Helping to keep the lights on,
businesses running
and communities strong®

System Studies for American Transmission Co.’s Benson Lake SVC Project

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Outline

- Introduction to ATC
- Benson Lake SVC Project Background
- Project Technical Specifications
- Design Phase Studies
- Other thoughts, pictures, questions

Introducing ATC

- Began in 2001
- First multi-state, transmission only utility in U.S.

Introducing ATC

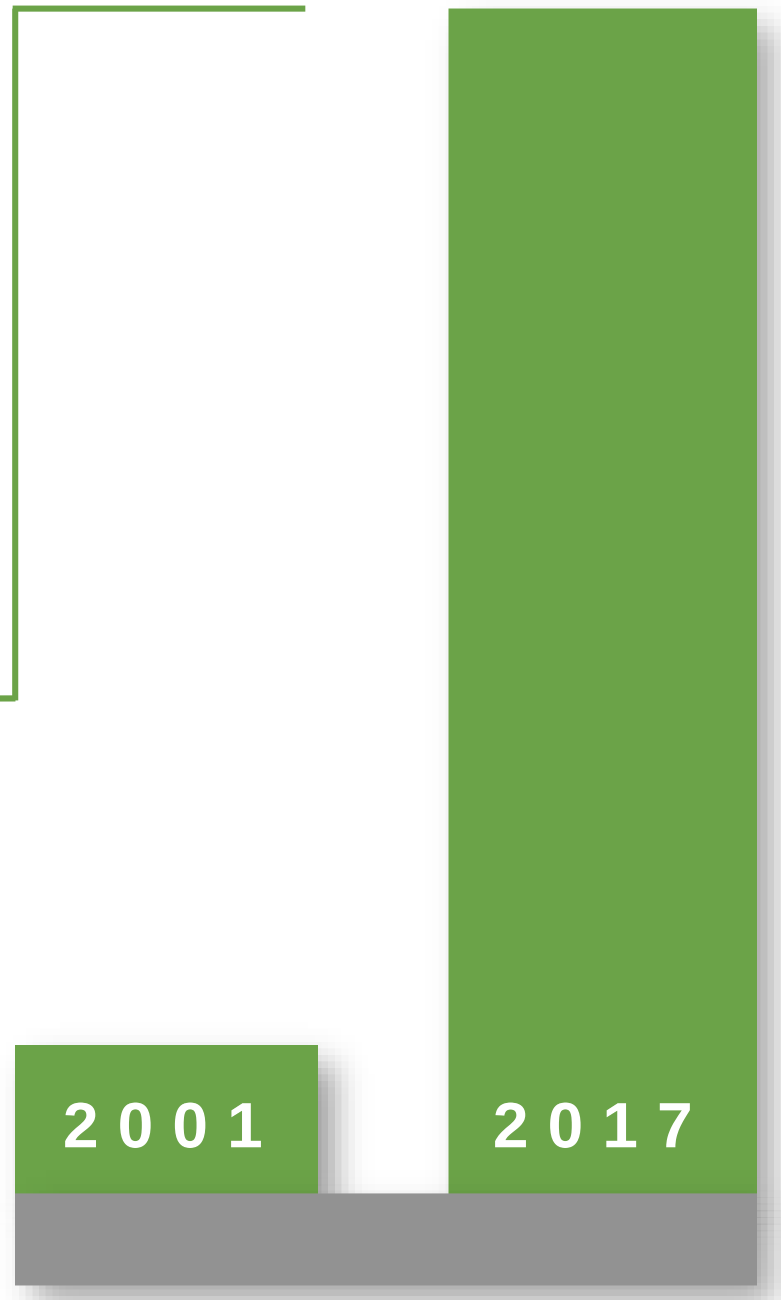
Headquartered in Pewaukee, Wis.

