2[1+\cos(\phi+\beta)]}$$

$$Q_{\max} \overset{\Delta}{=} Q|_{V=V_{critical}} = \frac{|E|^2 |Y| \sin\phi}{2[1+\cos(\phi+\beta)]}$$

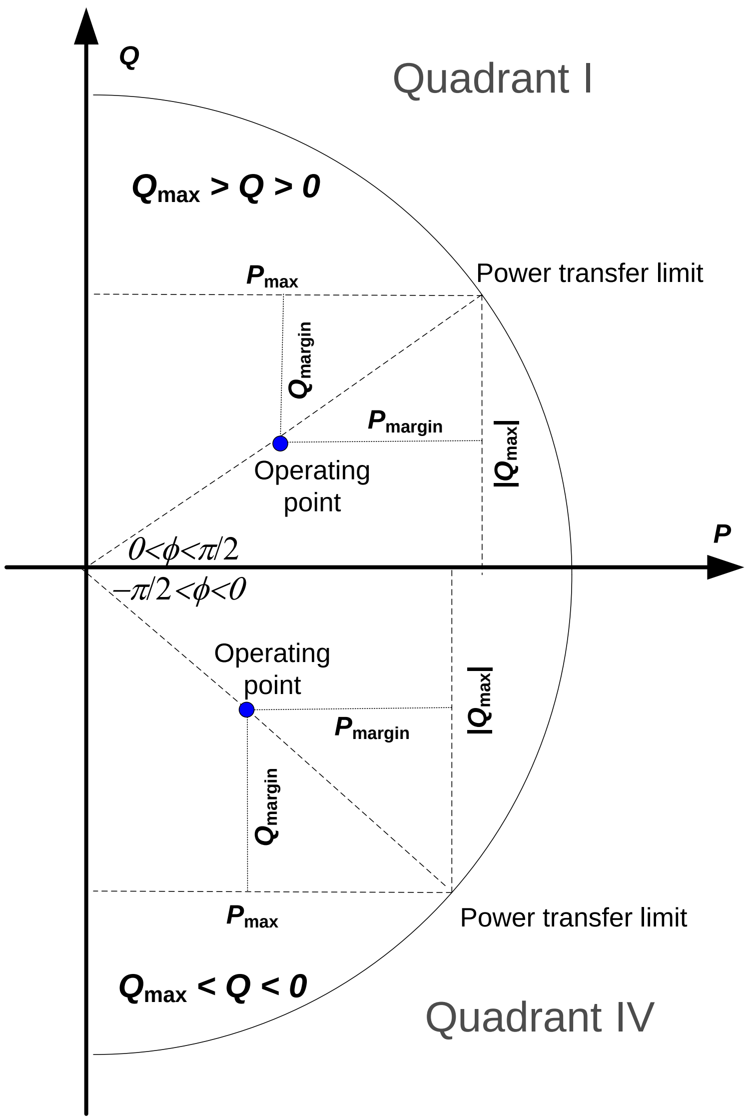
$\beta = -90^o$, $\phi = 0^o$

($Z_{Thev} = jX_{Thev}$, PF=1)

$$V_{\text{critical}} = \frac{|E|}{\sqrt{2}}$$

$$P_{\max} = \frac{|E|^2}{2X_{Thev}}$$

Voltage Stability Margin Indices



In terms of active power:

$$P_{margin} = P_{max} - P$$

In terms of reactive power:

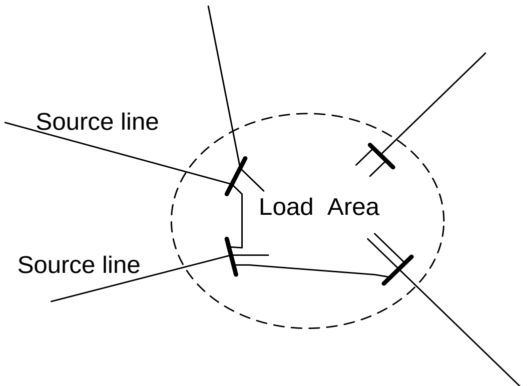
$$Q_{margin} = | Q_{max} - Q |$$

In terms of apparent power:

$$S_{margin} = S_{max} - | S | = \sqrt{P_{max}^2 + Q_{max}^2} - | S |$$

Methods on Measurement-based VSA

For a load pocket area



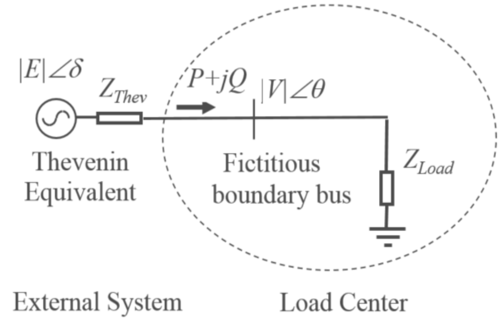
Measuring synchronized voltages V_i and currents I_i at all boundary buses

For a wider load area

Thevenin equivalent (1+1 buses) [1]-[5]

1. Merge all lines to be one

$$V = \sum_{i=1}^{N} V_i I_i^* \Big/ \sum_{i=1}^{N} I_i^* \;, \quad S = P + jQ = \sum_{i=1}^{N} V_i I_i^*$$



2. Estimate E and Z_{Thev} by, e.g., least squares

3. Transfer limit P_{max} is met when $|Z_{Load}| = |Z_{Thev}|$

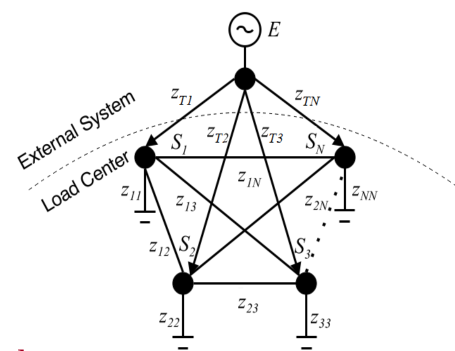
Multi-terminal network equivalent (N+1 buses) [6]-[10]

1. Consider equivalents with details on different transfer paths

$$\mathbf{I} = \mathbf{VY} = E\mathbf{Y_T} - diag(\mathbf{Y_T})\mathbf{V}$$

$$\mathbf{V} = E(\mathbf{Y} + diag(\mathbf{Y_T}))^{-1}\mathbf{Y_T}$$

$$\mathbf{P} = [P_1 \quad P_2 \quad \cdots \quad P_N]^T = \mathrm{Re}\left(diag(\mathbf{I}^*) \times \mathbf{V}\right)$$

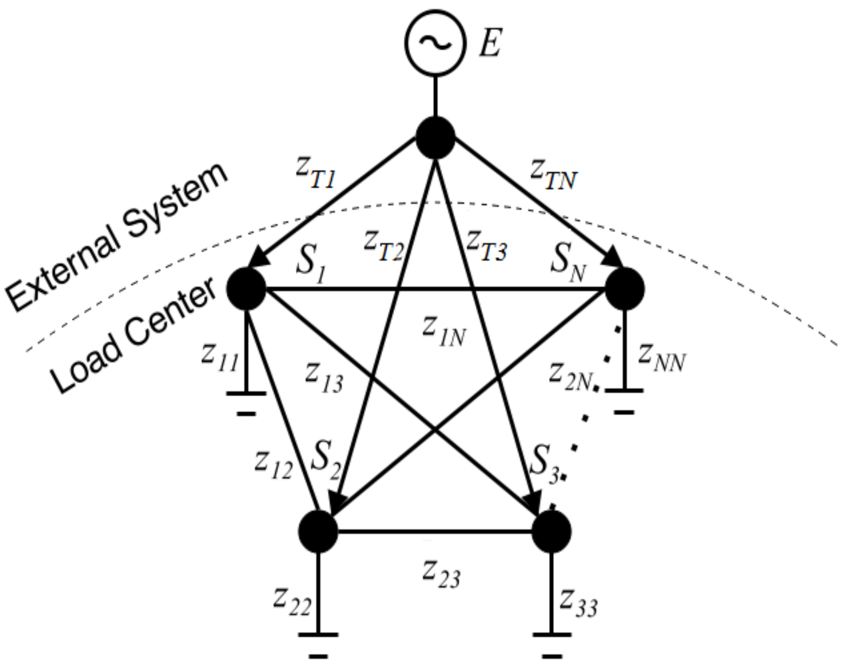


2. Estimate all equivalent E and Z parameters by optimization methods

3. Analytically solve the limit for each transfer path

$$P_i = P_{i,j}^{\mathrm{Max}} \quad \text{when} \quad \frac{\partial P_i(|y_{11}|, \cdots, |y_{NN}|)}{\partial |y_{jj}|} = 0$$

Using an N+1 buses Equivalent [6]-[10]



Derive the transfer limit of tie line *i* with respect to a load change near bus *j* as a function of all parameters of the equivalent

$$P_i = P_{i,j}^{\text{Max}} \quad \text{when} \quad \frac{\partial P_i(|y_{11}|,\cdots,|y_{NN}|)}{\partial |y_{jj}|} = 0$$

Offline place PMUs on boundary buses of the load area for voltage stability monitoring

Measure real-time voltage and current phasors

Estimate all parameters of the equivalent using phasor data over a sliding time window

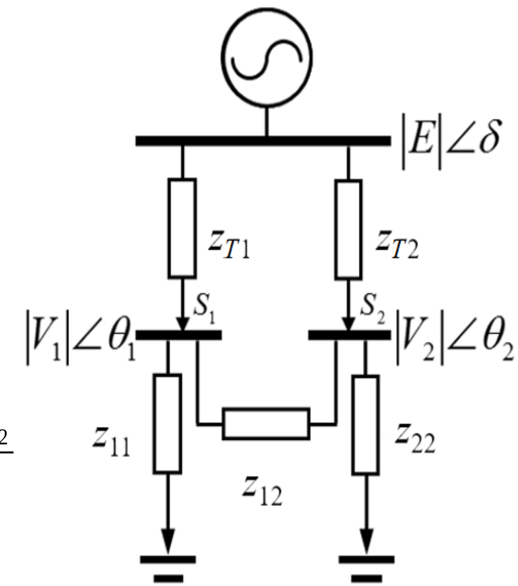
Calculate transfer limits of all tie lines by analytical expressions on $P_{i,j}^{\text{Max}}$

Real-time limit and margin information for operators

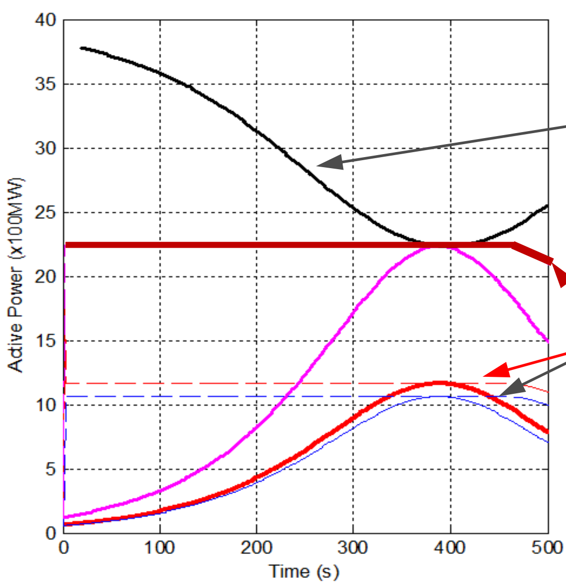
3 (2+1) -bus system

- If z_{T1}=j/b_{T1}, z_{T2}=j/b_{T2},z_{12}=j/b_{12}, z_{11}=1/g_{11}, z_{22}=1/g_{22}

$$P_{1,1}^{\mathrm{Max}} = \frac{|E|^2 b_{T1}}{2} \cdot \frac{\sqrt{[(b_{T2}+b_{12})^2+g_{22}^2]\cdot\{b_{T1}^2[(b_{T2}+b_{12})^2+g_{22}^2]+b_{T2}b_{12}(2b_{T1}b_{T2}+2b_{T1}b_{12}+b_{T2}b_{12})\}}+b_{T2}b_{12}g_{22}}{b_{T1}[(b_{T2}+b_{12})^2+g_{22}^2]+b_{12}(b_{T2}^2+b_{T2}b_{12}+g_{22}^2)}$$



