# Real-time Simulations Approach for Analyzing Voltage Instability Protection in Power Systems

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**(Based on MSc Thesis Research Work of Nataliia Petryshyn, December 2014)**

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1. Voltage stability analysis from the protection point
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3. Verification of Real-time Voltage Stability Index (RVSI)
4. Testing results of Real-time Fast Voltage Stability Index (RFVSI)
5. Verification of proposed Margin method using dynamic load variations
6. Conclusion

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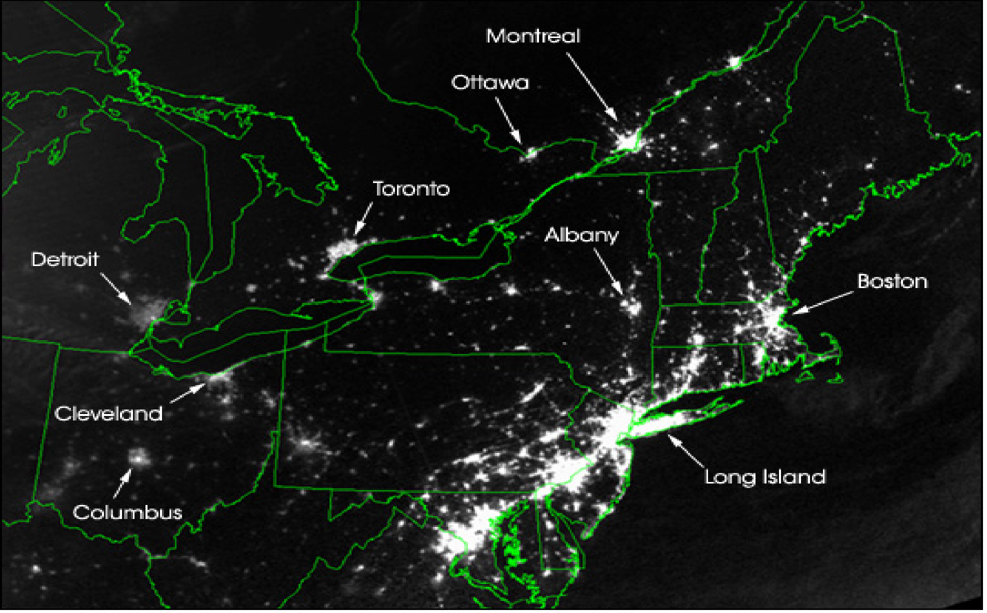
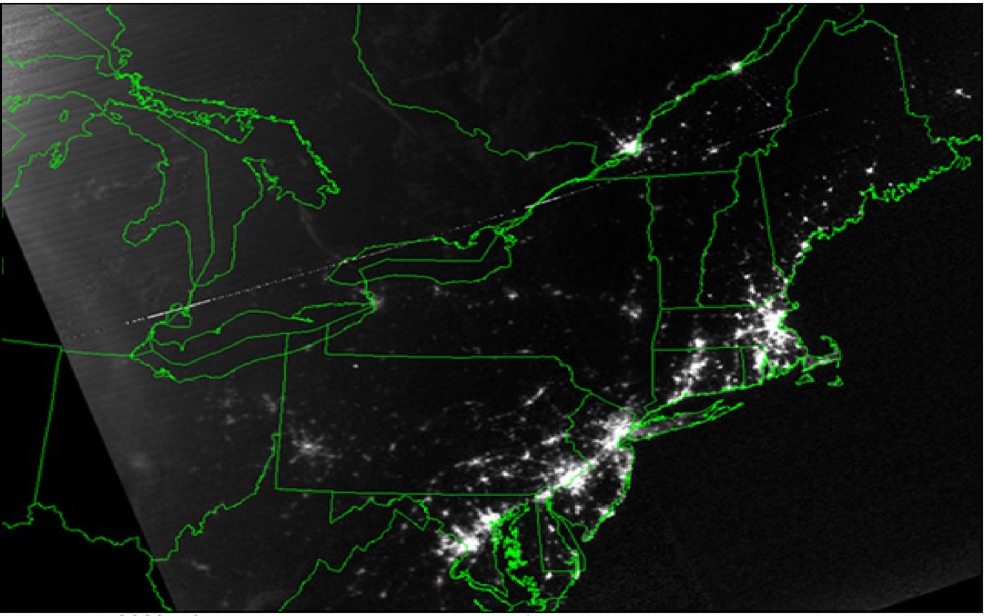



August 14, 2003 • 9:29 p.m. EDT • About 20 hours before blackout



August 15, 2003 • 9:14 p.m. EDT • About 7 hours after blackout

**Satellite image of the change in the night time city lights**

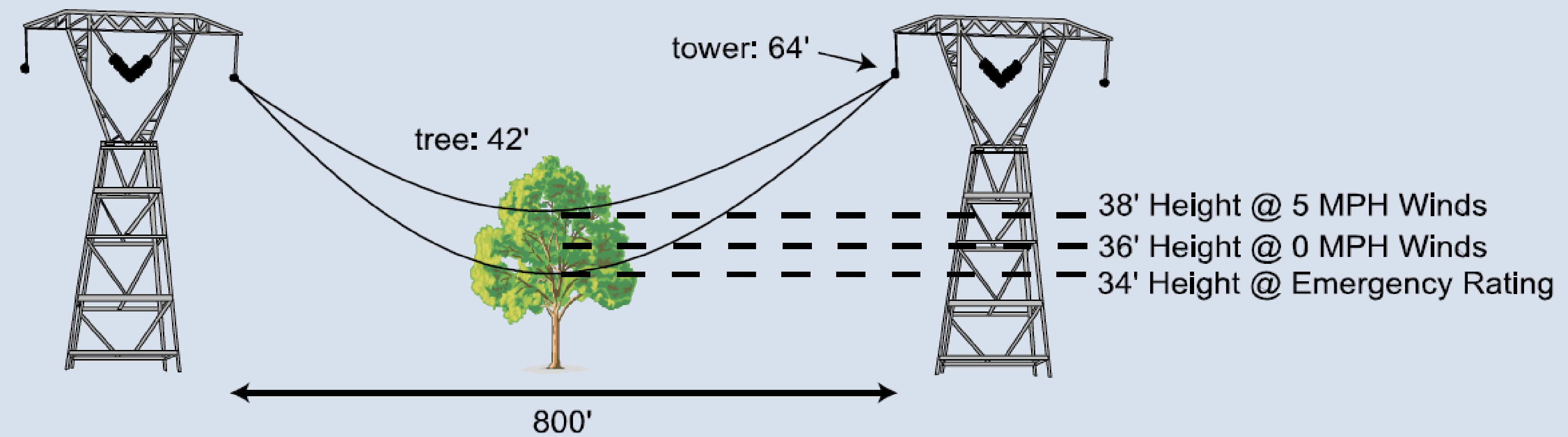
# US/CANADA BLACKOUT 2003

- 2nd most widespread blackout in history
- 55 million people in Ontario and eight U.S. states affected
- 265 power plants shut down
- 80% of the load loss

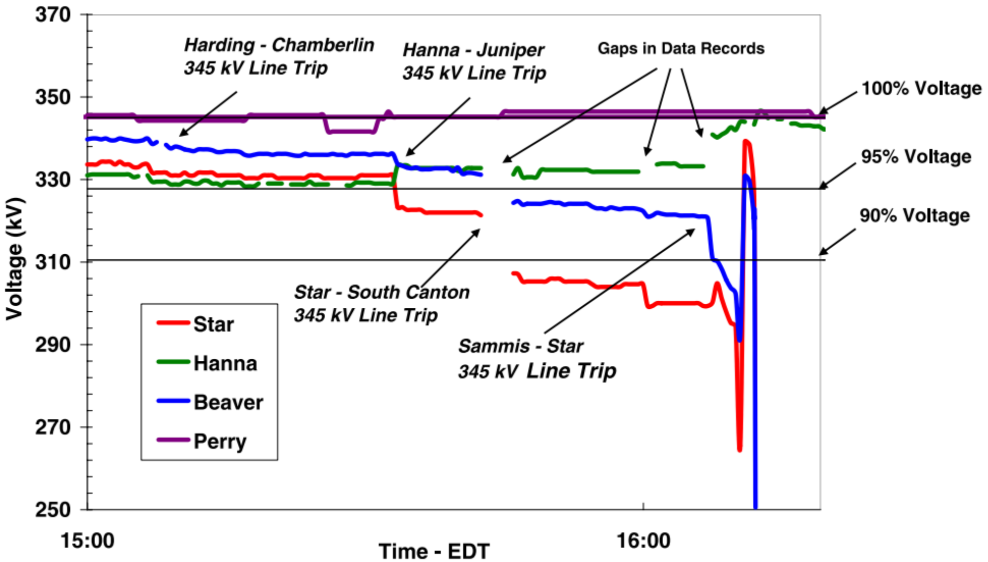
[1] Final Report on the August 14, 2003 Blackout in the United States and Canada. US-Canada Power System Outage Task Force, 2004.