Introducing ATC

Assets

$550 million in 2001

$4.6 billion today

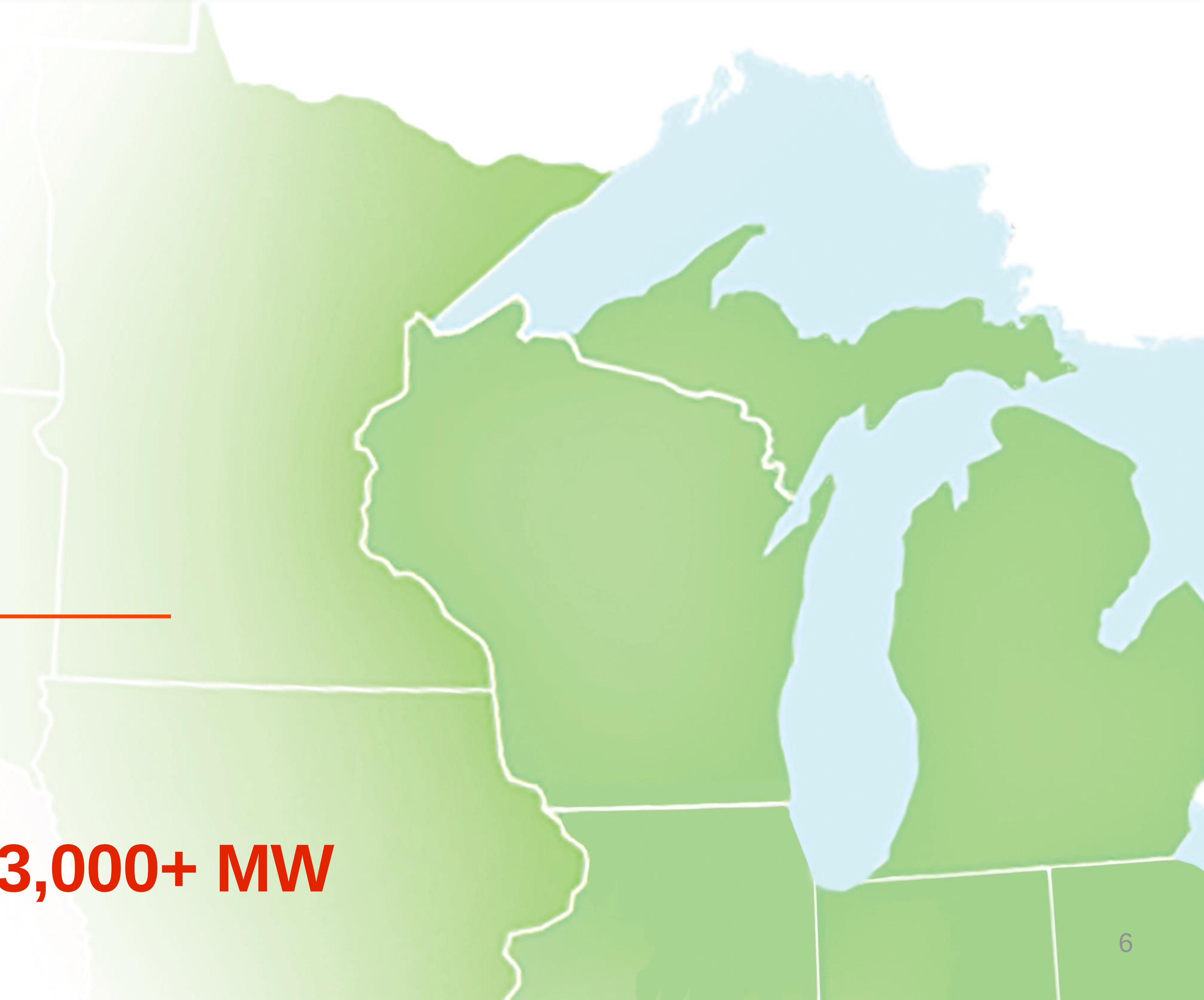


Introducing ATC

WE OPERATE

9,600+ miles of lines
& 554 substations in

Wisconsin	Michigan
Minnesota	Illinois



Historical Peak load of 13,000+ MW

Diverse ownership

PRIVATELY HELD BY

26 Owners

utilities	municipalities
electric companies	electric cooperatives

Introducing ATC

ATC owns and operates several unique devices

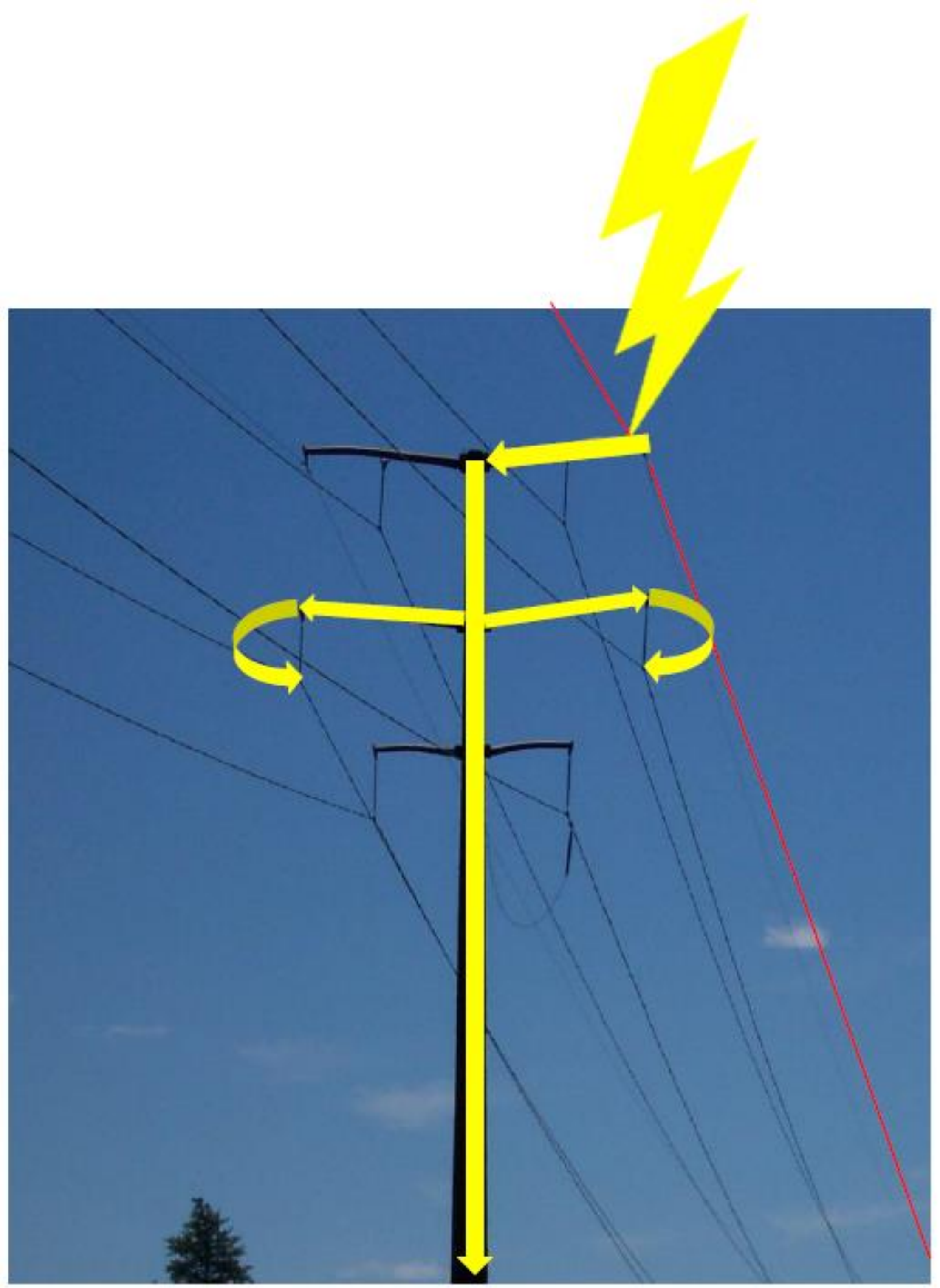
May 10, 2011 West & Central UP Blackout

- **Upper Peninsula (UP) of Michigan connections circa 2011**
  - East Connections: Two 138-kV submarine cables across the Straits of Mackinac
  - South-Central Connections: One 345-kV and two 138-kV lines from NE WI
  - South-West Connections: One 138-kV and one 69-kV line from North Central WI