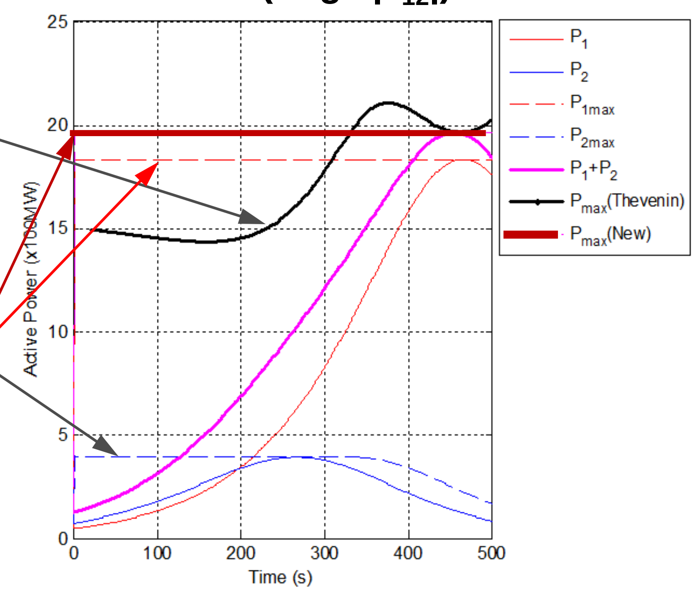
Strong coupling between boundary buses (small |z_{12}|)



From Thevenin equivalent:
- Inaccurate due to merging all tie lines

From the N+1 buses equivalent:
- Accurate total limit
- Accurate limit for each line

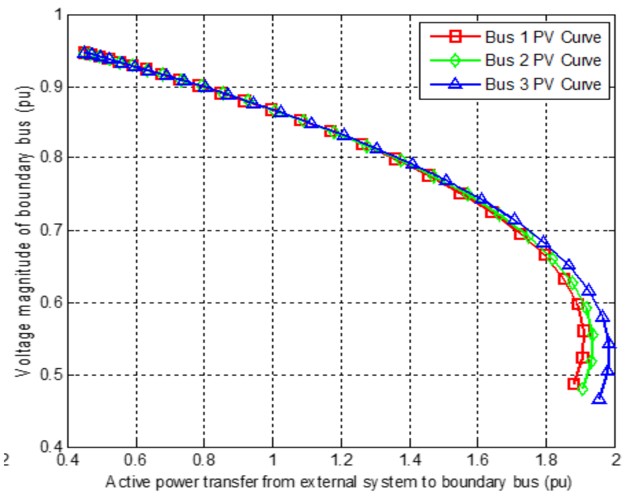
Weak coupling between boundary buses (large |z_{12}|)

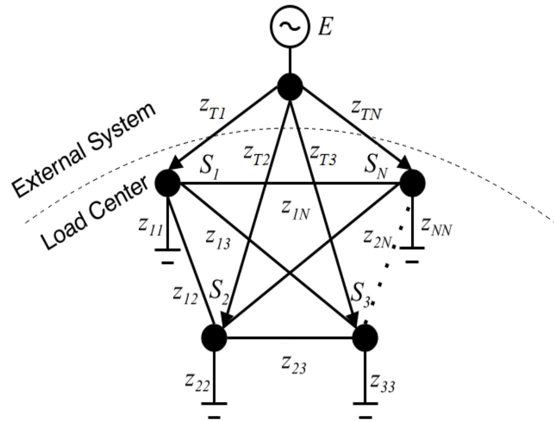


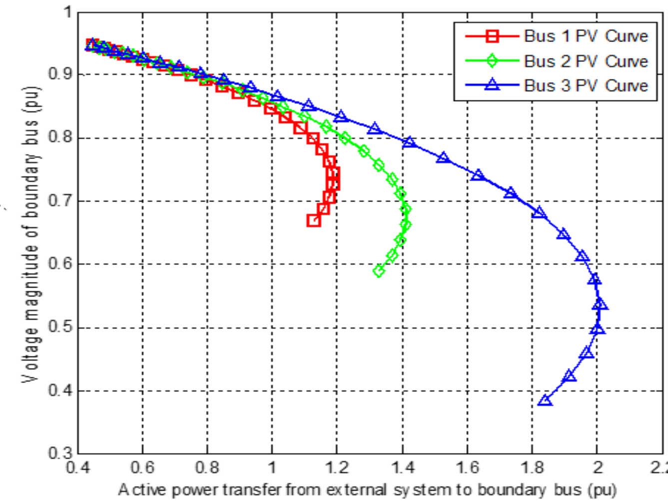
Consider a 4 (3+1) -bus system

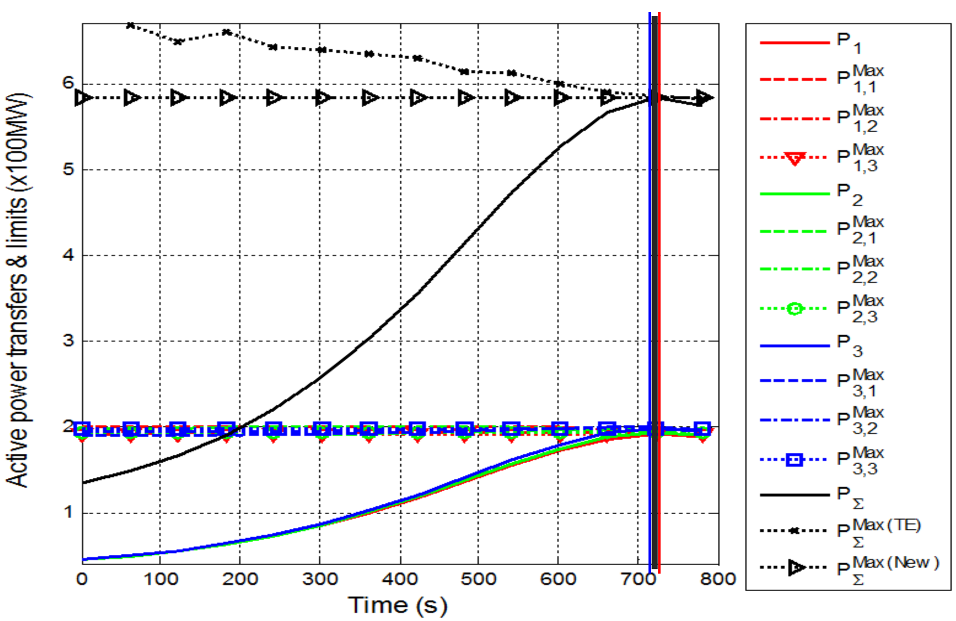
Strong coupling

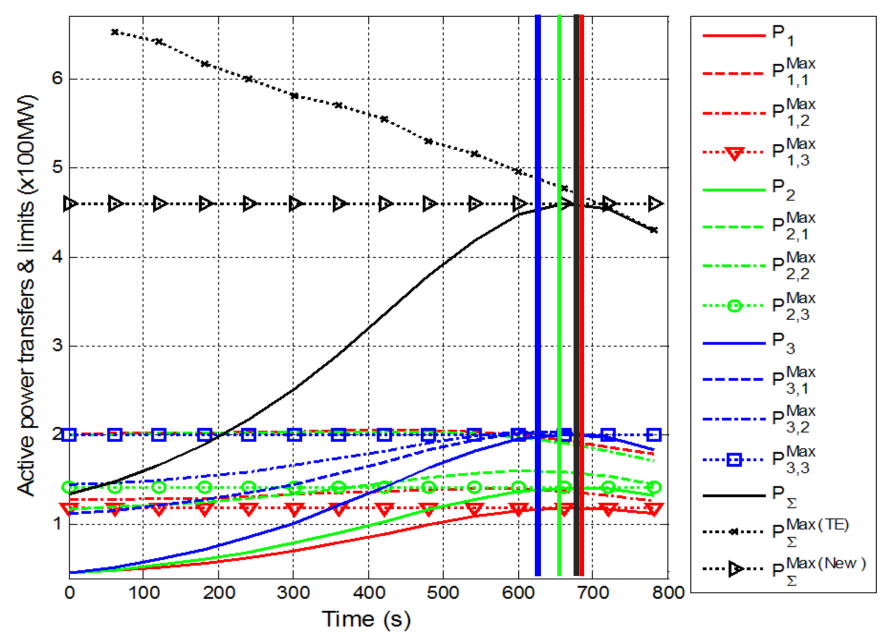
Weak coupling







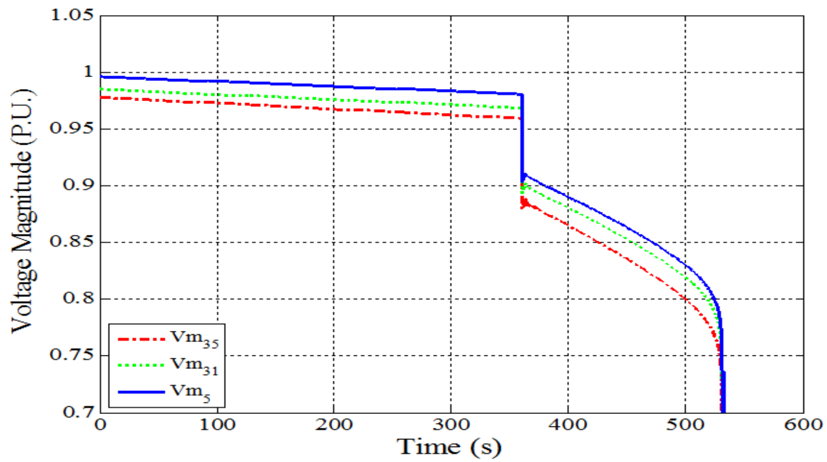


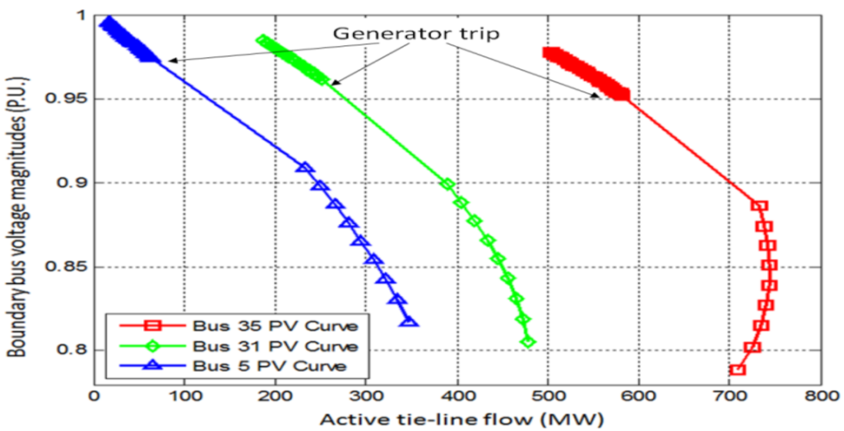


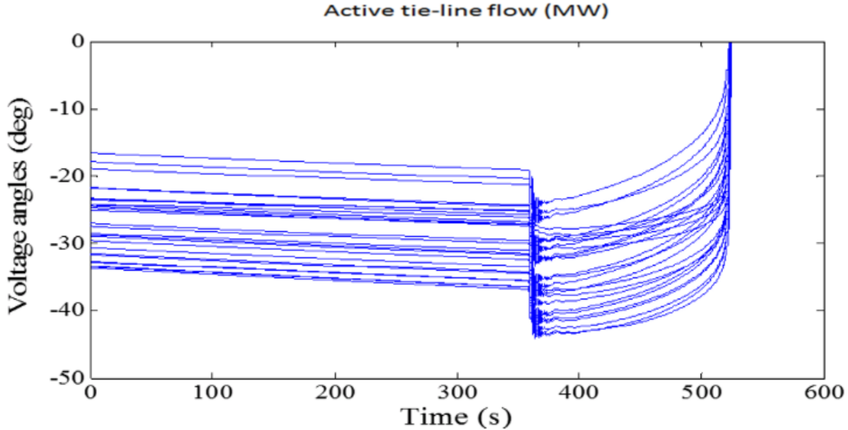
For a load area fed by multiple tie lines