# Main Cause and Result of the US/Canada Blackout 2003

## Tree-to-line contact resulting transmission outage




## Impacts of line trips on voltage profiles for FirstEnergy's 345-kV lines



# Factors that Contribute to Voltage Collapse:

- Increased loading on transmission lines
- Reactive power constraints
- Transformer On-Load Tap Changer (OLTC) dynamics
- Load characteristics
- Generator exciter current limits

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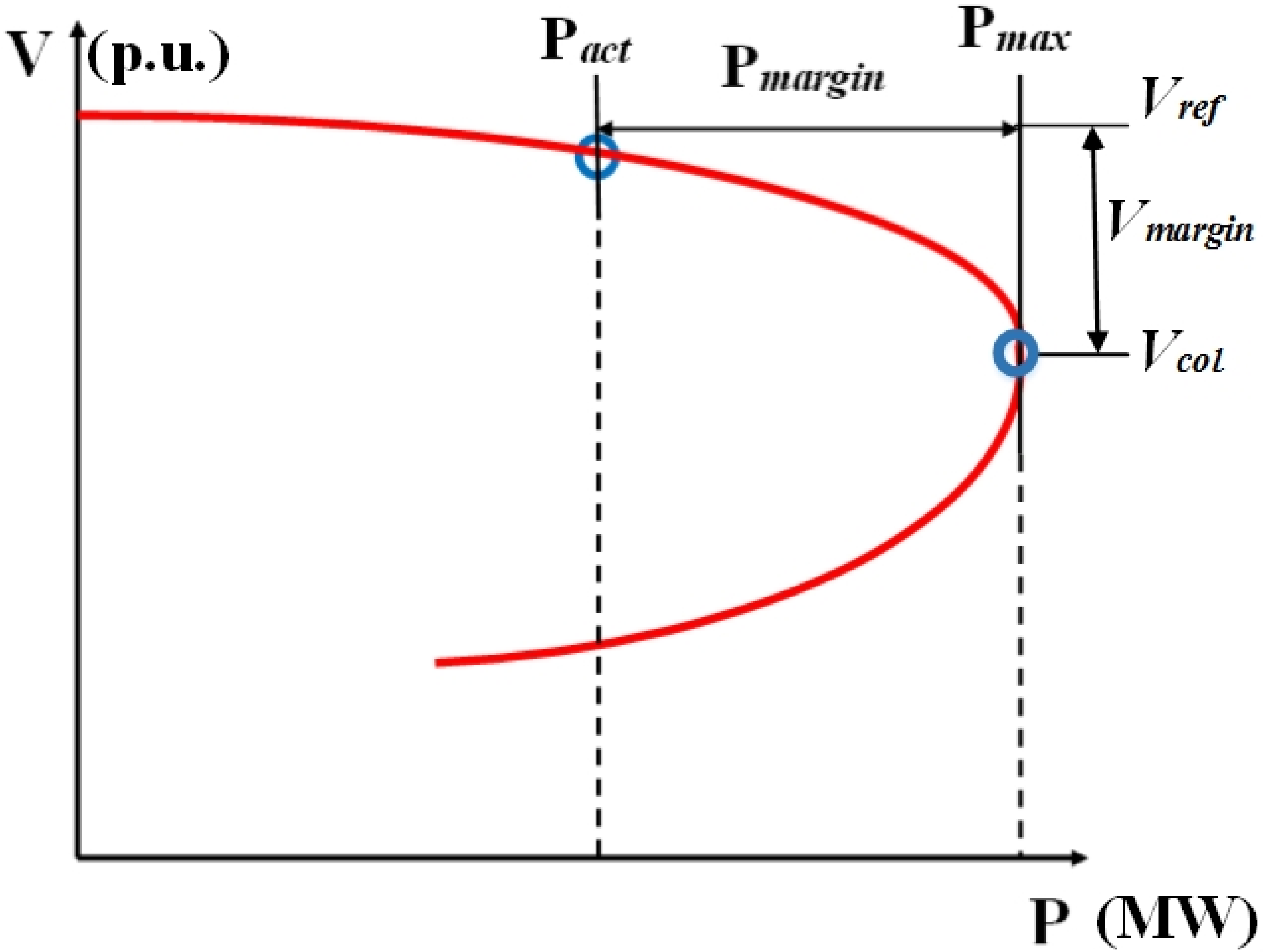
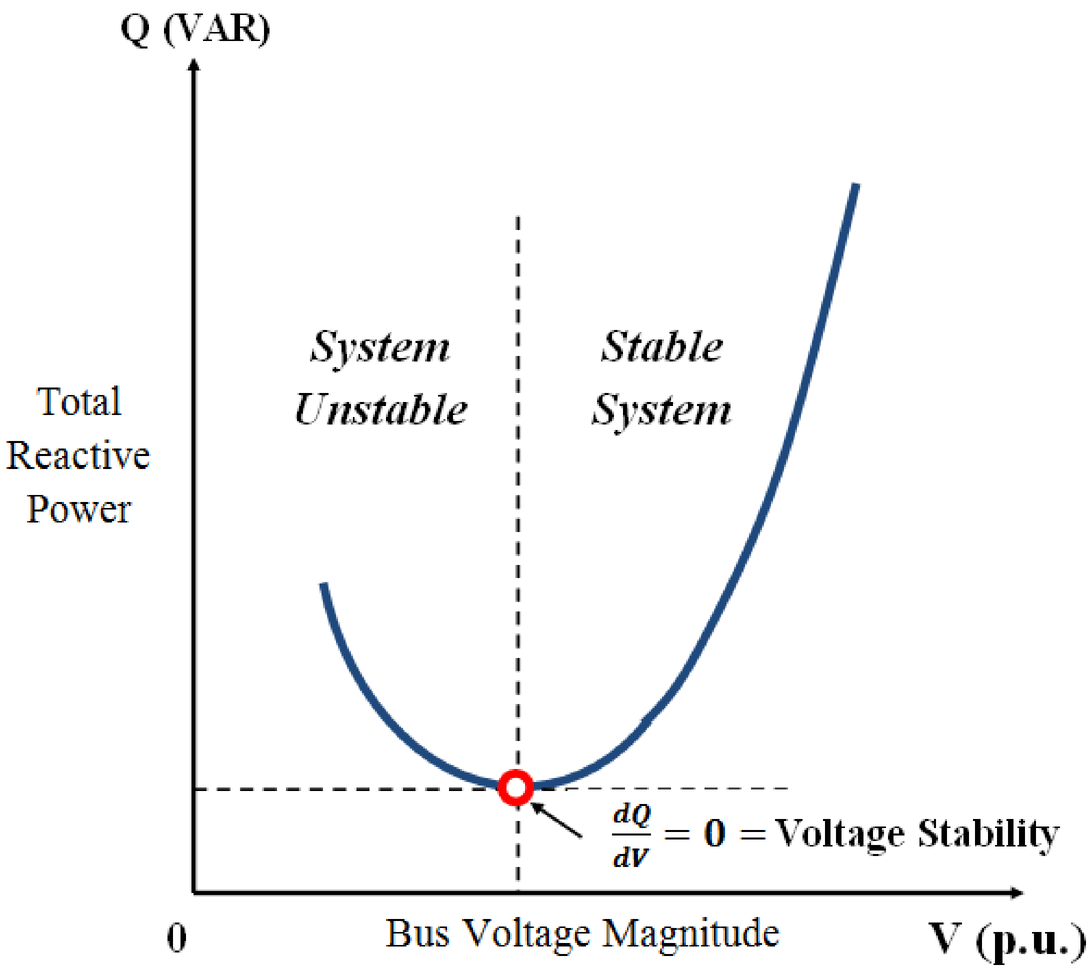
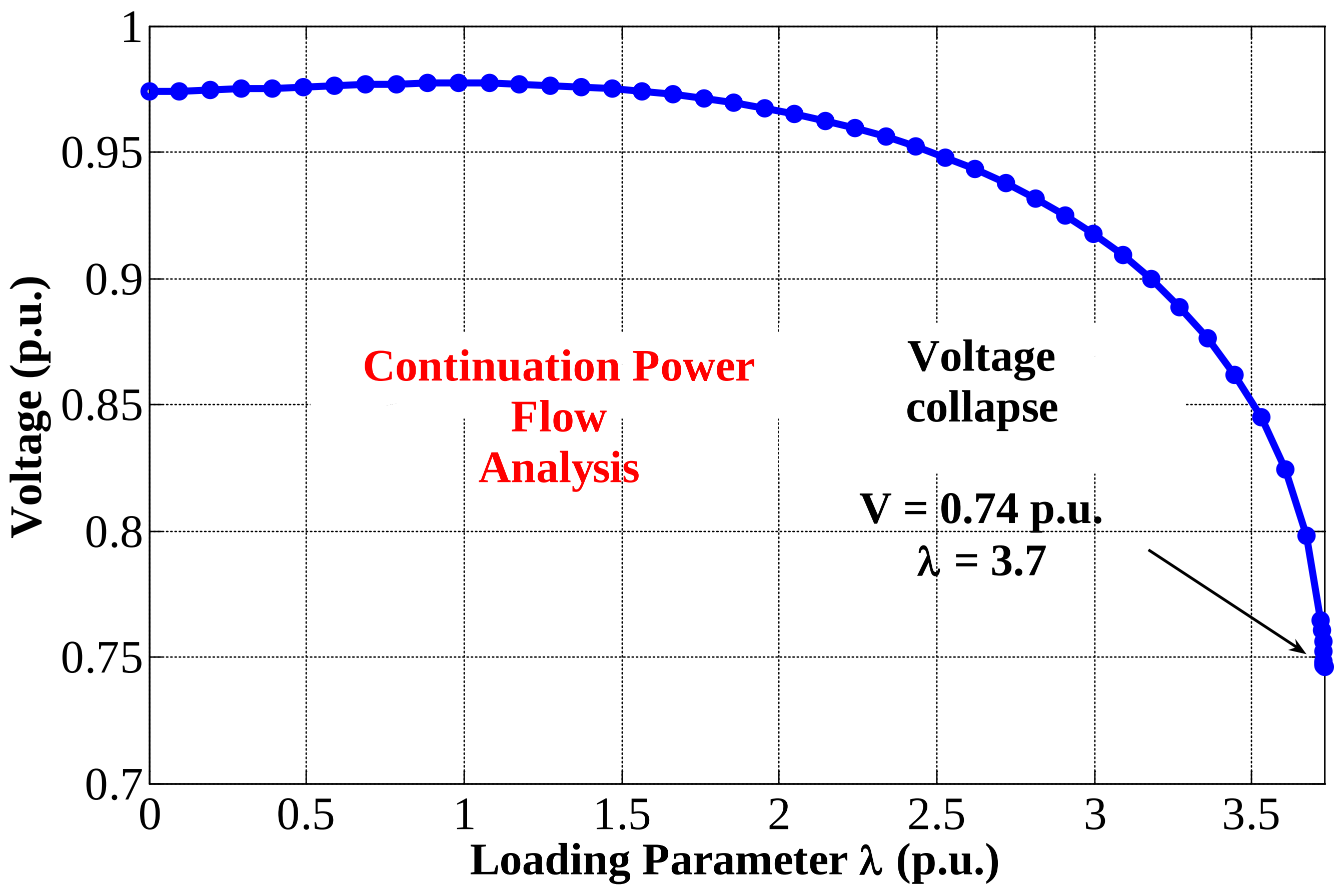
# Real-time Voltage Stability Margin (RVSM) Method