- **Load in the central and west UP in the 500 – 600 MW range**
- **East UP was split from the west and served radially from Lower Michigan**
  - Split was used to control system overloads due to high flows across the UP
  - Split no longer used due to addition of the Mackinac HVDC project

May 10, 2011 West & Central UP Blackout

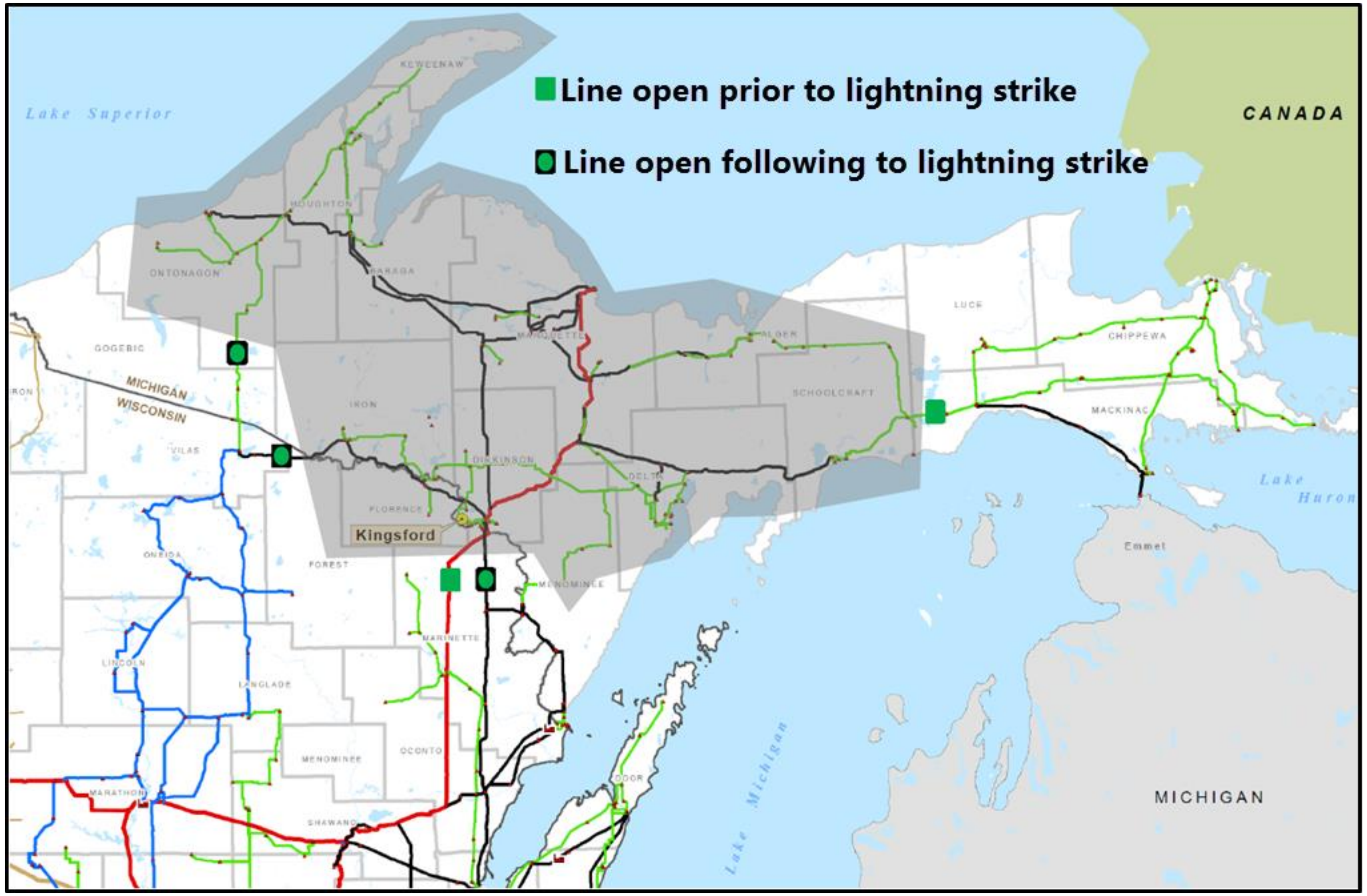
- **Planned outage of the 345-kV circuit**
  - All outage planning and system operating policies and procedures were followed
- **93 kA Lightning strike caused fault on double circuit 138-kV lines**
  - Autoreclose unsuccessful due to large phase angle
- **Remaining 138-kV & 69-kV ties tripped within ~2.5 sec to form an island**
- **Outage scenario exceeded operating policies of the time**