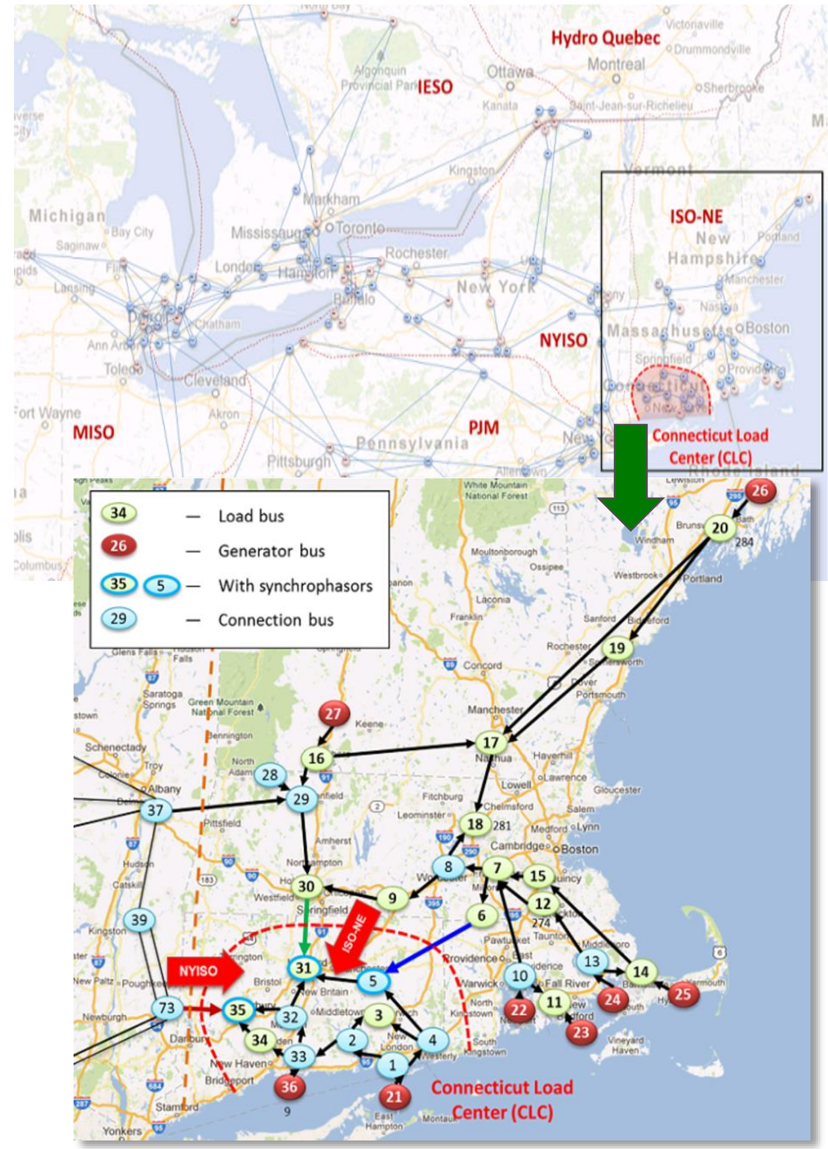
- Using a Thevenin equivalent
  - Only estimates the total transfer limit of all tie lines
- Using an N+1-bus equivalent
  - Estimates the transfer limit for each line and can better detect and control voltage instability if any line hits its limit earlier than the others
  - Gives the limits of each line with respect to different scenarios of load changes
  - More accurate in estimating the total transfer limit by considering the coupling among boundary buses

Demonstration on the NPCC 140-bus System (Case 1)





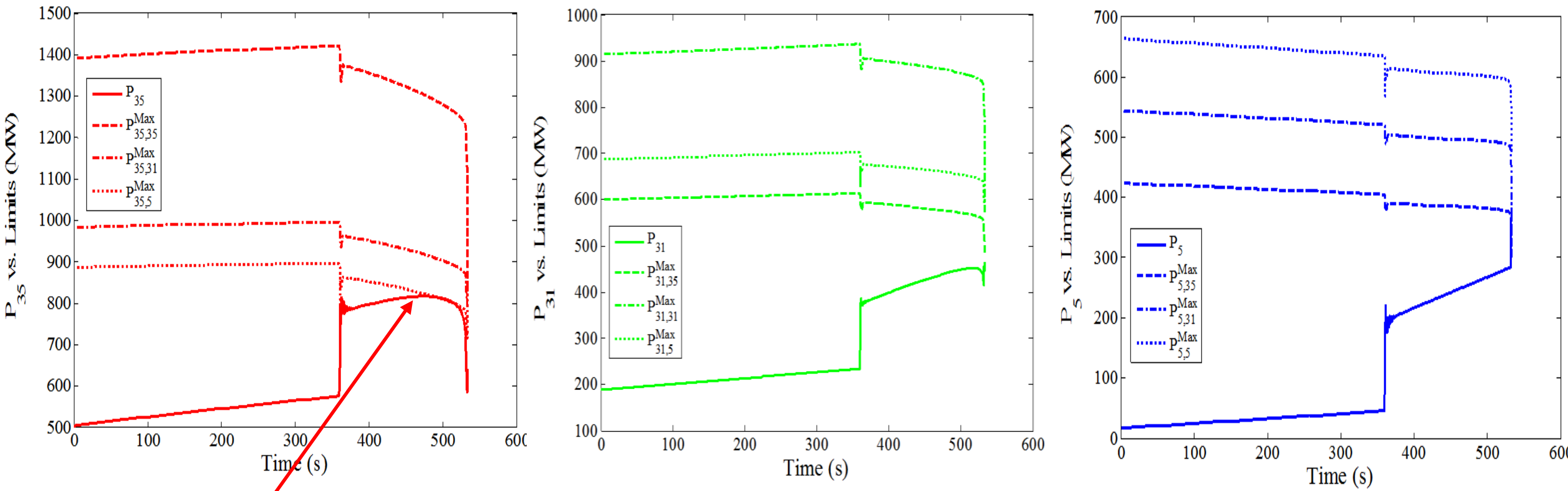




Generator 21 outage followed by load increase leading to voltage collapse

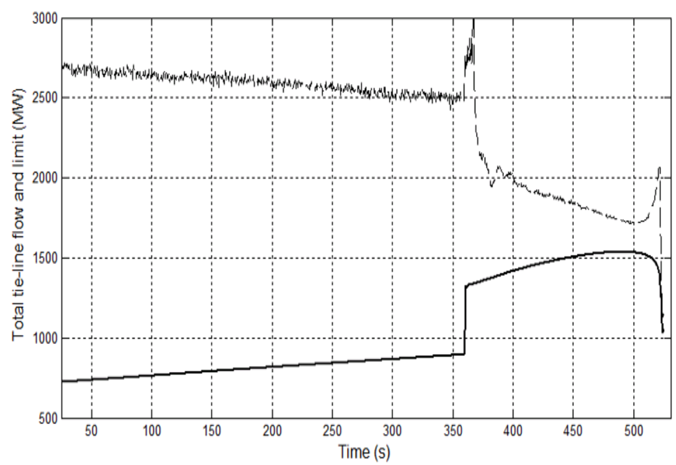
Comparison of two MB-VSA methods (Case 1)

3+1-bus equivalent



Zero margin at t=473s

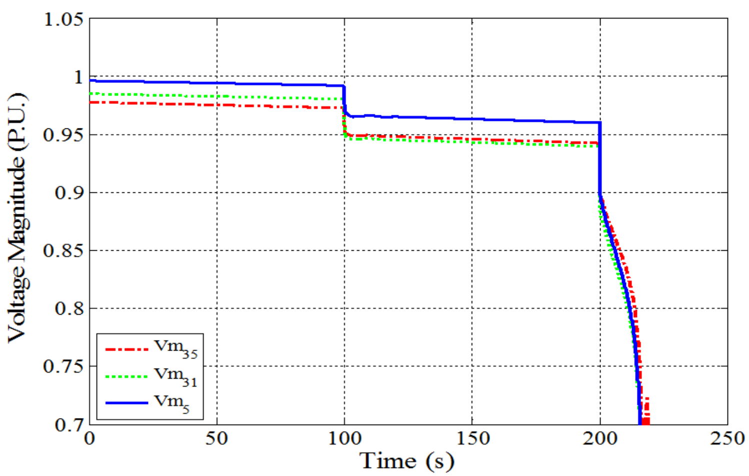
Thevenin equivalent

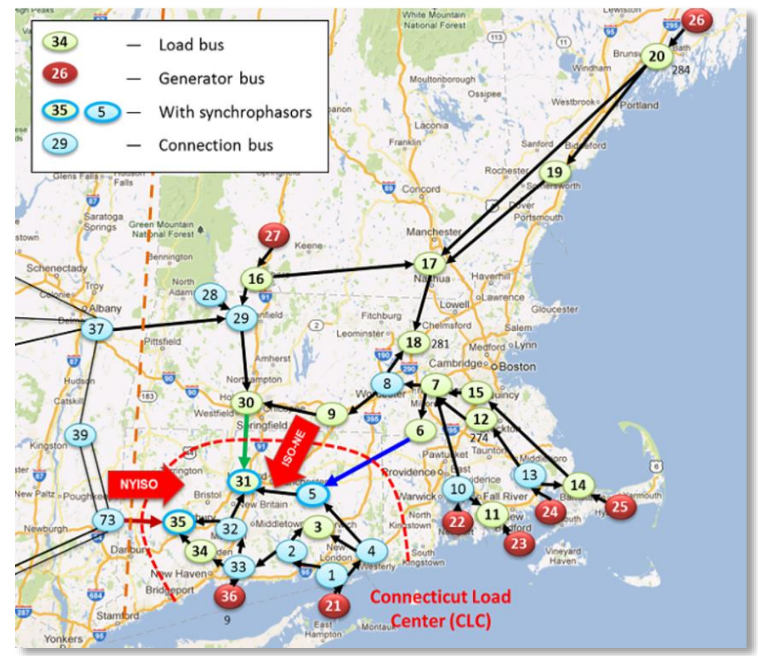


Positive margin when voltage collapse happens.

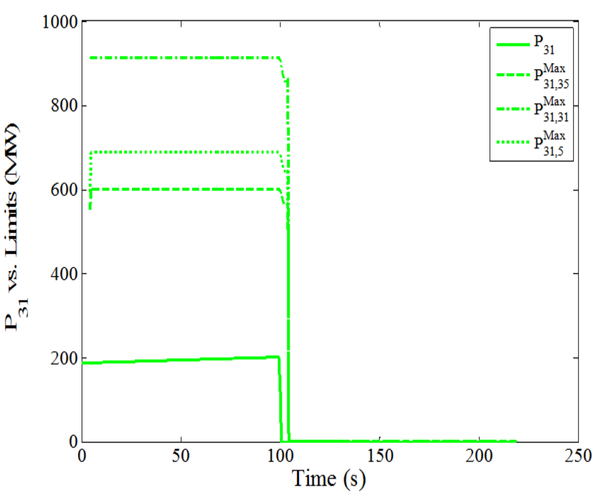
Voltage collapse caused by an N-2 contingency (Case 2)

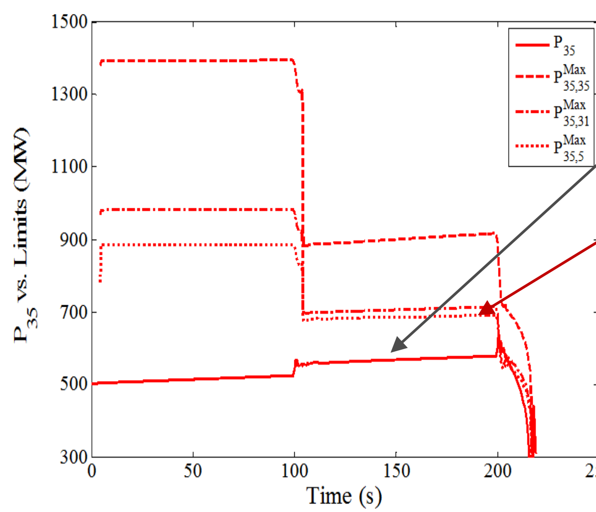
- Trip tie line 31-30 at 110s and then tie line 6-5 at 200s
- Before the 2^{nd} tie-line is tripped, the total power into the CLC area is 733MW (>677 MW, the limit of tie-line 73-35), so the 2^{nd} tie-line trip causes zero margin on tie-line 73-35 and the following voltage collapse.