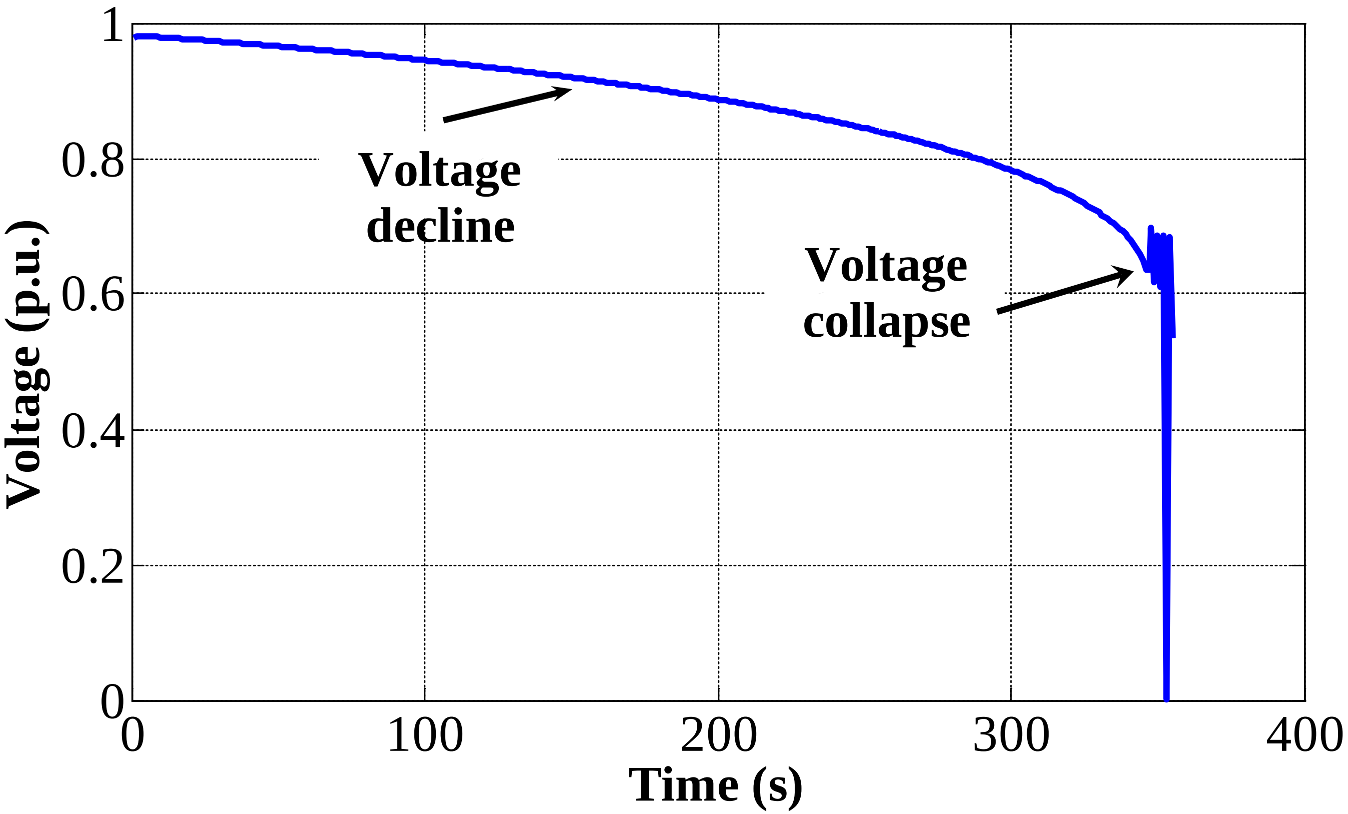
# QV CURVE


Q (VAR)
Total
Reactive
Power
System
Unstable
Stable
System
$\frac{dQ}{dV} = 0 =$ Voltage Stability
0
Bus Voltage Magnitude
V (p.u.)