May 10, 2011 West & Central UP Blackout

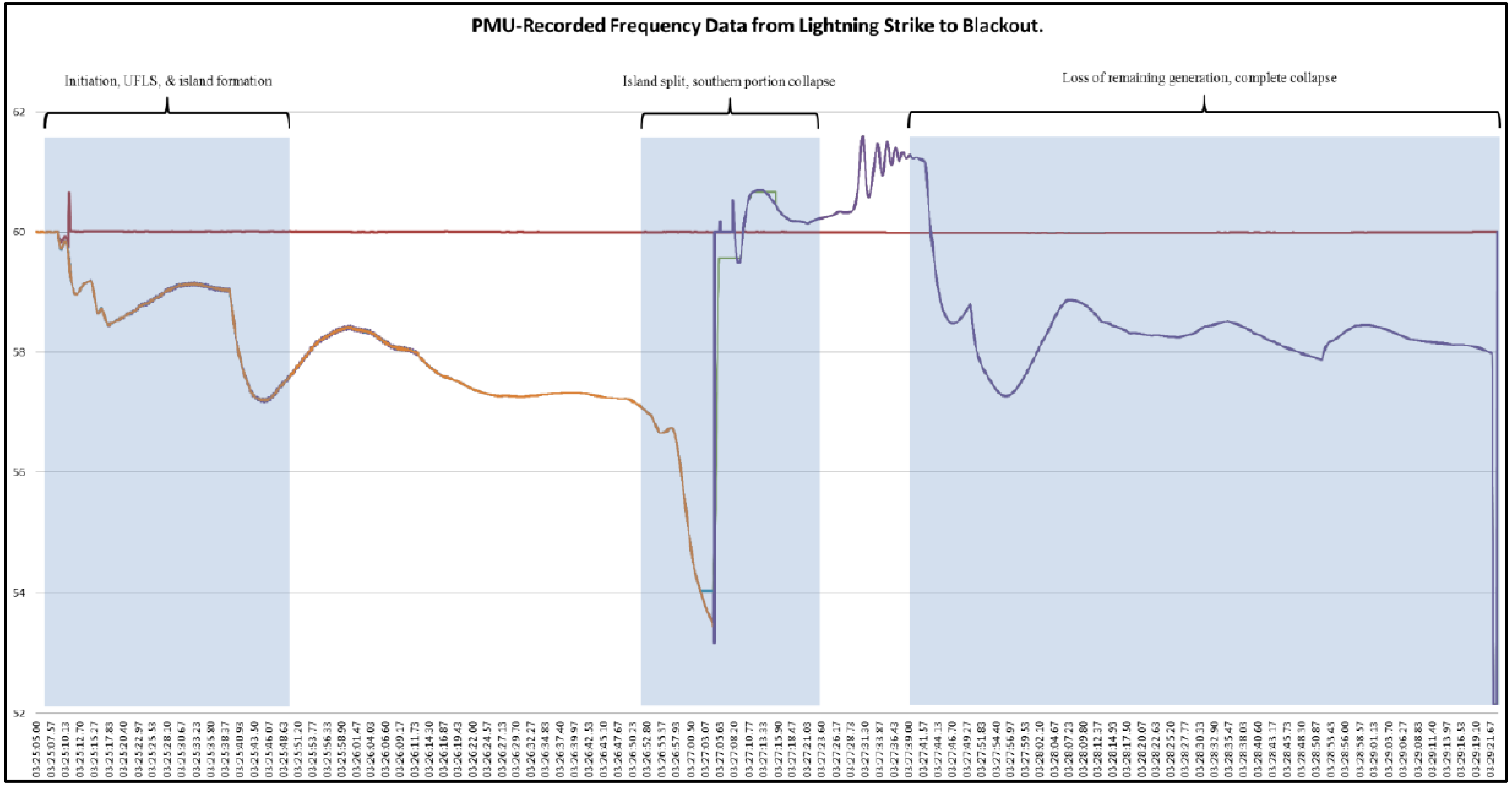


- **Shield wire received a direct stroke of 93 kA**
- **Poor high impedance grounding causes tower to elevate in voltage**
  - Due to difficult area geology, not line construction
- **Results in insulation flash-over and faults the middle phase of both circuits**
  - Arresters had been installed on the bottom phase of both lines