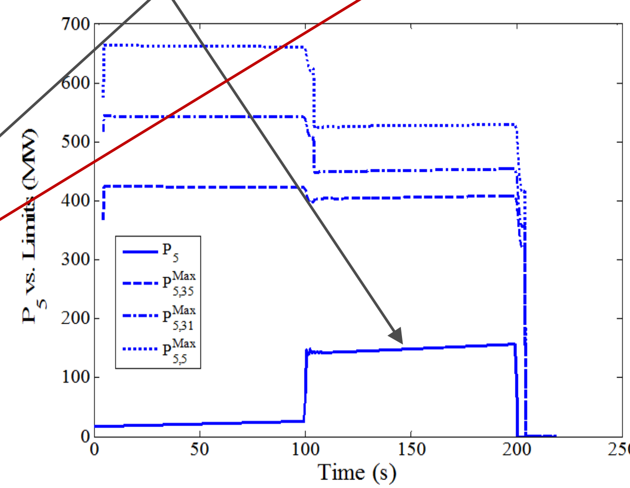




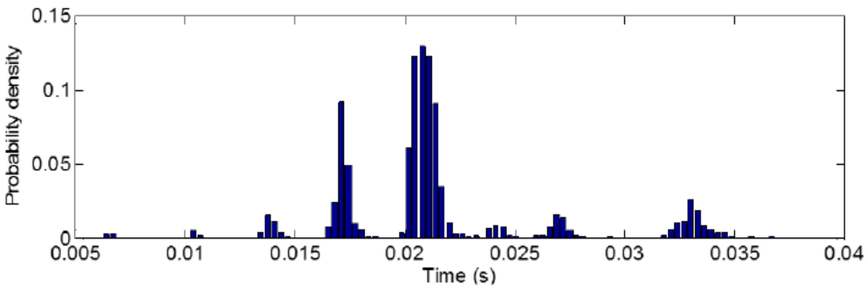
After the 2^{nd} trip, P_{35} = 733MW > Limit 667MW



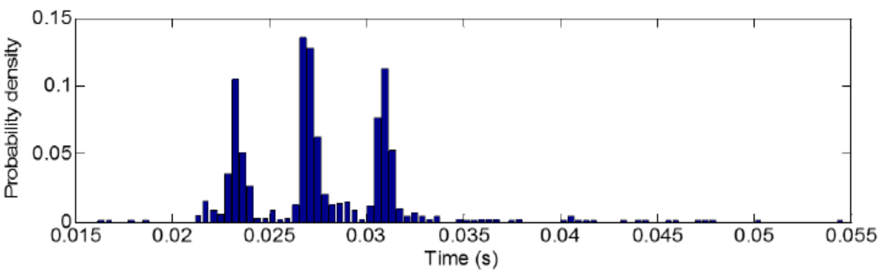




More performance test results

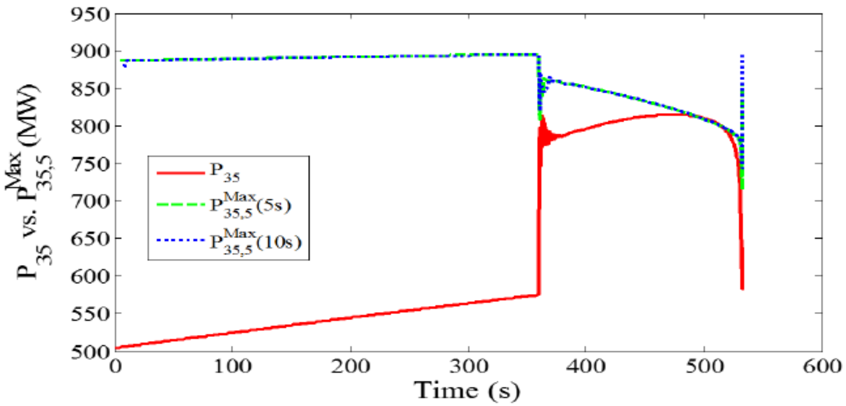


(a) Time for estimating external system parameters.

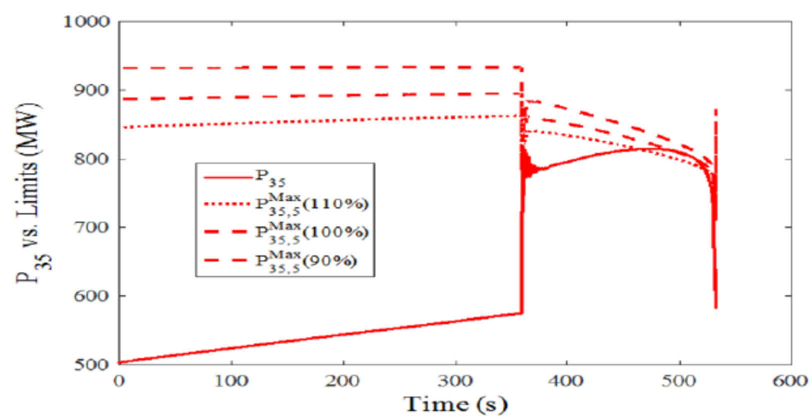


(b) Time for estimating load area parameters.

Time performances on online parameter estimation.

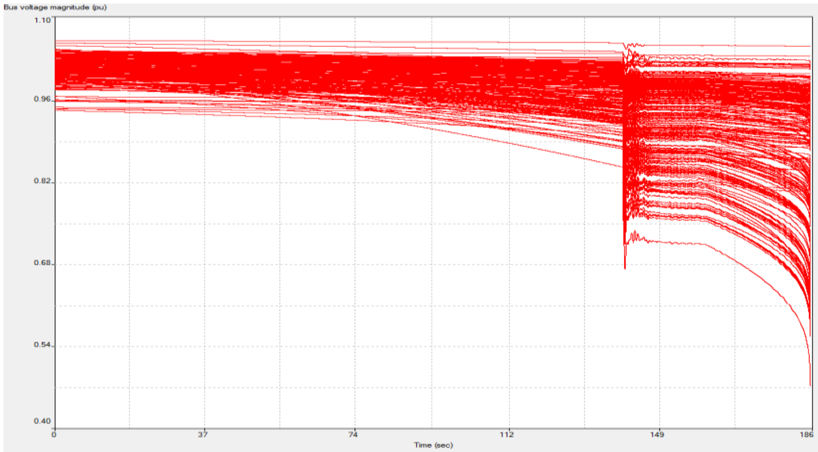


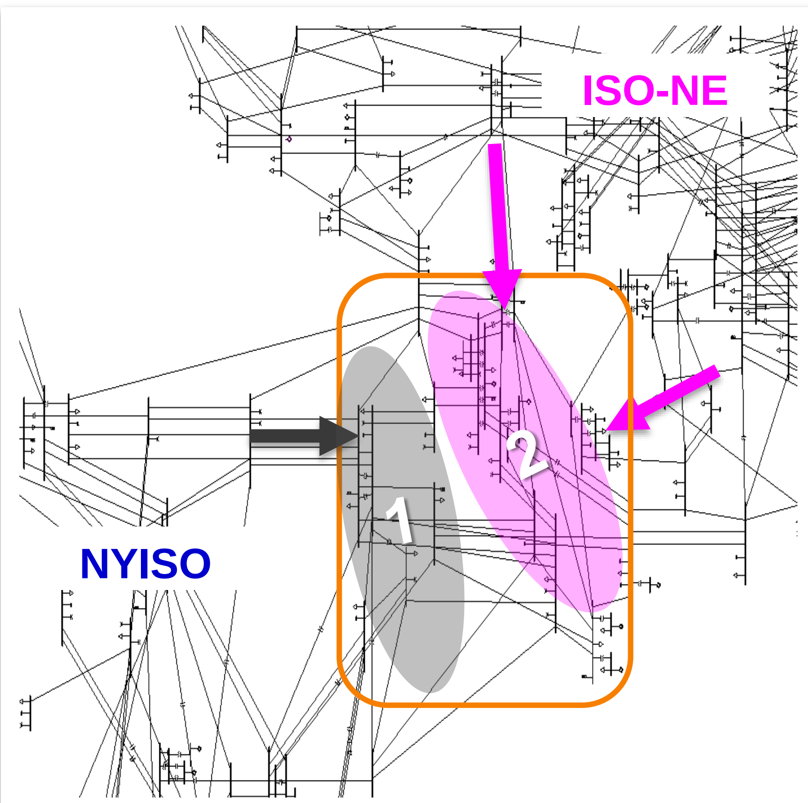
Comparison of different optimization time windows.

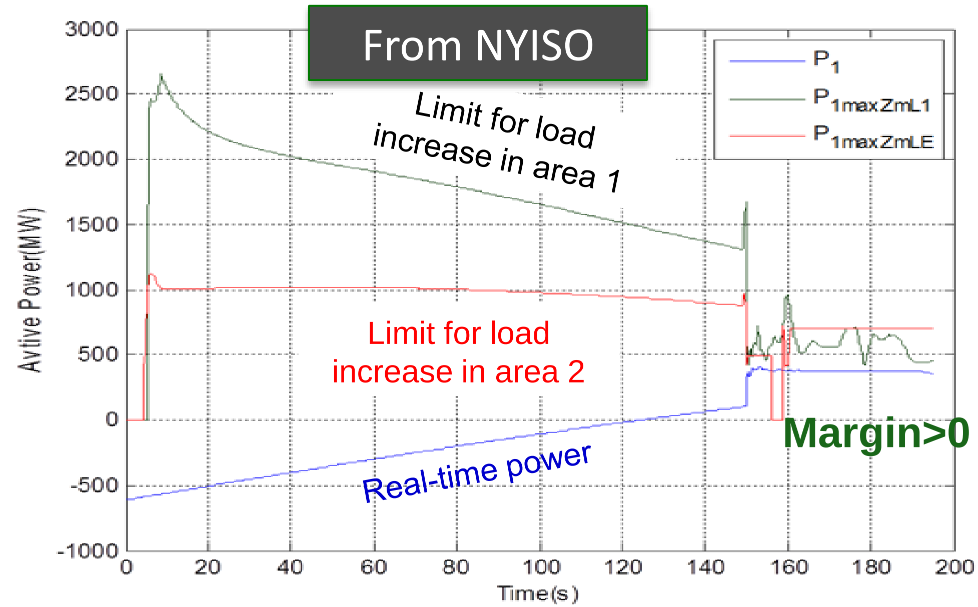


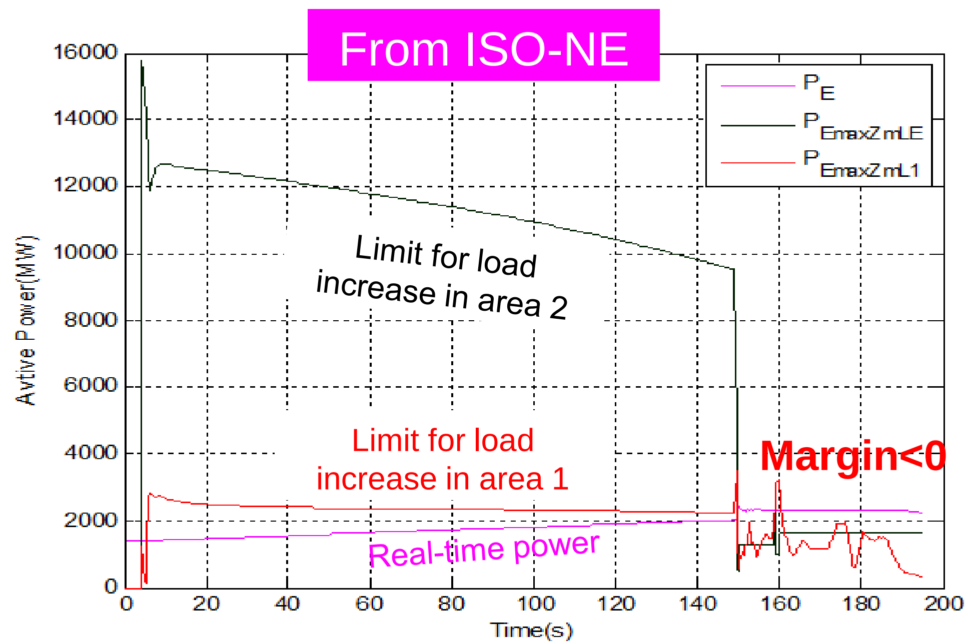
Comparison of initial values with errors.