# TWO-BUS SYSTEM STATIC ANALYSIS

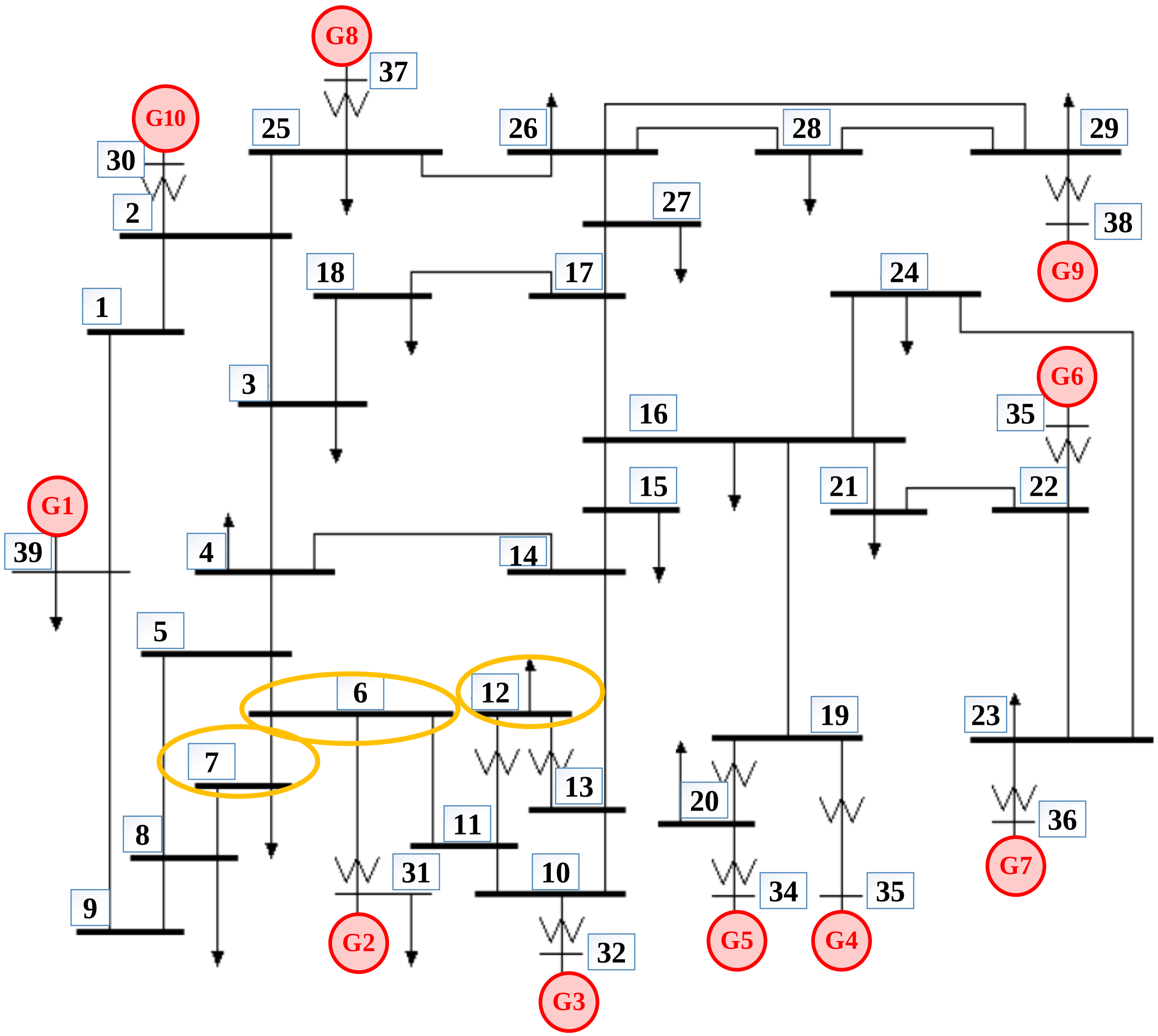


# DYNAMIC ANALYSIS

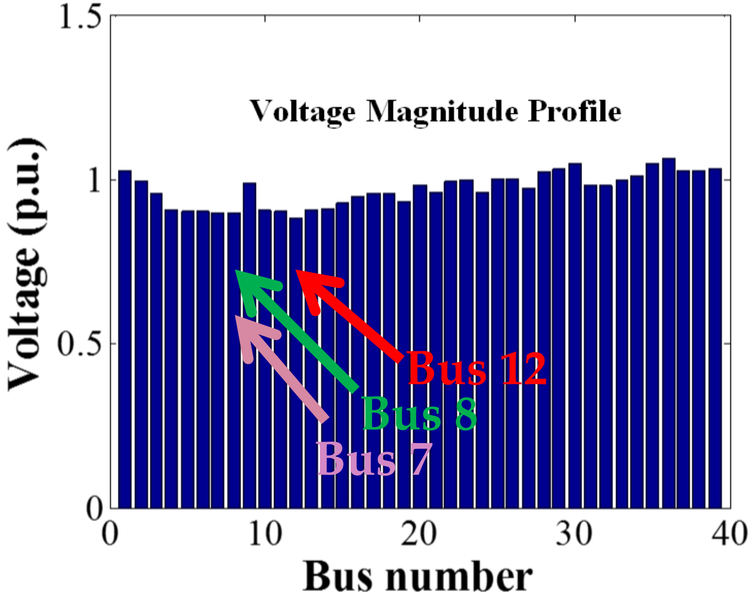


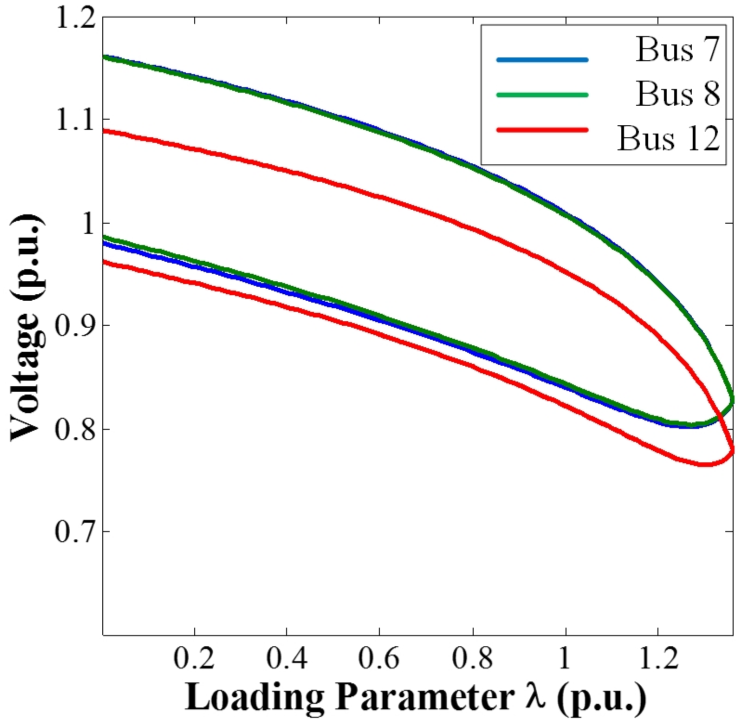
# Test Power Systems

## IEEE 39-bus system network diagram



# Critical Buses Determination

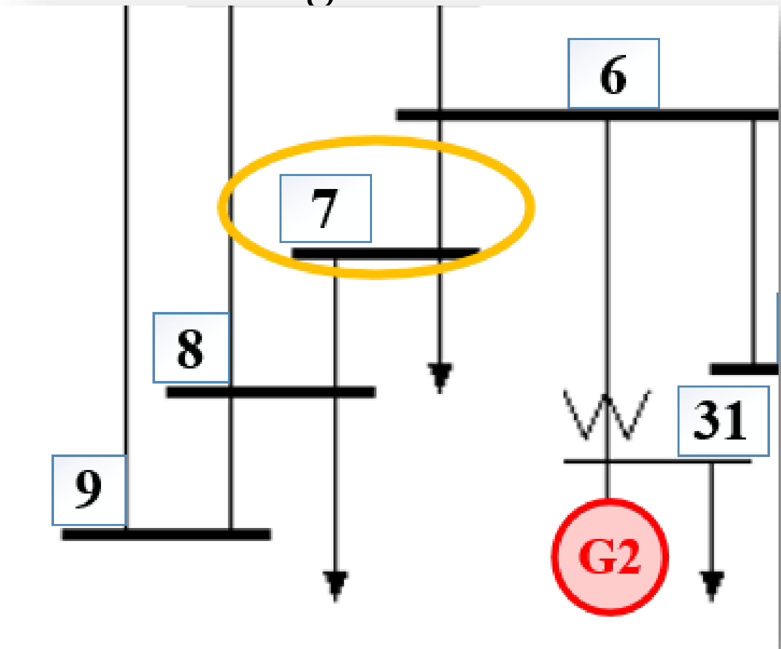


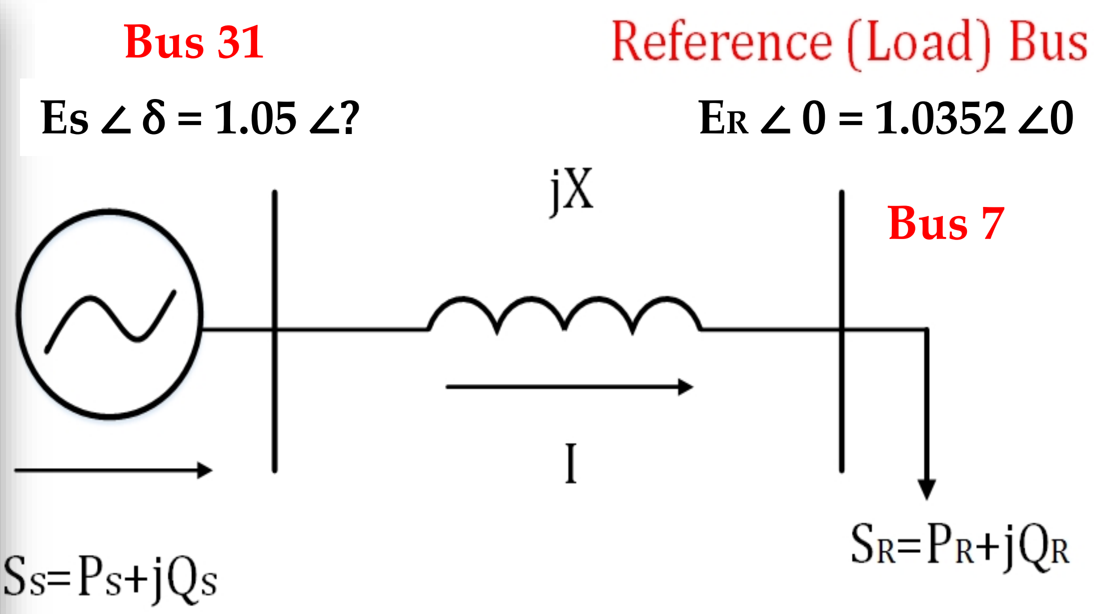




| **Power Flow** | **Continuation Power Flow** |
|---|---|
| Nominal Voltages (pu) | Nose Point Voltages (pu) |
| Vbus 12 = 0.8792 | Vbus 12 =0.7778 |
| Vbus 7 = 0.8973 | **Vbus 7 = 0.8266** |
| Vbus 8 = 0.8997 | Vbus 8 = 0.8262 |

# Real-time (RTDS) Simulations for RVSM Testing

- Continuous load increase of 10% per second at Bus 7
- Remaining loads were increased to 150% of nominal values



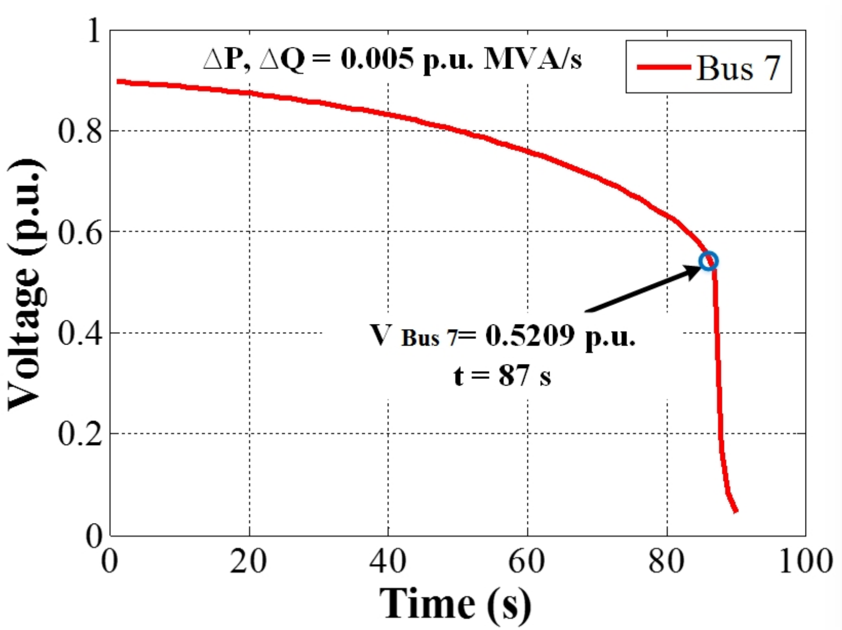



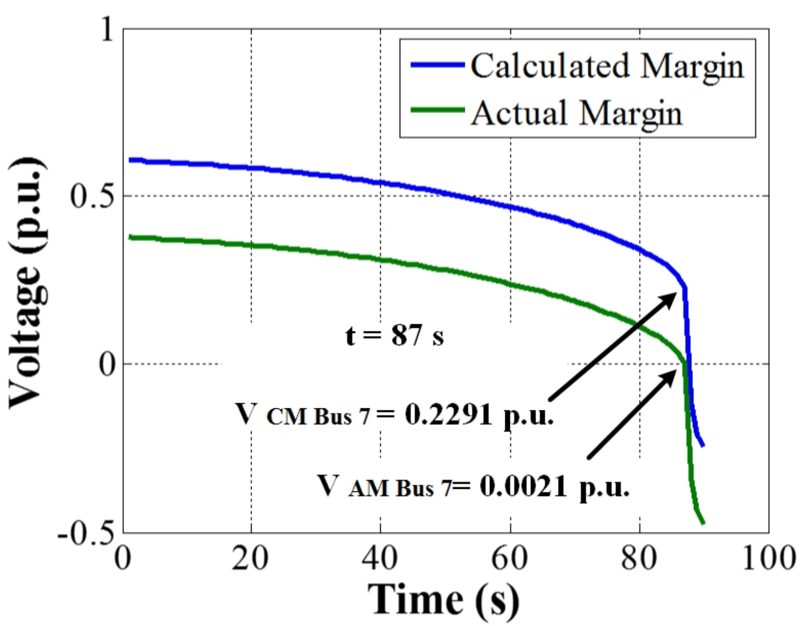

| Quantity | Real-time Simulations | |
|---|---|---|
| | Calculated | Actual |
| $V_R$, [pu] | - | 1.0352 |
| $V_C$, [pu] | 0.2918 | 0.5206 |
| $V_M$, [pu] | 0.1743 | 0.0041 |
| t, [s] | - | 68 |