May 10, 2011 West & Central UP Blackout



May 10, 2011 West & Central UP Blackout



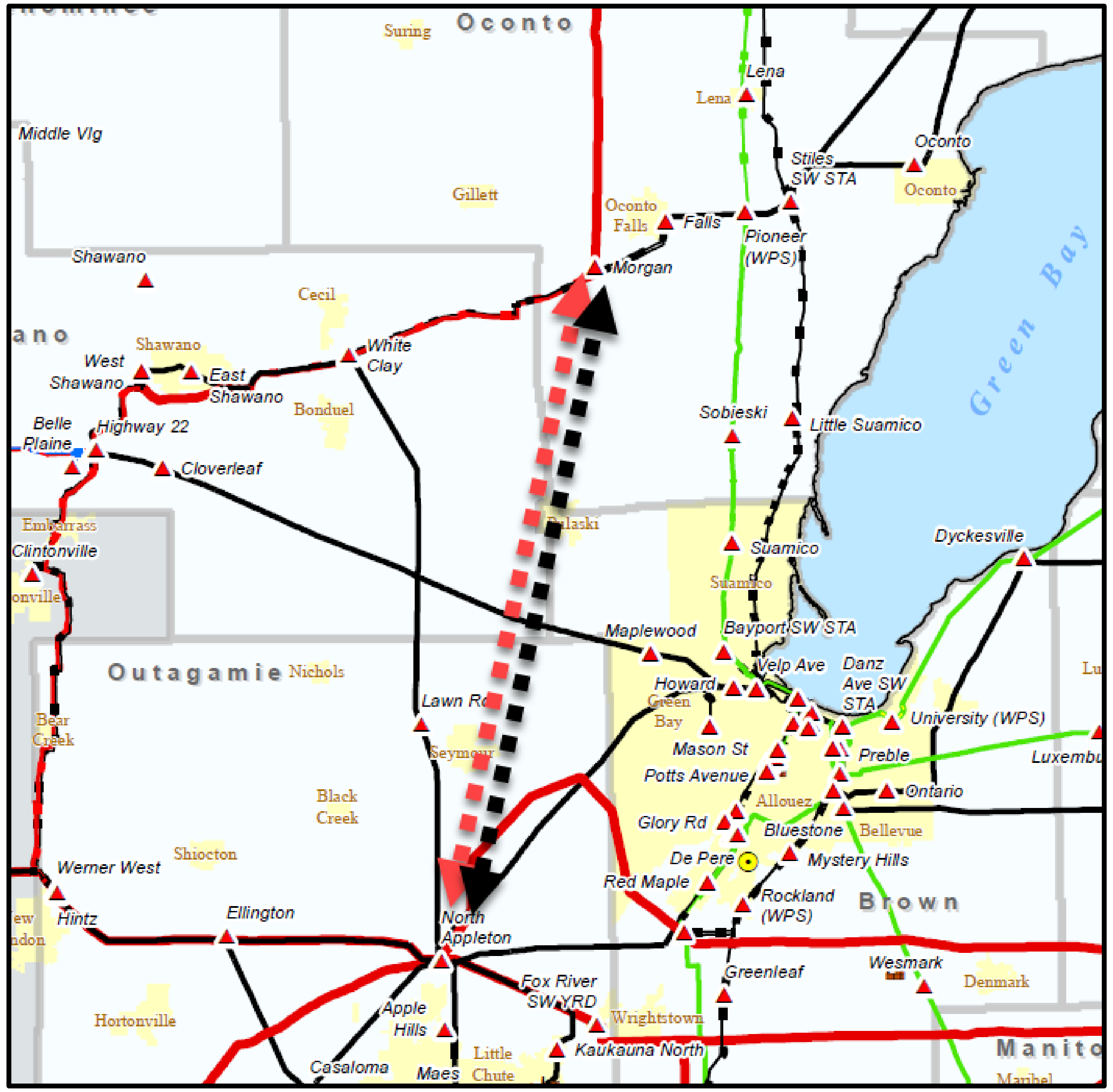
May 10, 2011 West & Central UP Blackout

- **Event Outcomes**
  - Update Power Plant protection settings
  - Update T-line reclosing settings
  - Update Operating Procedures