Test on a 25k-bus Eastern Interconnection model

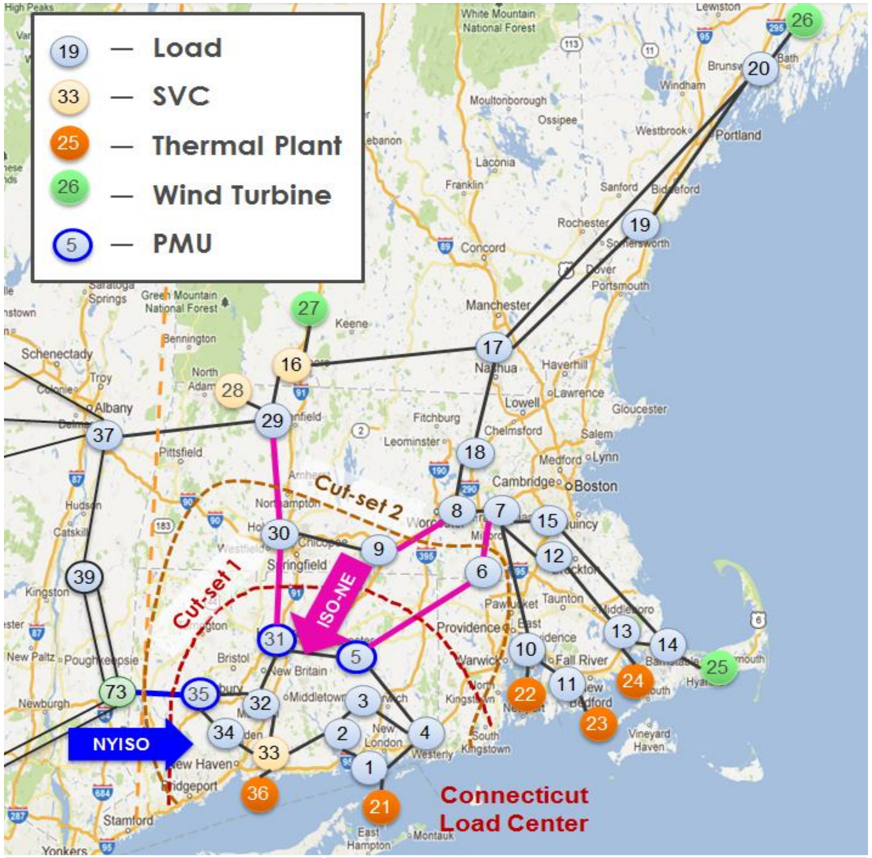




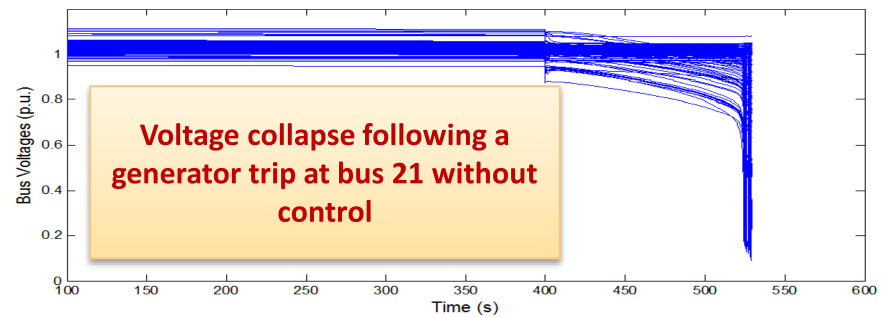


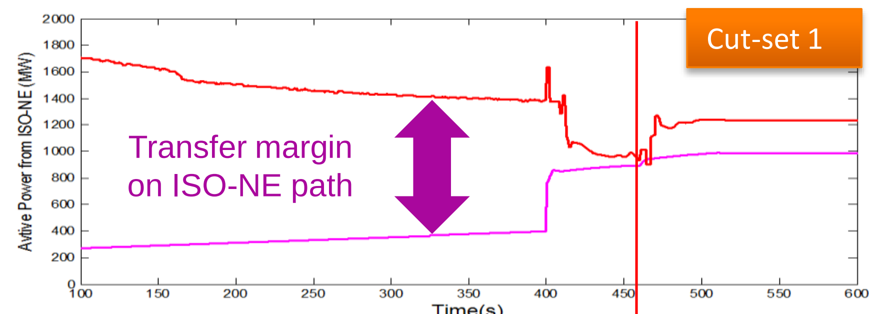


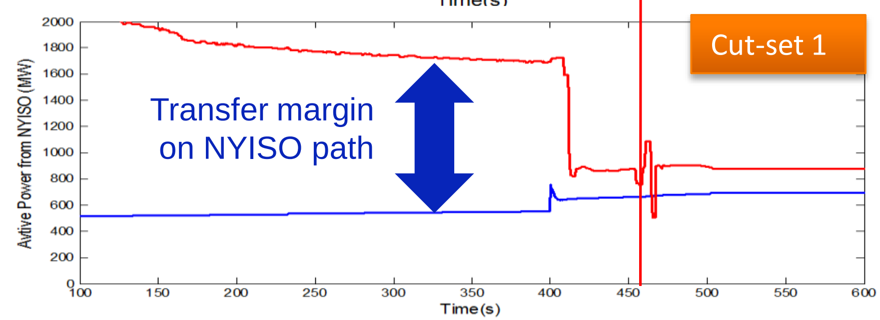
Application of the New MB-VSA Method in System Operations

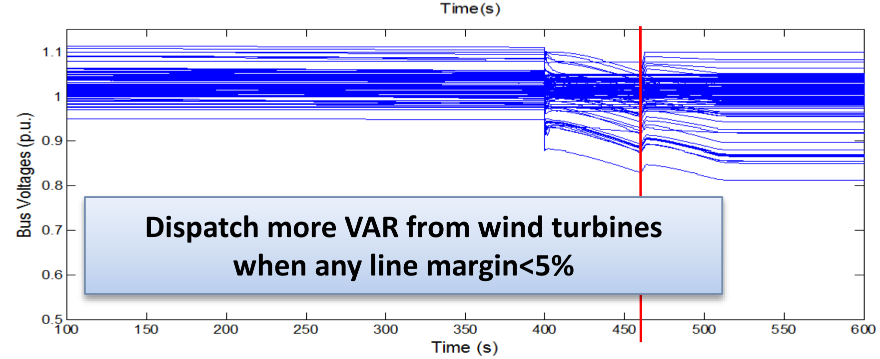


Time (s)	Tie lines ranked by MBVSA
Before generator trip at Bus 21	30-31, 6-5 (most critical)
	29-30, 8-9, 7-6
	73-35
After generator trip at Bus 21	29-30, 8-9, 7-6 (most critical)
	30-31, 6-5
	73-35

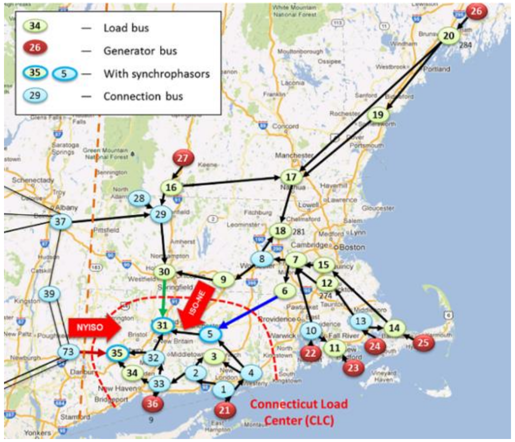


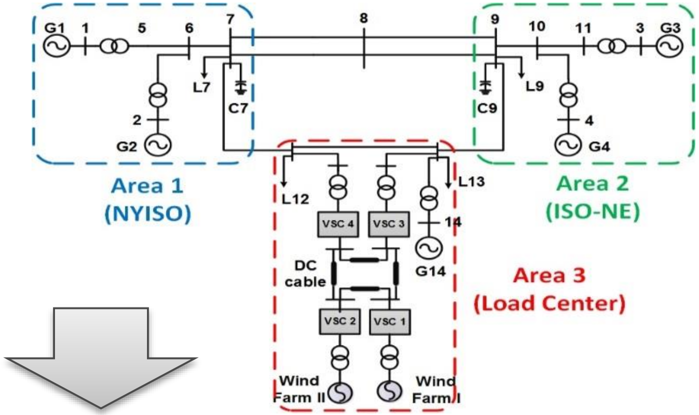


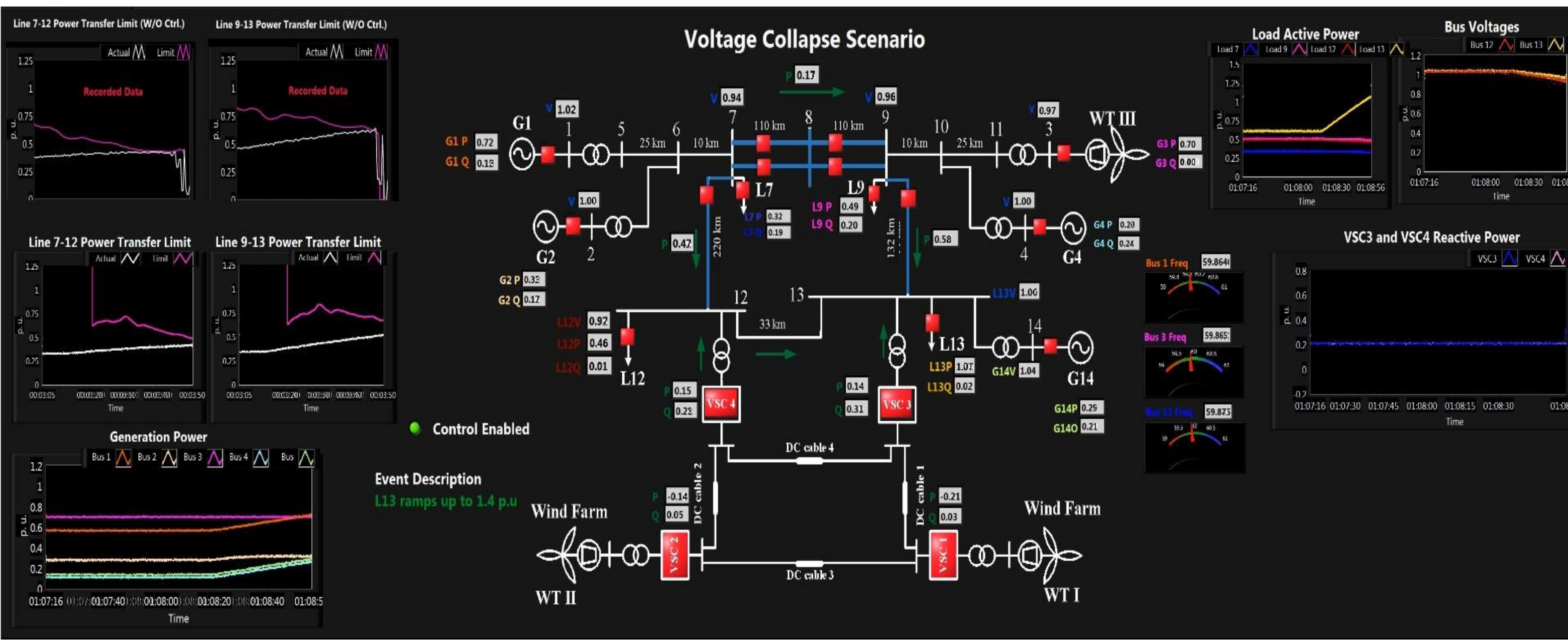




Demonstration on CURENT Hardware Test Bed System [9]







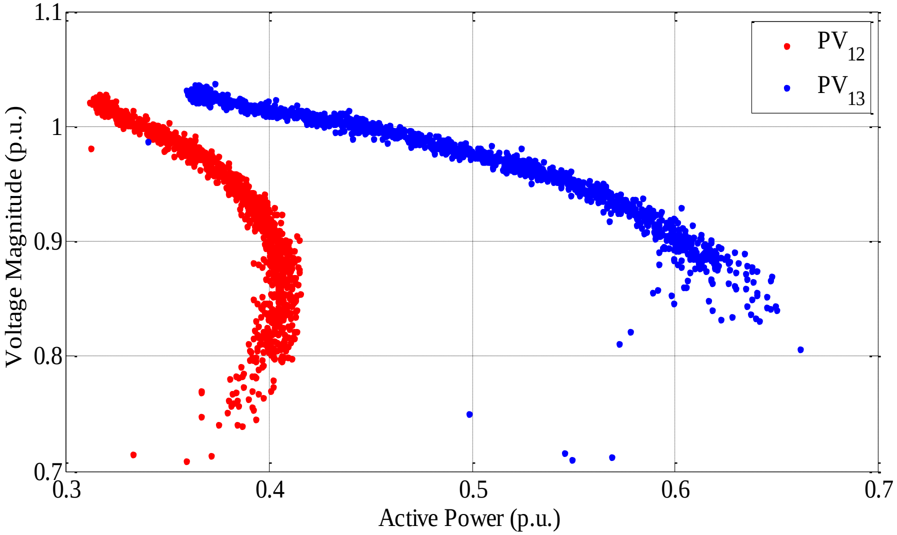
Closed-loop control to prevent voltage collapse