# Off-line (PSAT) Simulations for RVSM Testing

$$Voltage\ Margin_{Bus\ 7}(i) = V_{R\ Bus\ 7}(i) - V_{C\ Bus\ 7}$$

| Quantity | Off-line Simulations | |
|---|---|---|
| | Calculated | Actual |
| $V_R$, [pu] | - | 0.8973 |
| $V_C$, [pu] | 0.2918 | 0.5209 |
| $V_M$, [pu] | 0.2291 | 0.0021 |
| $t$, [s] | - | 87 |



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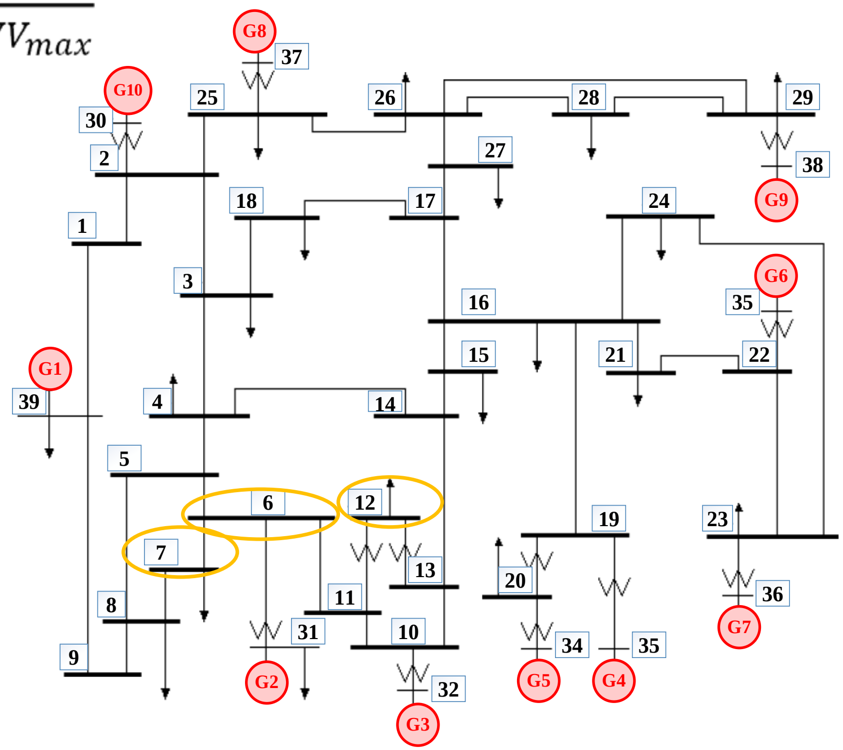
# Real-time Voltage Stability Index (RVSI)

- Modification of Improved Voltage Instability Monitoring Method (IVIMI) [3] into Real-time Voltage Stability Index (RVSI)
- Index requires wide area measurements of voltage magnitude and the rate of voltage change at all load buses
- Able to predict voltage collapse in the system

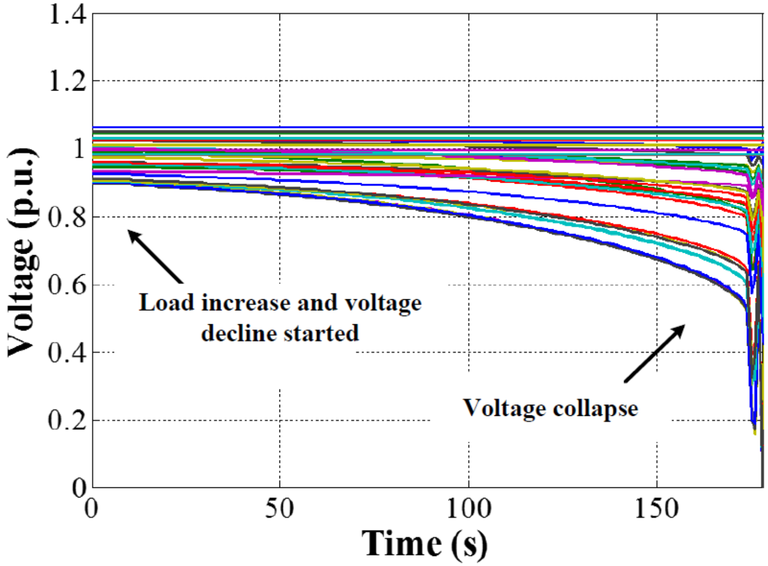
$$RVSI_i = w_1(i) \times \frac{VVN_i}{VVN_{max}} + w_2(i) \times \frac{CVV_i}{CVV_{max}}$$

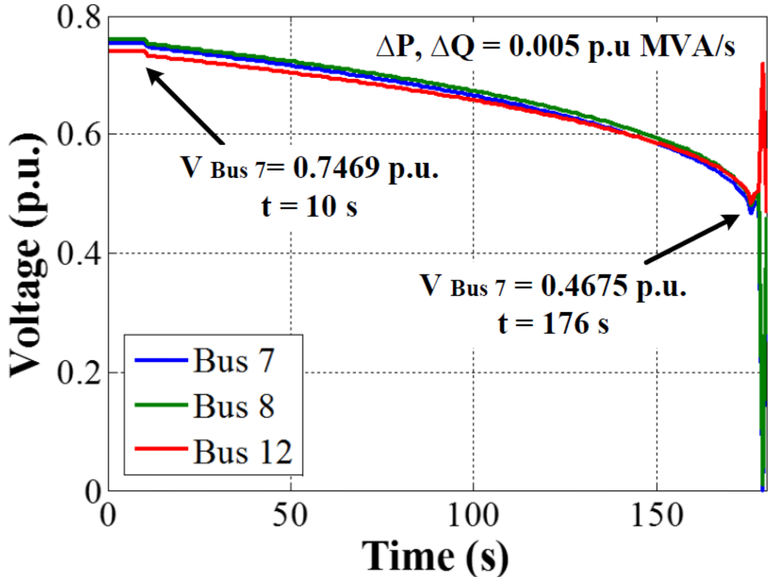
- **$VVN_i$ , $VVN_{max}$** - voltage variation and maximum voltage variation from reference value at the *i*-th measuring instant;
- **$CVV_i$ , $CVV_{max}$** - consecutive voltage variation and maximum consecutive voltage variation at the *i*-th measuring instant;
- **$w_1$(i), $w_2$(i)** - weights of the rate of the two criteria




[3] R. Sodhi, S. C. Srivastava and S. N. Singh, "A Simple Scheme for Wide Area Detection of Impending Voltage Instability", IEEE Transactions on Smart Grid, Vol.2, No. 3, pp 818-827, June 2012.

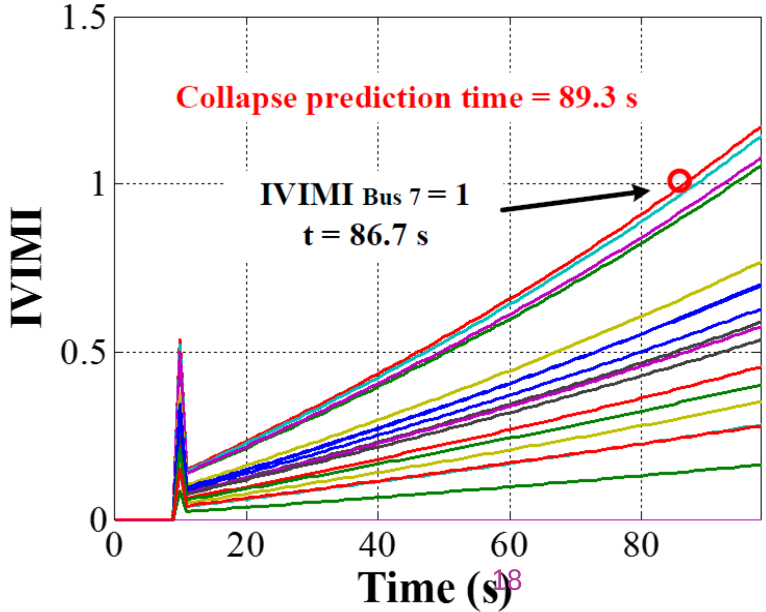
# Off-line Verification of Improved Voltage Instability Monitoring Index (IVIMI)