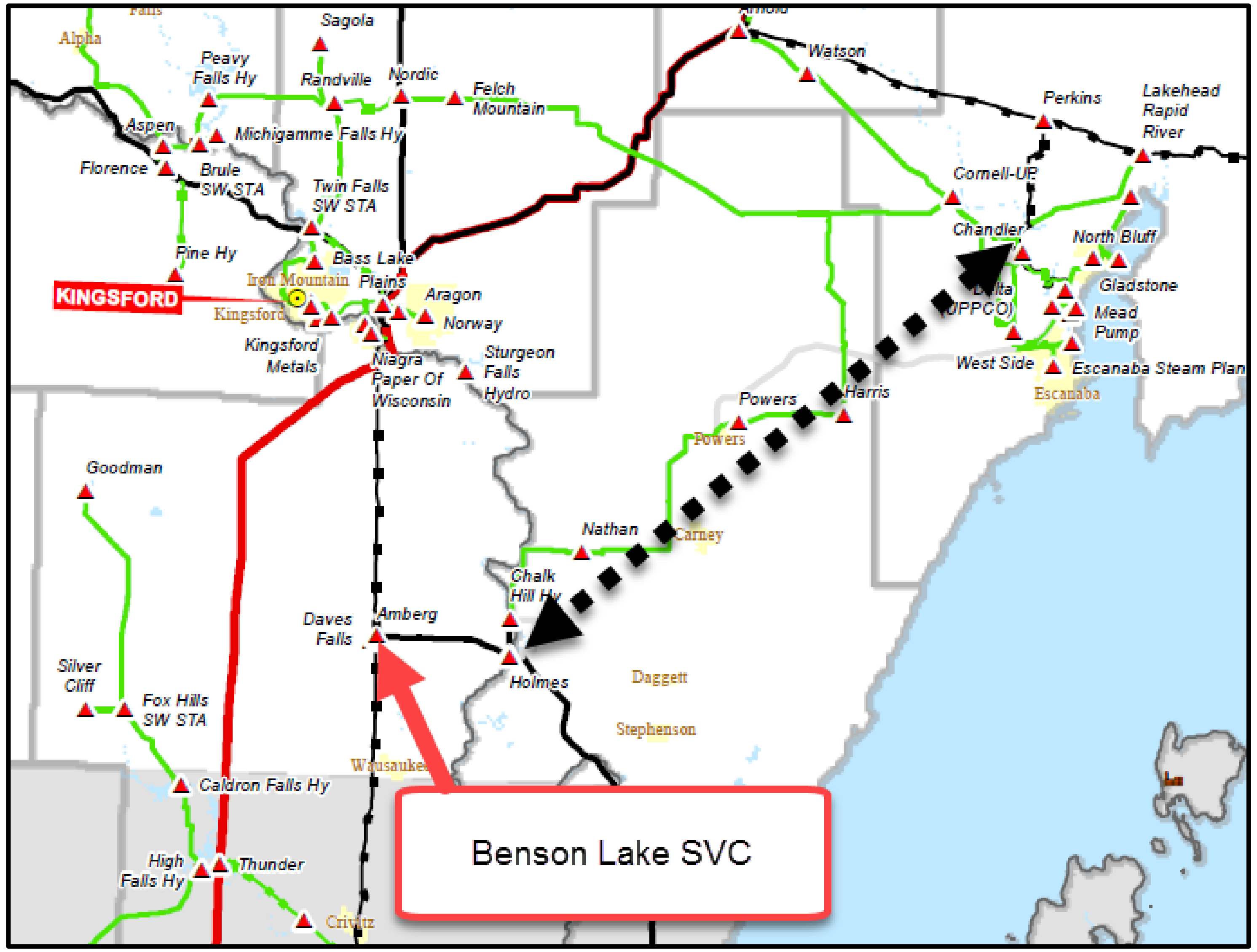
- **Transmission Projects Needed**
  - Address series of events leading to May 10, 2011 outages
  - Retirements of old generation
  - Large iron ore mine load changes

Bay Lake Projects

New North Appleton to Morgan transmission lines



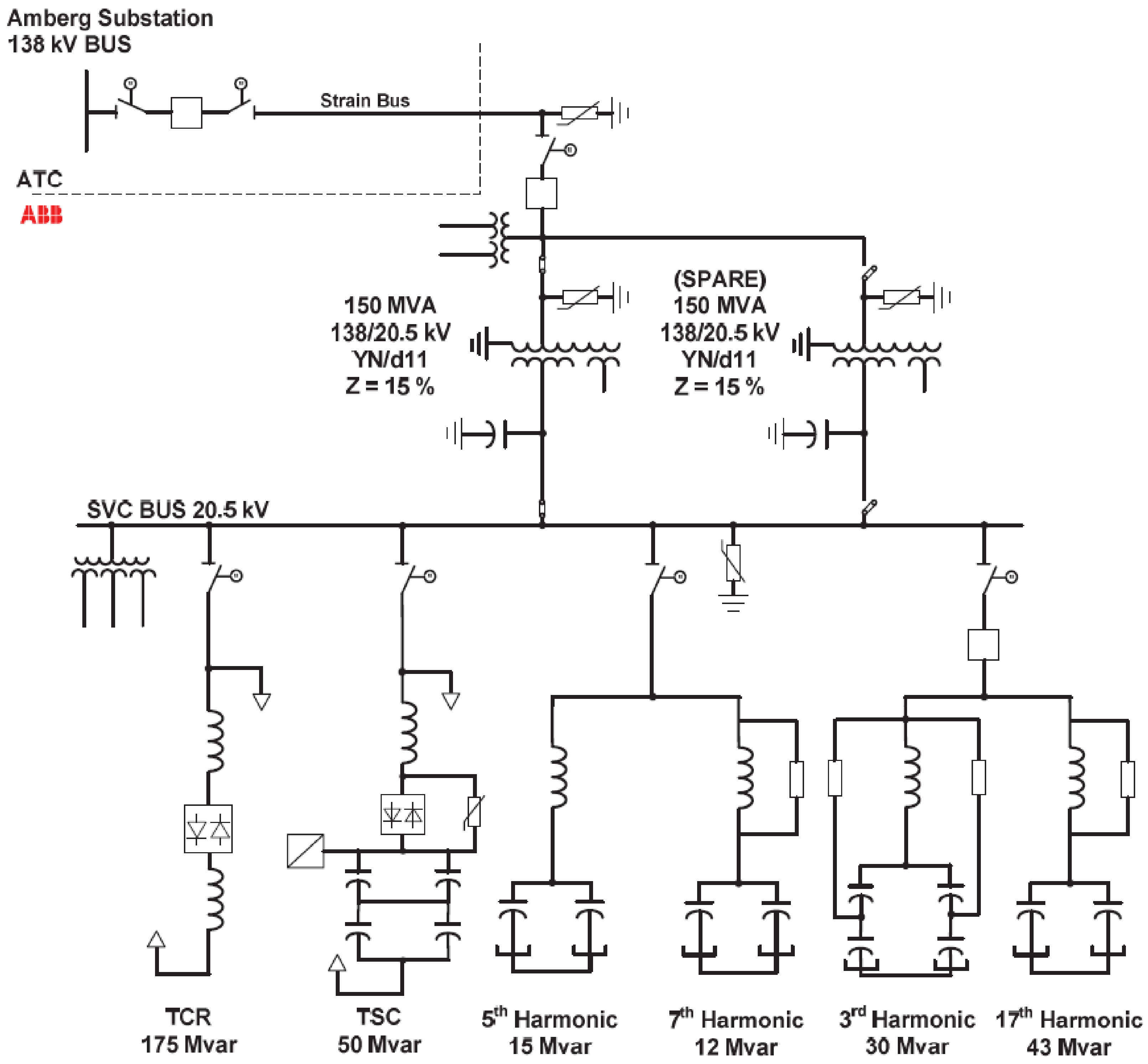
New Holmes to Old Mead Road line and Benson Lake SVC