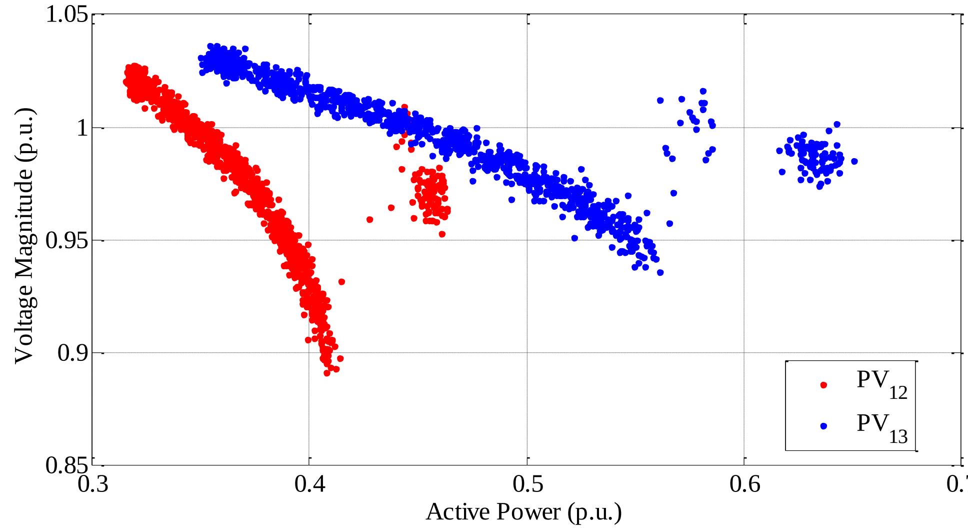
Without control

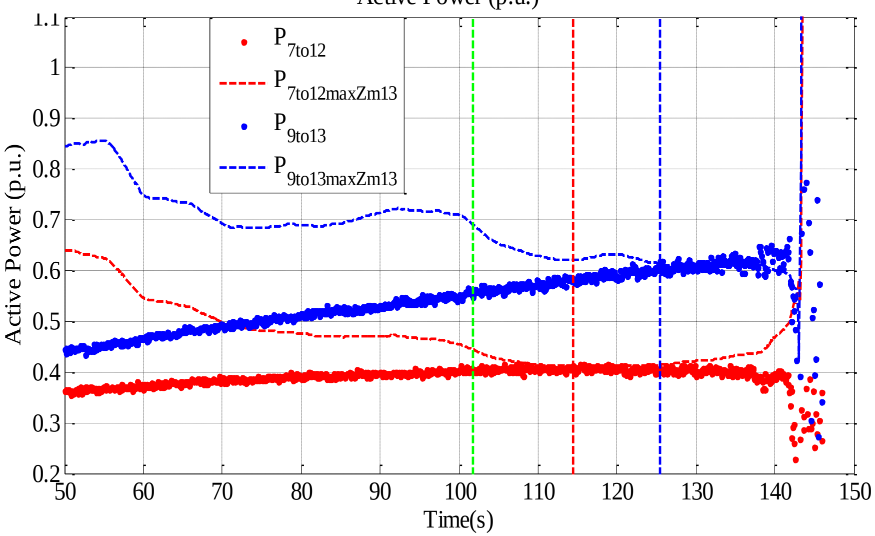
Load increases in the load area leading to voltage collapses.

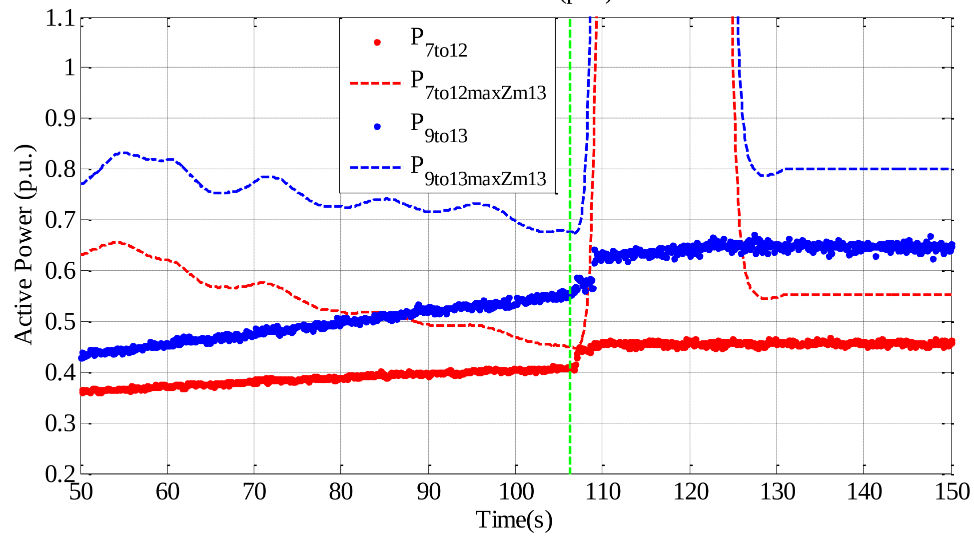
With control

Provide Q via MT-HVDC when any tie line margin is below a threshold









Comparison of Two VSA Approaches

Model-based VSA

- Strengths
  - Ability to look at N-1 and other "what if" scenarios.
  - Ability for control strategy.
- Limitations
  - Model dependent.
  - Computationally intensive.
  - Convergence problems under stressed conditions.

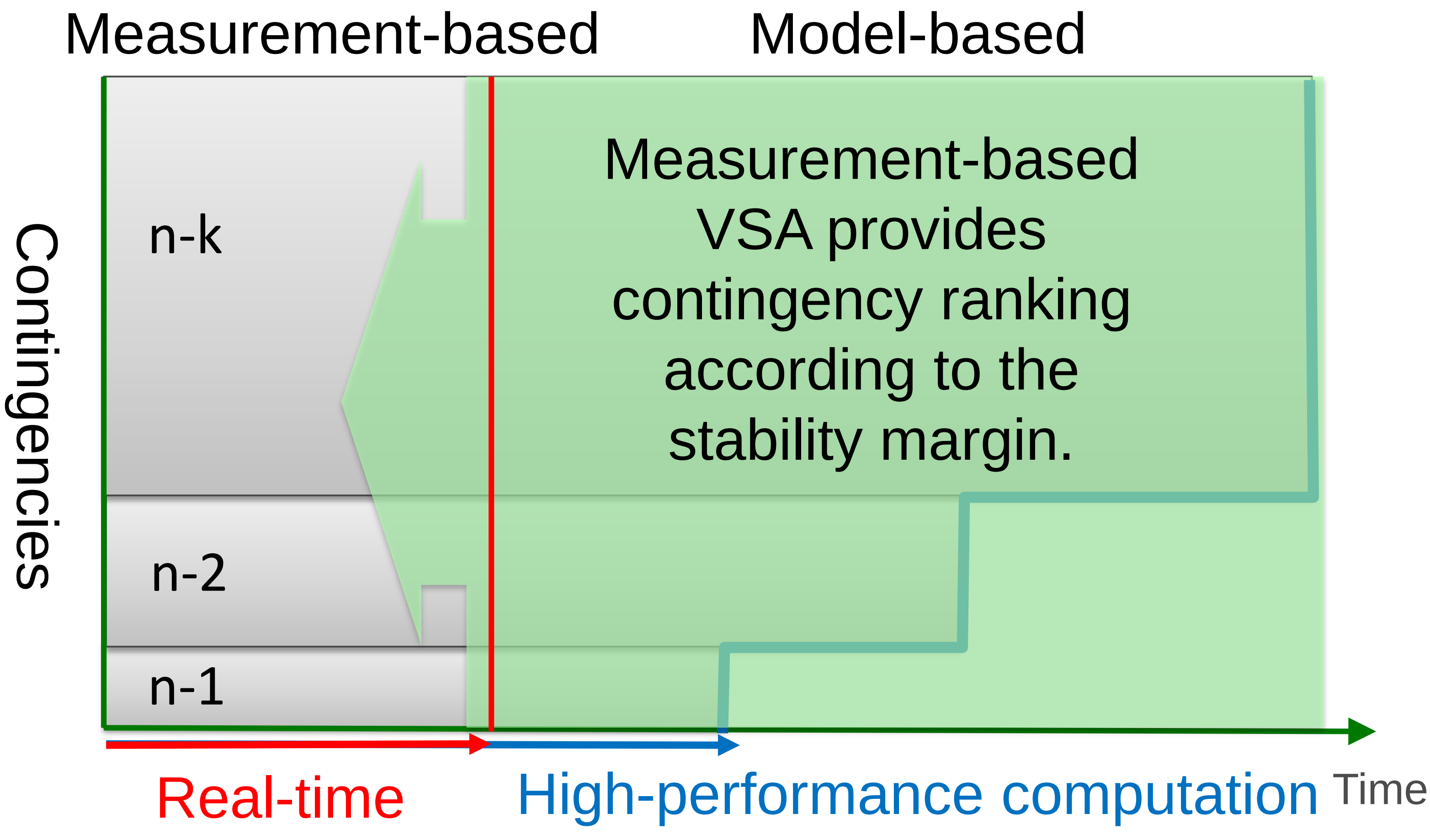
Measurement-based VSA

- Strengths
  - Not dependent on model.
  - Reflects real time system data and scenario.
  - Light computation burden.
- Limitations
  - Inability or inaccuracy for assessing N-1 security.
  - Inaccuracy for non-radial load areas (Thevenin equivalent).

A hybrid approach integrating the two approaches may have the advantages of both.

Hybrid Voltage Stability Assessment and Control

- A hybrid approach: measurement-based + model-based



A Framework for Hybrid Voltage Stability Assessment and Control [11]-[13]

Measurement Based Analysis

- Identifies criticality of the system when simulation results are not available
- Identifies vulnerable regions and critical grid components
- Triggers emergency control actions
- Model reduction

Simulation Based Analysis

- "What-if" analysis. Identifies potential N-1 violations
- Preventive control actions recommendations
- HPC enabled faster than real-time performance

Hybrid Approach Intelligence

- Combines strengths of both approaches
- Analyzes, manages, coordinates, and post-processes results from the different modules to generate actionable information
- Information and visualizations with focus on the operator needs &perspective