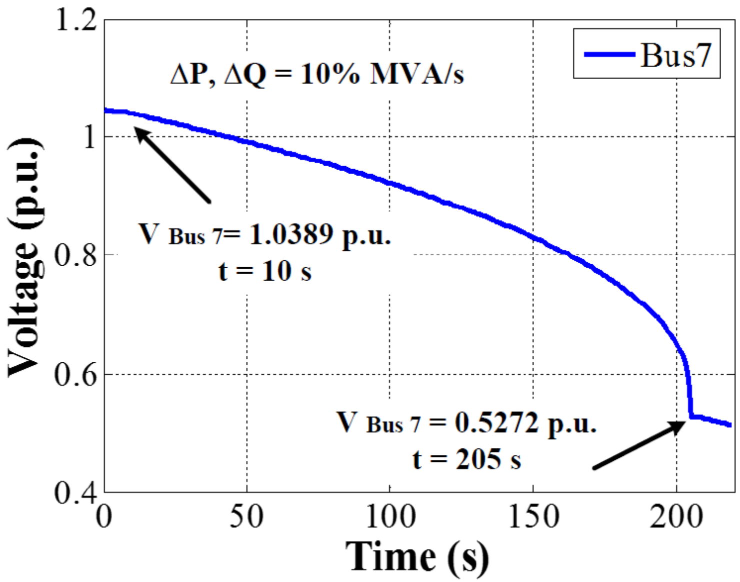



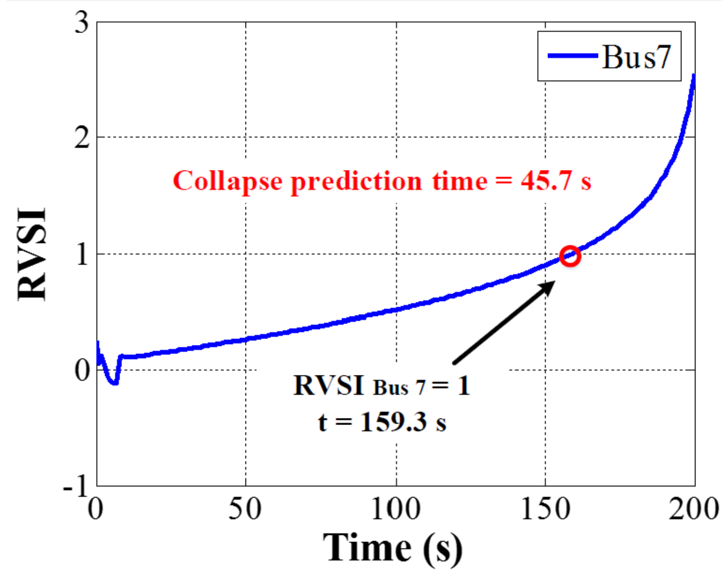

- Continuous load increase of 0.005 pu MVA/s at 19 load buses, starting at $t = 10$ s
- Voltage collapse $V_{C\ Bus\ 7}$=0.4675 pu at $t = 176$ s
- IVIMI = 1 at t = 86.7 s
- Collapse prediction time

  $t = 176 - 86.7 = \underline{89.3\ \text{s}}$



# On-line Simulations of modified Real-time Voltage Stability Index (RVSI)



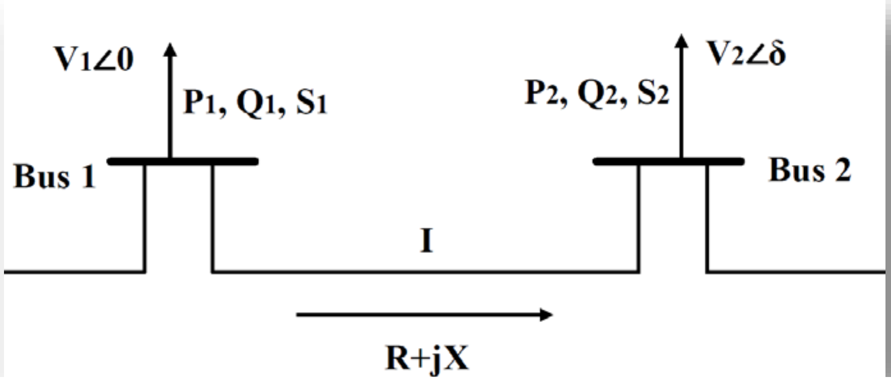




| Simula-tions type | Type of load | Load increase, pu MVA/s | Weakest buses | Collapse voltage, pu | Collapse time, s | IVIMI=1 time, s | Prediction time, s |
|---|---|---|---|---|---|---|---|
| Off-line | PQ | 0.005 | 6, 5, 7 | 0.5182 | 87 | 74.68 | 12.32 |
| | ZIP | 0.005 | 7, 8, 12 | 0.4675 | 176 | 86.7 | 89.3 |
| Real-time | PQ | 10 % | 7 | 0.5272 | 205 | 45.7 | 159.3 |

# CONTENTS OF THE PRESENTATION:

# Real-time Fast Voltage Stability Index (RFVSI)

- Tested Fast Voltage Stability Index (FVSI) [4,5] using off-line & real-time simulations (RFVSI)
- Index requires loading information at each bus, voltage measurements at receiving end buses & transmission lines impedances
- Able to determine critical lines, maximum transferrable power and voltage collapse point




$$\boldsymbol{RFVSI_{ij}(i) = \frac{4Z^2 Q_j(i)}{[V_i(i)]^2 X}}$$

$X$, $Z$ - line reactance and impedance (constant values),

$$\boldsymbol{Q_j(i) \leq Q_{j\,max}}$$

$$\boldsymbol{V_i(i) \geq V_{i\,min}}$$

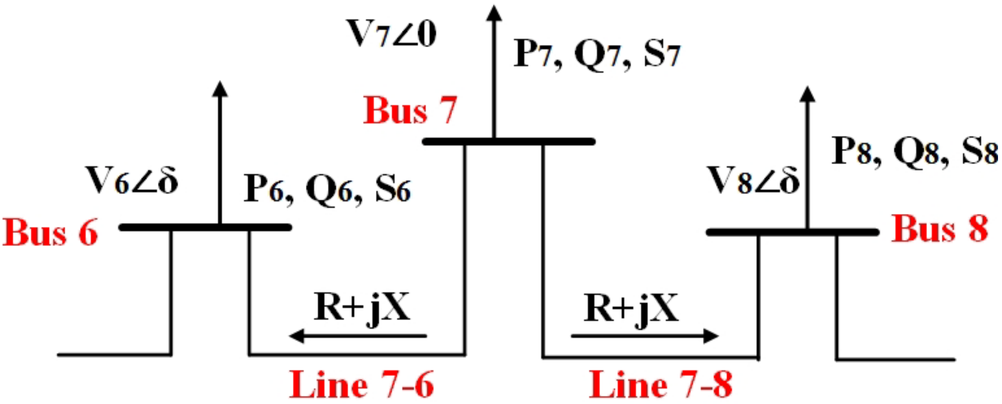
$Q_j$, $Q_{j\,max}$ - reactive power and maximum allowable reactive power at the receiving bus at each measuring instant $i$,

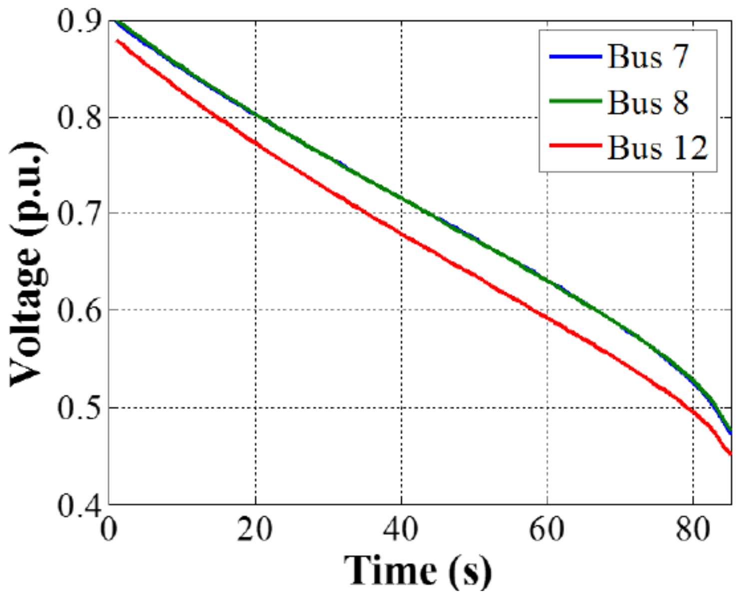
$V_i$, $V_{i\,min}$ - voltage and minimum allowable voltage at the sending bus at each measuring instant $i$

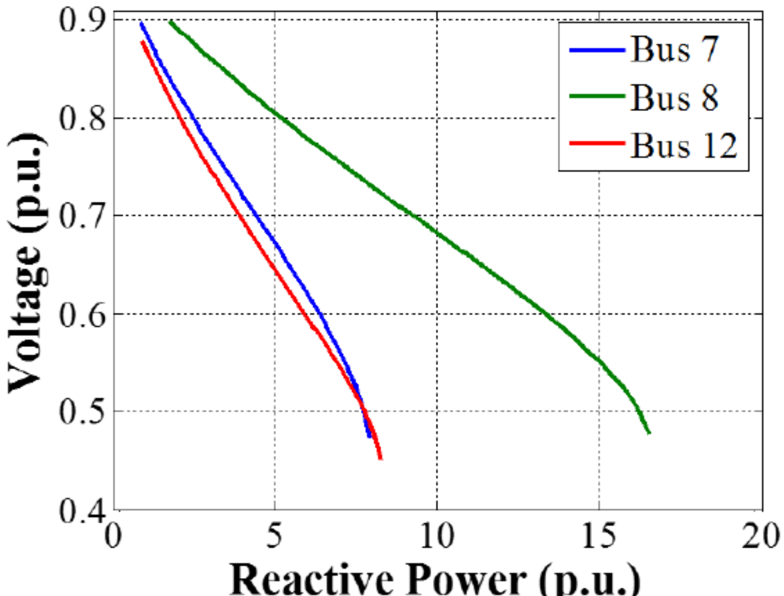

[4] C. Cardet, "Analysis on Voltage Stability Indices", Master Thesis, Institute for Automation for Complex Power Systems, German Energy Research Center, 2010.

[5] I. Musirin and T. Rahman, "Novel Fast Voltage Stability Index (FVSI) for Voltage Stability Analysis in Power Transmission System", 2002 Student Conference on Research and Development Proceedings, Slah Alam, Malaysia, pp. 265-268, July 2002.