Benson Lake SVC

- **Project Highlights**
  - Vendor: ABB
  - **Rated for 150 Mvar capacitive and 75 Mvar inductive**
  - 175 Mvar TCR
  - 50 Mvar TSC
  - 100 Mvar filters: 3rd, 5th, 7th, and 17th/HP
  - Rated for continuous operation between 0.90 and 1.1 pu voltage on the 138-kV system
  - Size and location of device determined based on dynamic stability studies
- **Commissioning Dates**
  - Cold Commissioning: Started March, 2017
  - Hot Commissioning: Started April, 2017 and concluded with transmission testing mid-May.
- **Commercial as of June 30/July 3**

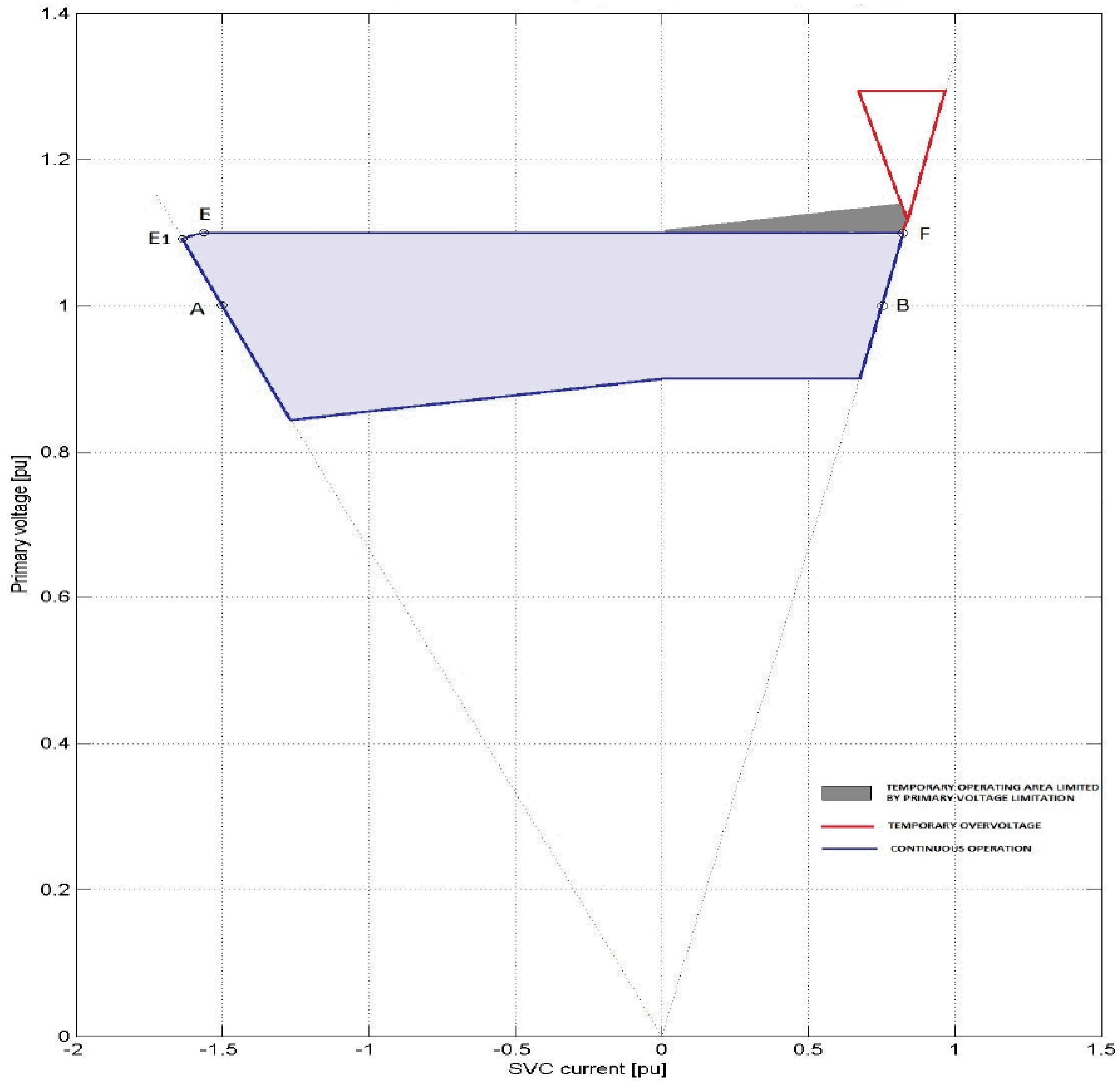
Benson Lake SVC



Simplified Single-line Diagram

Courtesy of ABB

Benson Lake SVC



VI Diagram, 100 MVA base

Courtesy of ABB

Benson Lake SVC

- **Many controls to tune and coordinate**
- **Control Highlights – Planning POV**
  - Auto/Manual: Control of voltage/reactive power
  - Power Oscillation Damping Controller (POD): Damp area low frequency oscillations
  - Undervoltage Control Strategy: Optimize behavior during and after system faults
  - Gain Supervision, Optimizer, & Reset: Optimize control gains for weakened system
  - Slow Reactive Power Control: Help ensure voltage control is spread among devices
  - Negative Phase Sequence Controller: Reduce negative sequence area voltages