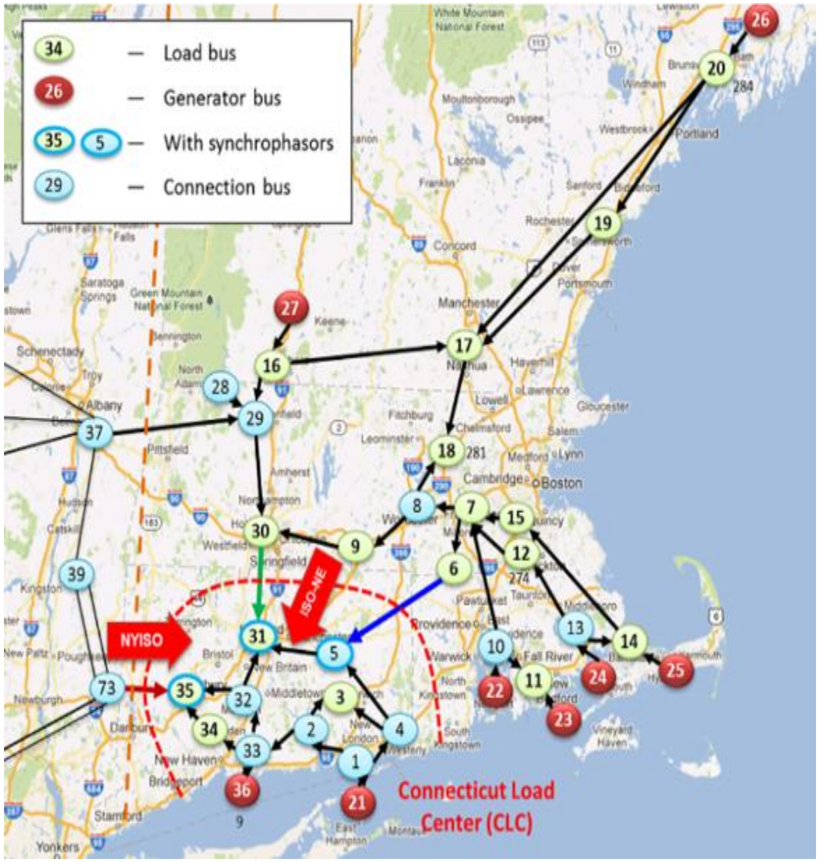
Real-time Stability Margins

Real-Time Alerts

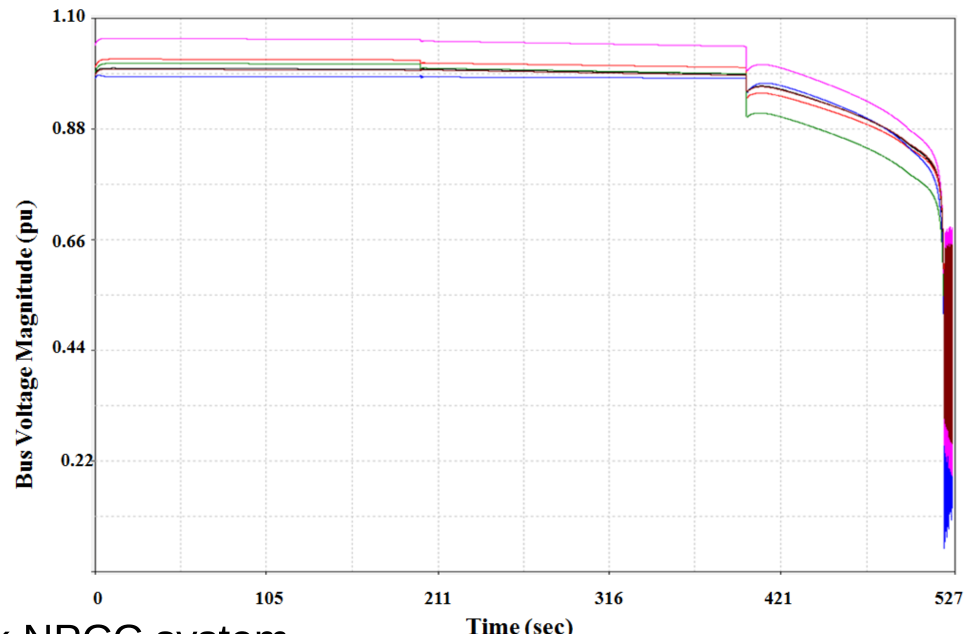
Emergency Automated Actions

Recommendations on Preventive Actions

Illustrative Example on a Hybrid VSA Scheme [12]

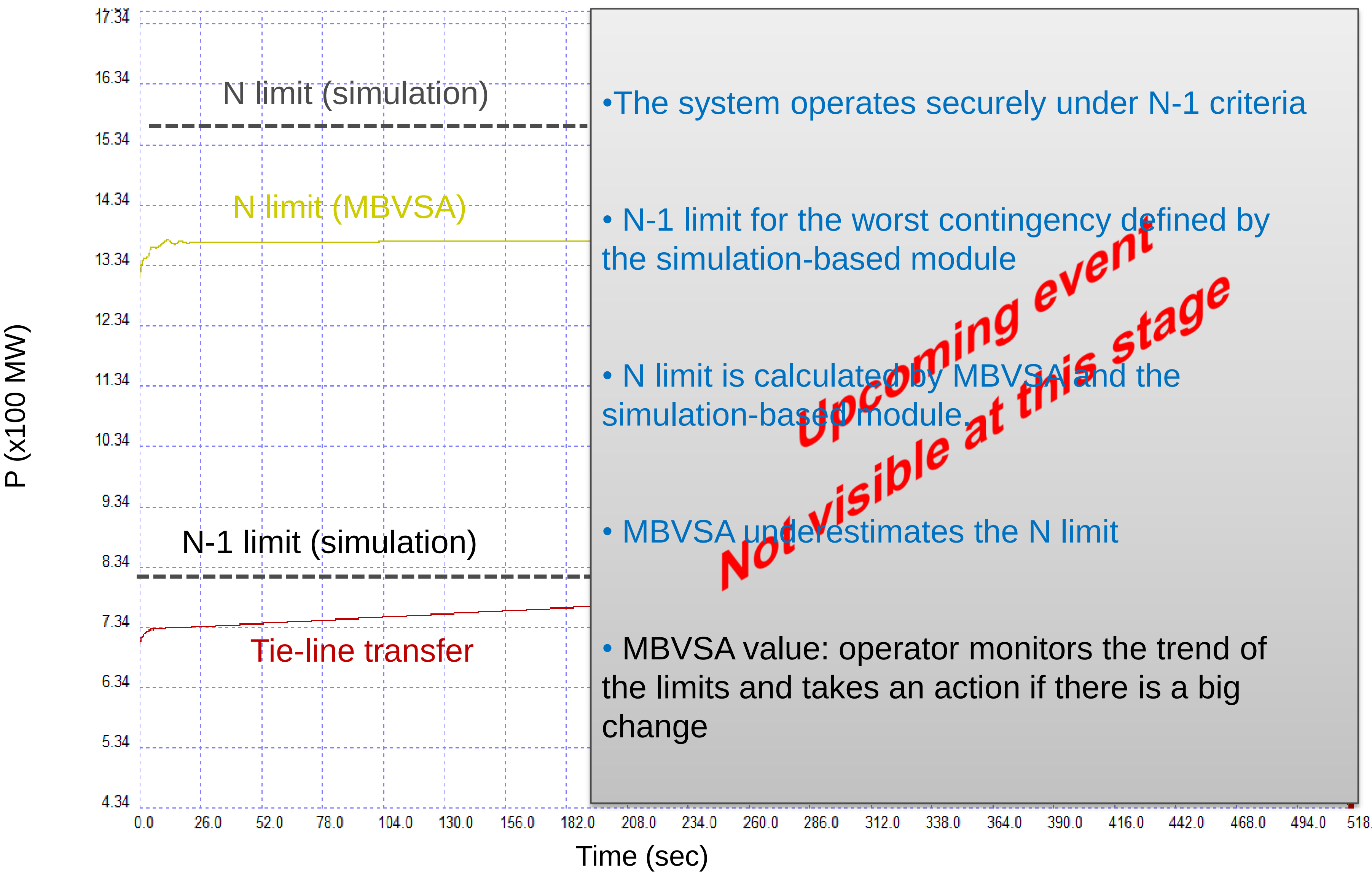


Stage 1	No Contingency
Stage 2	Line 31-32 tripped
Stage 3	Lines 31-32 & 30-31 tripped



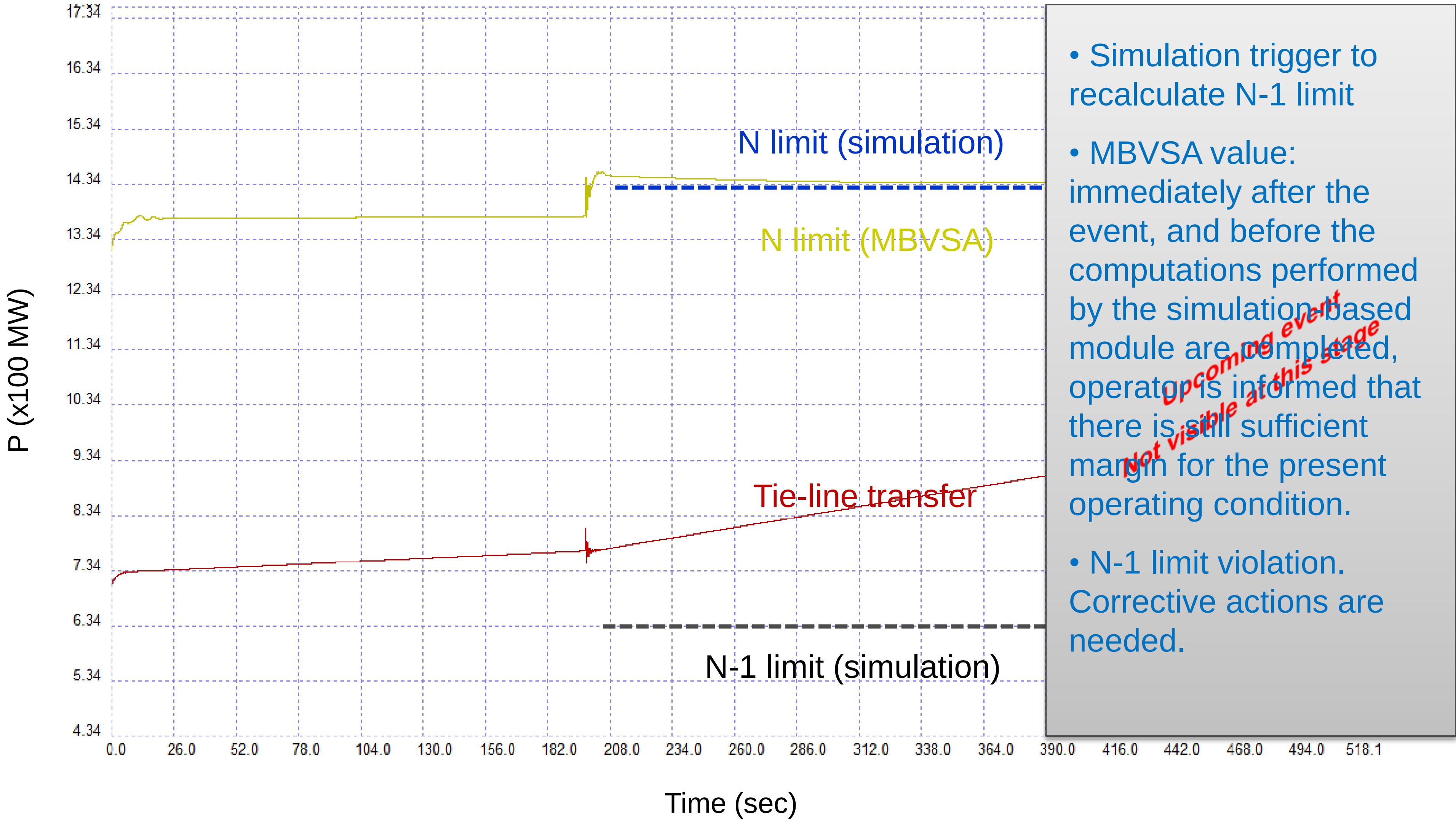
- 140 bus benchmark NPCC system
- Focus on the ISO-NE Connecticut Load Center

Stage 1



- The system operates securely under N-1 criteria
- N-1 limit for the worst contingency defined by the simulation-based module
- N limit is calculated by MBVSA and the simulation-based module.
- MBVSA underestimates the N limit
- MBVSA value: operator monitors the trend of the limits and takes an action if there is a big change