# Off-line Testing of Fast Voltage Stability Index (FVSI)




- Transmission lines between buses 7 – 6, and 7 - 8
- Constant reactive load increase at a rate of 0.1 pu MVAR/s
- Voltage collapse occurred at $t$=85 s
- Maximum reactive power transferred $Q_{max}$=778.7 MVAR
- Line 76 found to be more critical than line 78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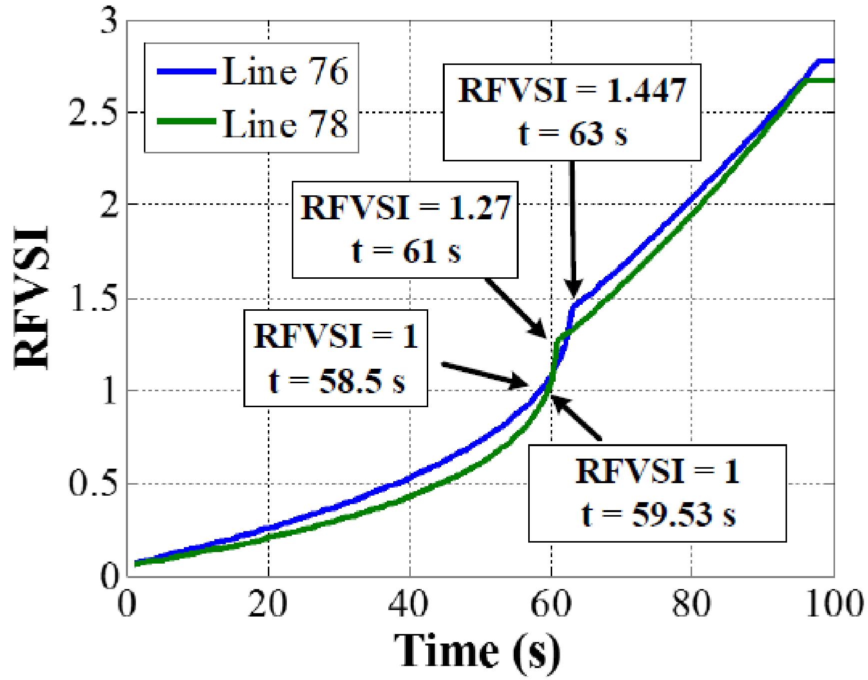
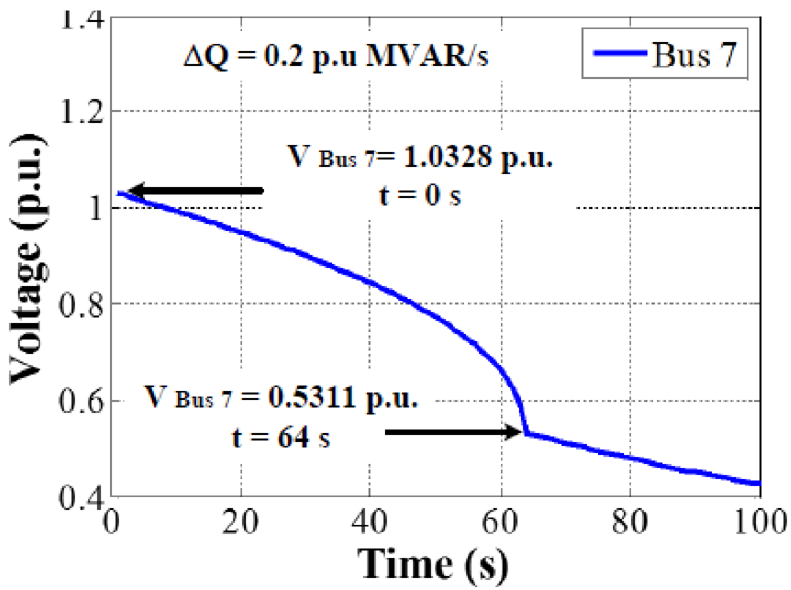
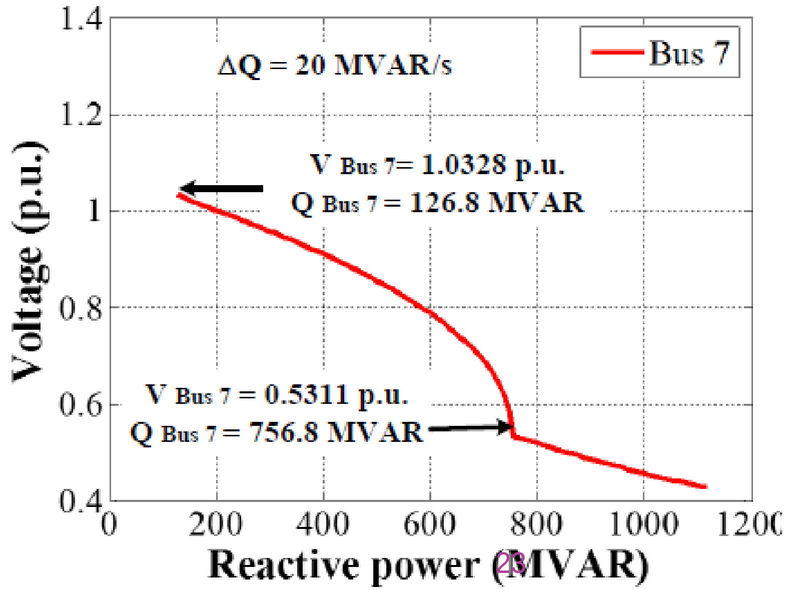
# RTDS Simulations of Fast Voltage Stability Index (RFVSI)

- Transmission lines between buses 7 – 6, and 7 - 8
- Constant reactive load increase at a rate of 0.2 pu MVAR/s
- Nominal loading at remaining buses at 150%
- Voltage collapse $V_C$=0.5311 pu occurred at $t$=64 s
- Maximum reactive power injected $Q_{max}$=756.8 MVAR
- Line 76 is more critical than line 78



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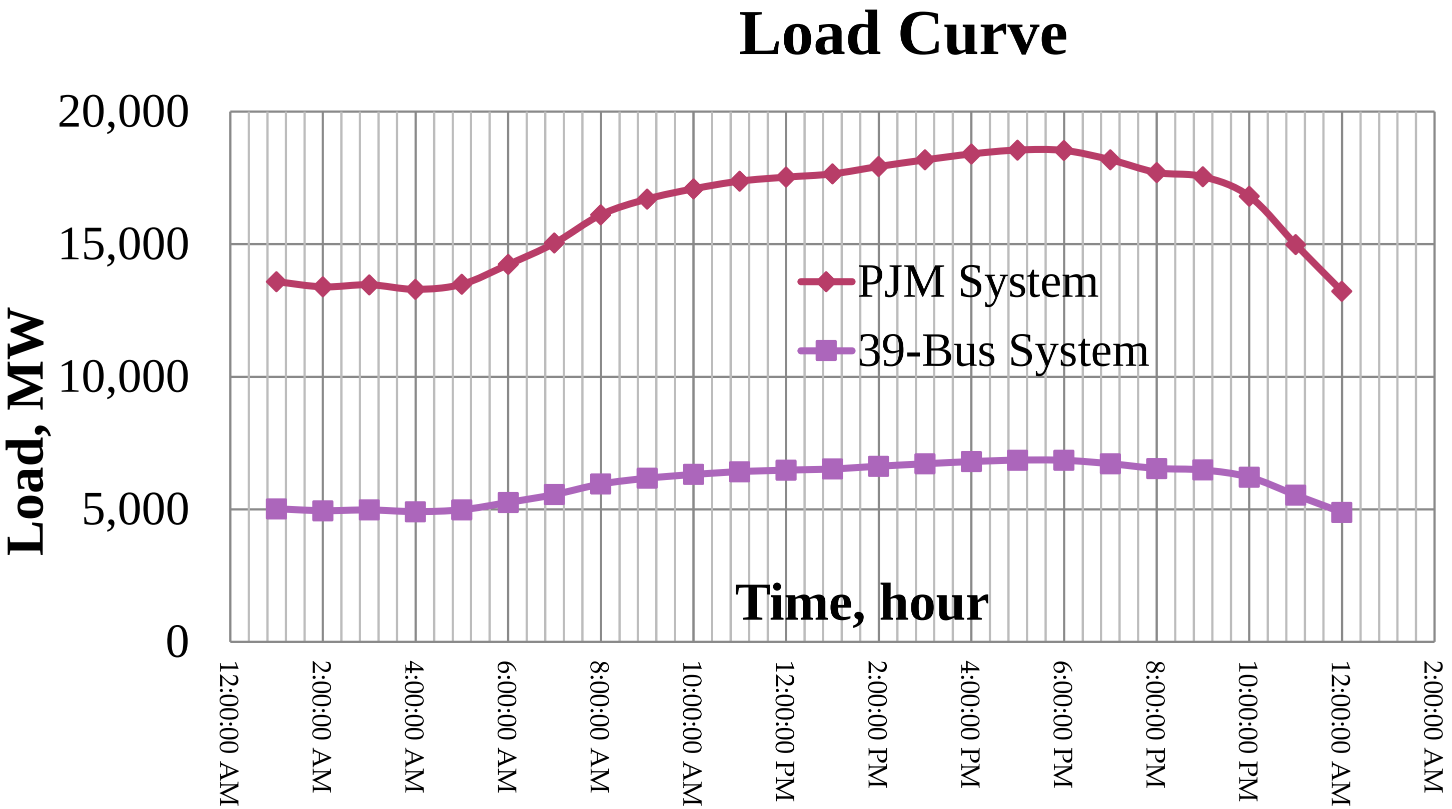
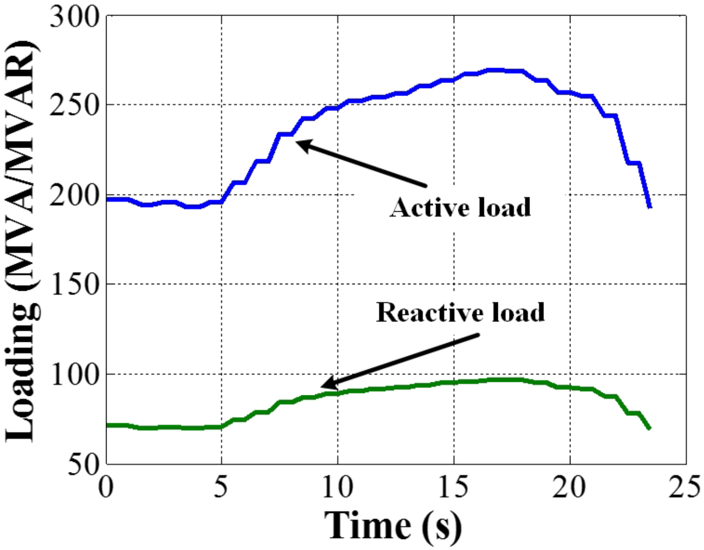
# Verification of Proposed RVSM Method with Dynamic Load Variations

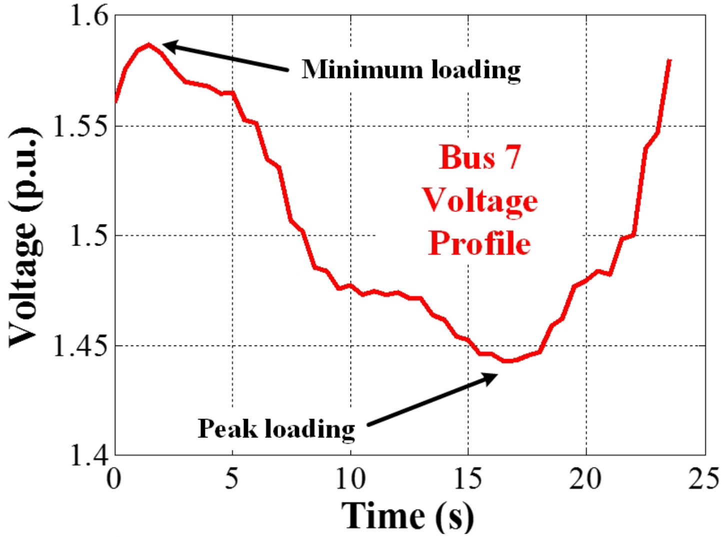



- Dynamic load curves
- PJM Summer 2013 peak load profile – 155,100 MW
- 24-hours PJM system load data scaled to IEEE 39-bus system
- 24 hours load profile is simulated in 24 seconds

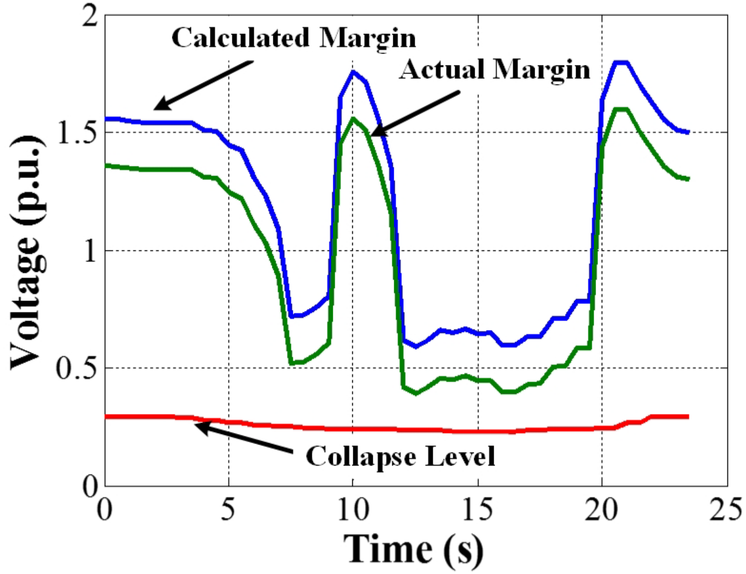
# Real-time (RTDS) Simulations for RVSM Testing

Normally Loaded System



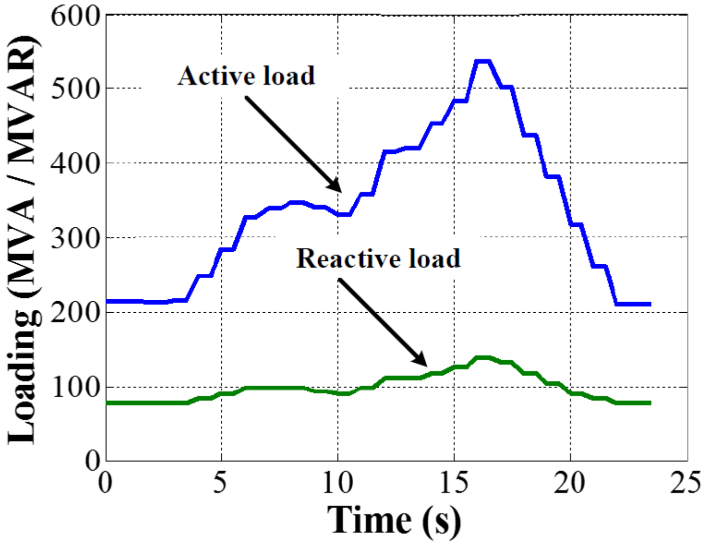



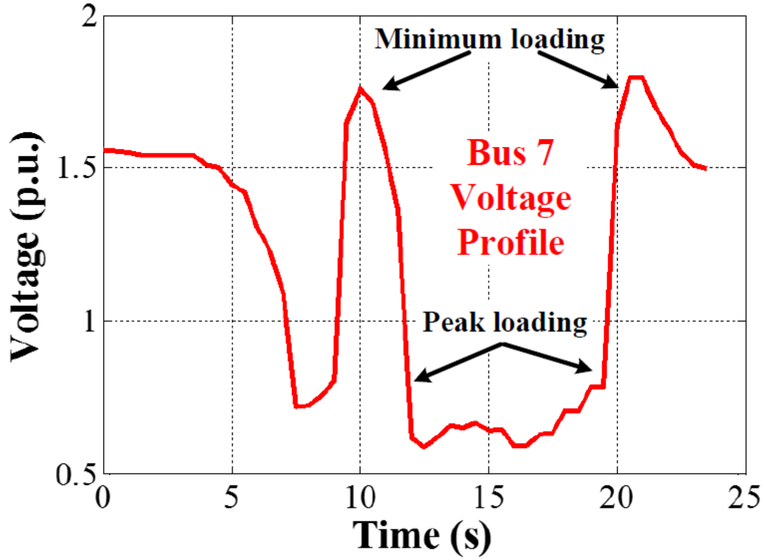

- Bus 7 voltage stability margins
- Voltage collapse $V_C$ between 0.2289 pu and 0.2928 pu
- Minimum calculated margin:
  - $M_C = 0.5875$ pu
- Minimum actual margin:
  - $M_A = 0.3875$ pu



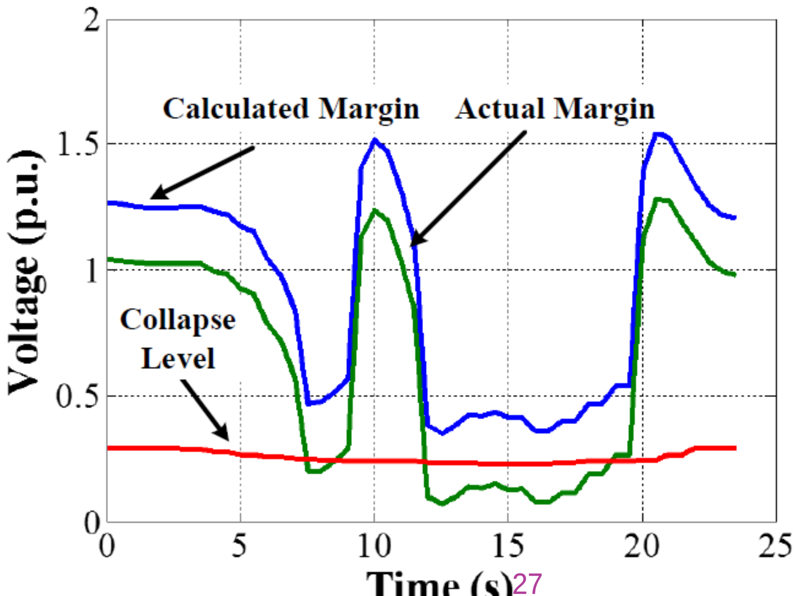
# Real-time (RTDS) Simulations for RVSM Testing

## Heavily Loaded System




- Bus 7 voltage stability margins at peak load
- Voltage collapse $V_C$ between 0.2289 pu and 0.2928 pu (same)
- Minimum calculated margin:
  - $M_C = 0.3524$ pu
- Minimum actual margin:
  - $M_A = 0.0710$ pu



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# Conclusion

- **Real-time Voltage Stability Margin (RVSM) method** – proved to be accurate (off-line and real-time simulations). Used local measurements to find maximum admissible loading, voltage collapse point and determine voltage stability margins at critical buses.
- **Real-time Voltage Stability Index (RVSI)** – verified using wide area measurements of voltage deviations with ZIP and PQ load models; able to find voltage collapse prediction time at each bus.
- **Real-time Fast Voltage Stability Index (RFVSI)** – tested to determine weakest lines in the system, maximum reactive power to be transferred and voltage collapse point.
- **On-line RVSM (Margin Method)** was verified using dynamic load variations (realistic daily load curves) for normal and stressed conditions.