Stage 2



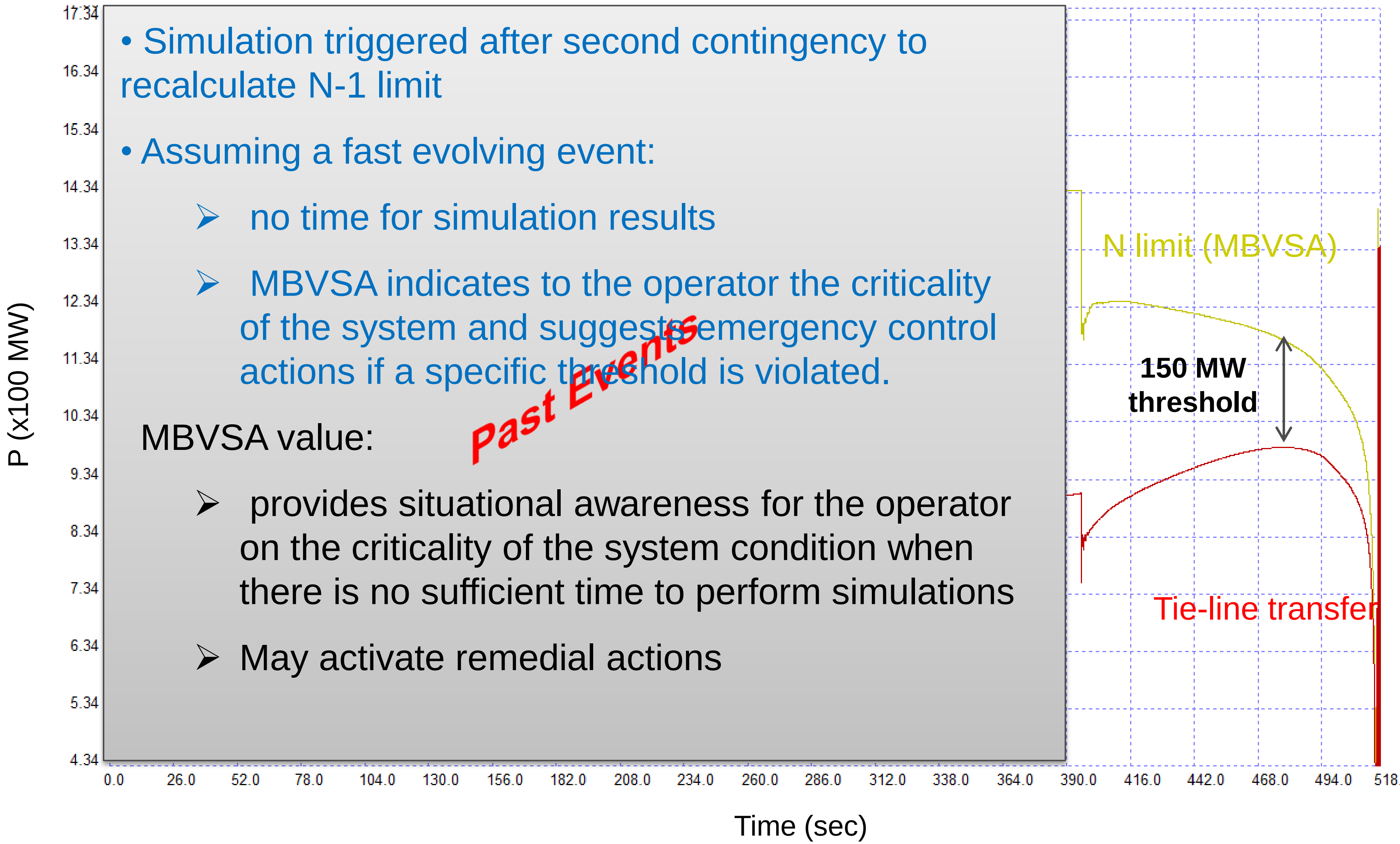
- Simulation trigger to recalculate N-1 limit
- MBVSA value: immediately after the event, and before the computations performed by the simulation-based module are completed, operator is informed that there is still sufficient margin for the present operating condition.
- N-1 limit violation. Corrective actions are needed.

Stage 3

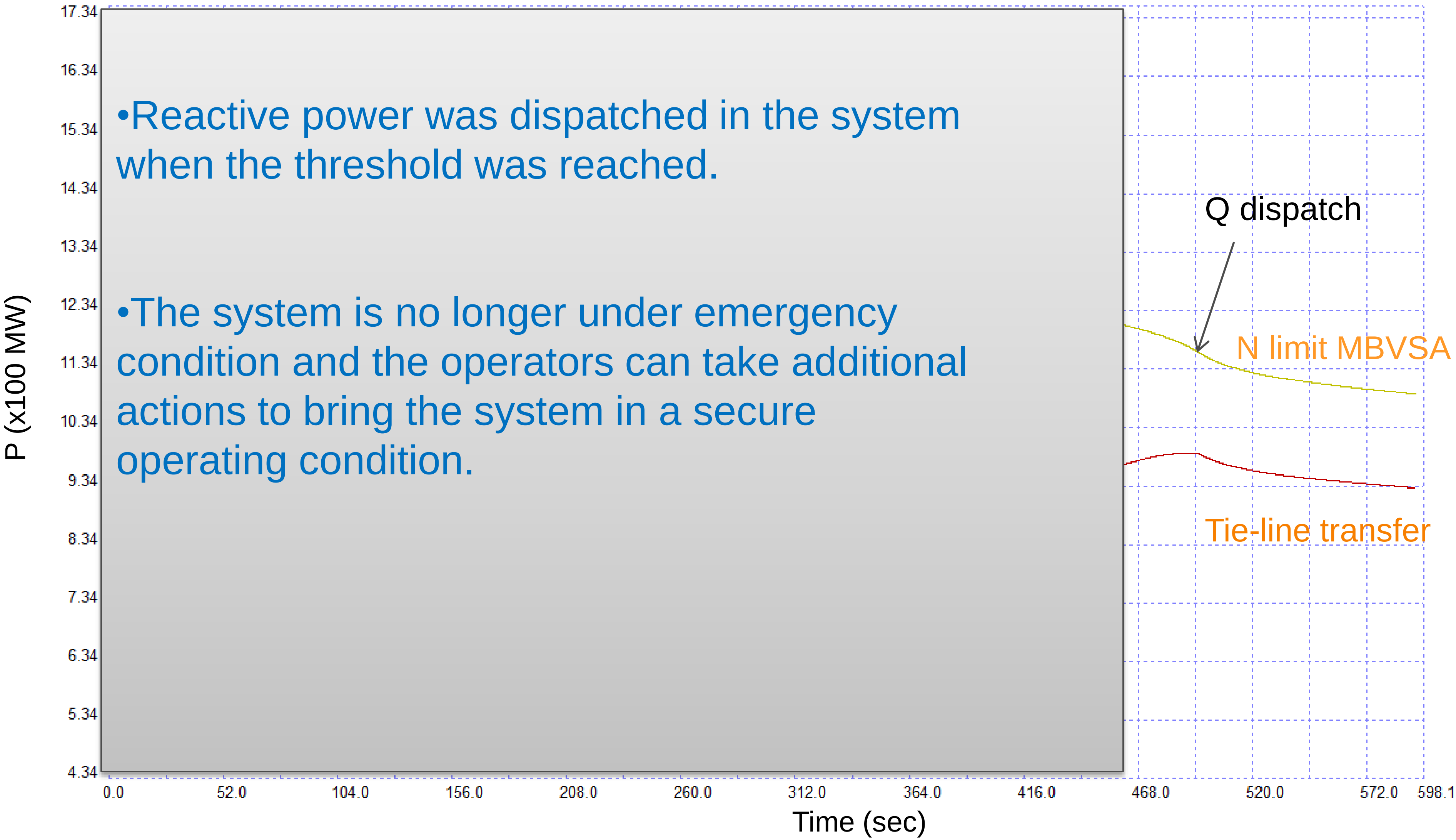
- Simulation triggered after second contingency to recalculate N-1 limit
- Assuming a fast evolving event:
  - no time for simulation results
  - MBVSA indicates to the operator the criticality of the system and suggests emergency control actions if a specific threshold is violated.

MBVSA value:

- provides situational awareness for the operator on the criticality of the system condition when there is no sufficient time to perform simulations
- May activate remedial actions



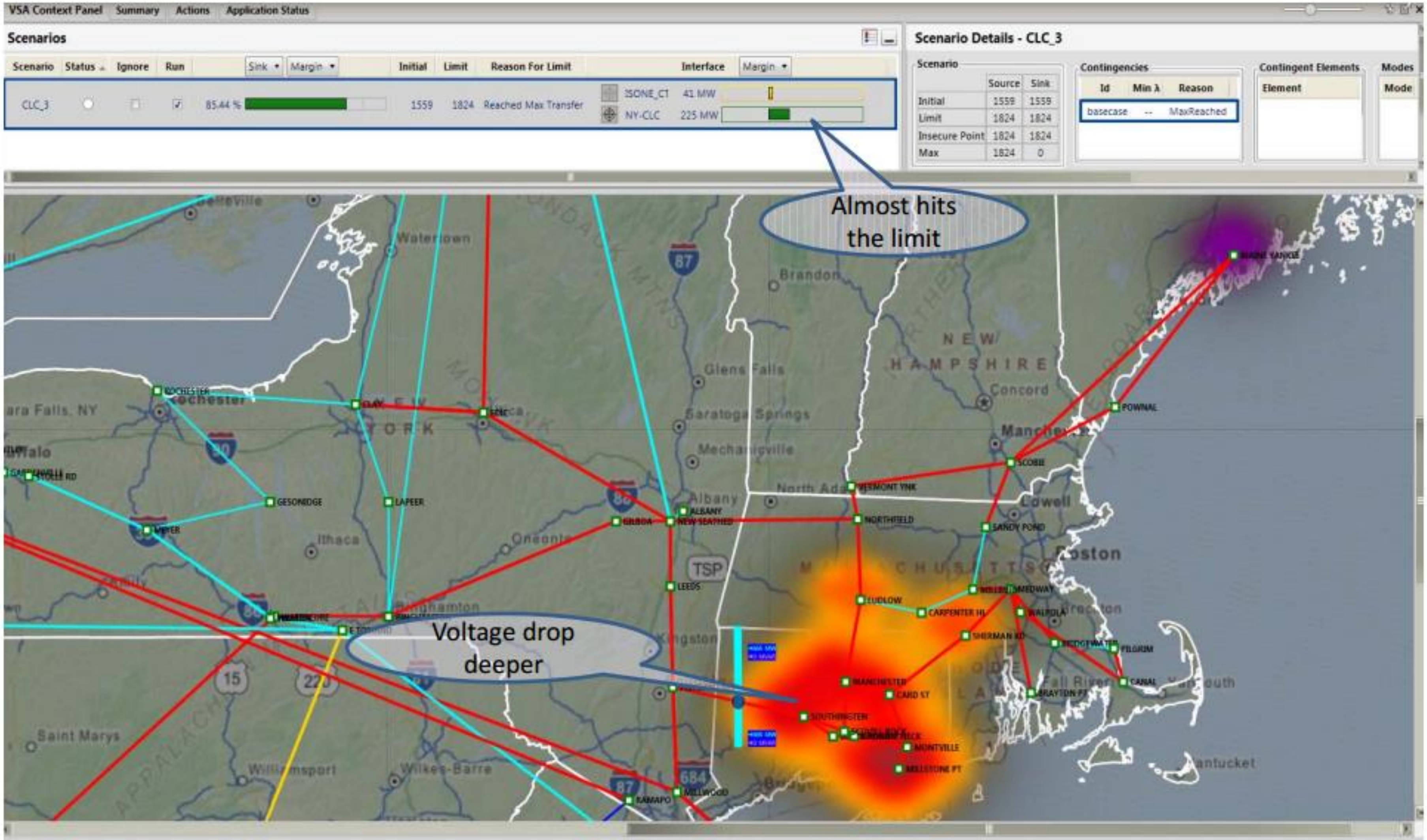
Remedial Action



- Reactive power was dispatched in the system when the threshold was reached.

- The system is no longer under emergency condition and the operators can take additional actions to bring the system in a secure operating condition.

Visualization of Hybrid VSA Results on e-terra*vision* [13]



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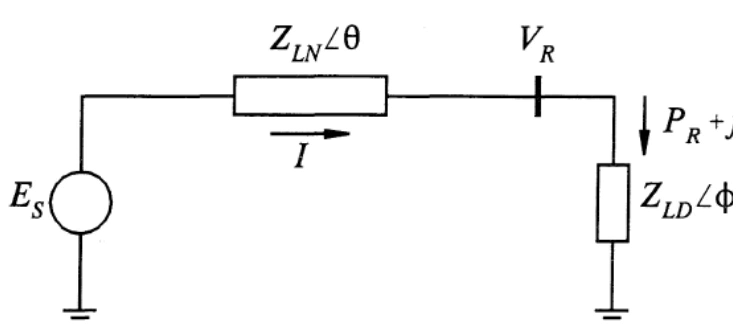
Final Exam Problem

- Let E_S be 1.2 (pu), Z_{LN}=0.2 (pu), θ=84.3°, ϕ=18.2°.
- Create data for a period of 50 sec:
  1) initially, let Z_{LD} be 0.6 (pu);
  2) decrease Z_{LD} by 0.01 pu / sec until Z_{LD} =0.1 (pu).
- Calculate phasors of V_R and I over the above 50 sec period and use those data to estimate the Thevenin equivalent, i.e. Z_{LN}, θ and E_S by the least squares method.
- Plot Z_{LD} and the estimated Z_{LN} vs. Time



P_R=P_{RMAX} when Z_{LN}=Z_{LD}