  - Ground Fault Locator: Detects and locates faults in TSC. Can allow auto restart.
  - TSC Blocking – Symmetrical and Unsymmetrical: Prevents overvoltage after fault clearing

Benson Lake SVC - POD

- 60+ faults simulated across intact and prior outage cases (PSS/E Dynamics)

- Least Squares analysis performed on frequency signal from simulations
  - PSS/E PSSPLT program; suitable given system characteristics
  - Frequency is used as a local proxy for rotor speed of area machines

- All faults analyzed which results in a range of dominant modes

- With known system topology and modal analysis results the system can be simplified to a second order system

Benson Lake SVC - POD

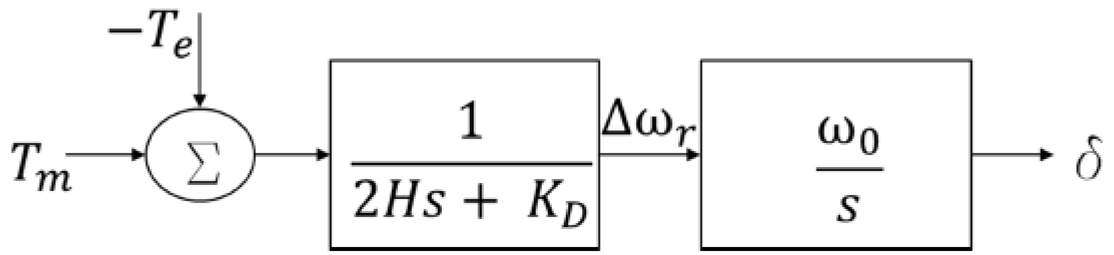
- **Rotor swing equations can be used as starting point for POD design**

- **Application of a signal (K_D) proportional to change in rotor speed can damp the oscillation**

$$\frac{d\Delta\omega_r}{dt} = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega_r)$$

$$\frac{d\,\delta}{dt} = \omega_0\Delta\omega_r$$

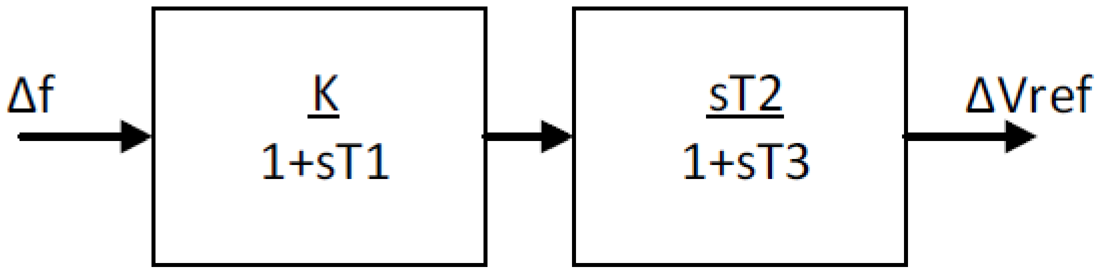
$$\frac{1}{\omega_0}\frac{d^2\delta}{dt^2} + \frac{K_D}{2H\omega_0}\frac{d\delta}{dt} - \frac{1}{2H}(T_m - T_e) = 0$$



Rotor Mechanical Equations

Benson Lake SVC - POD

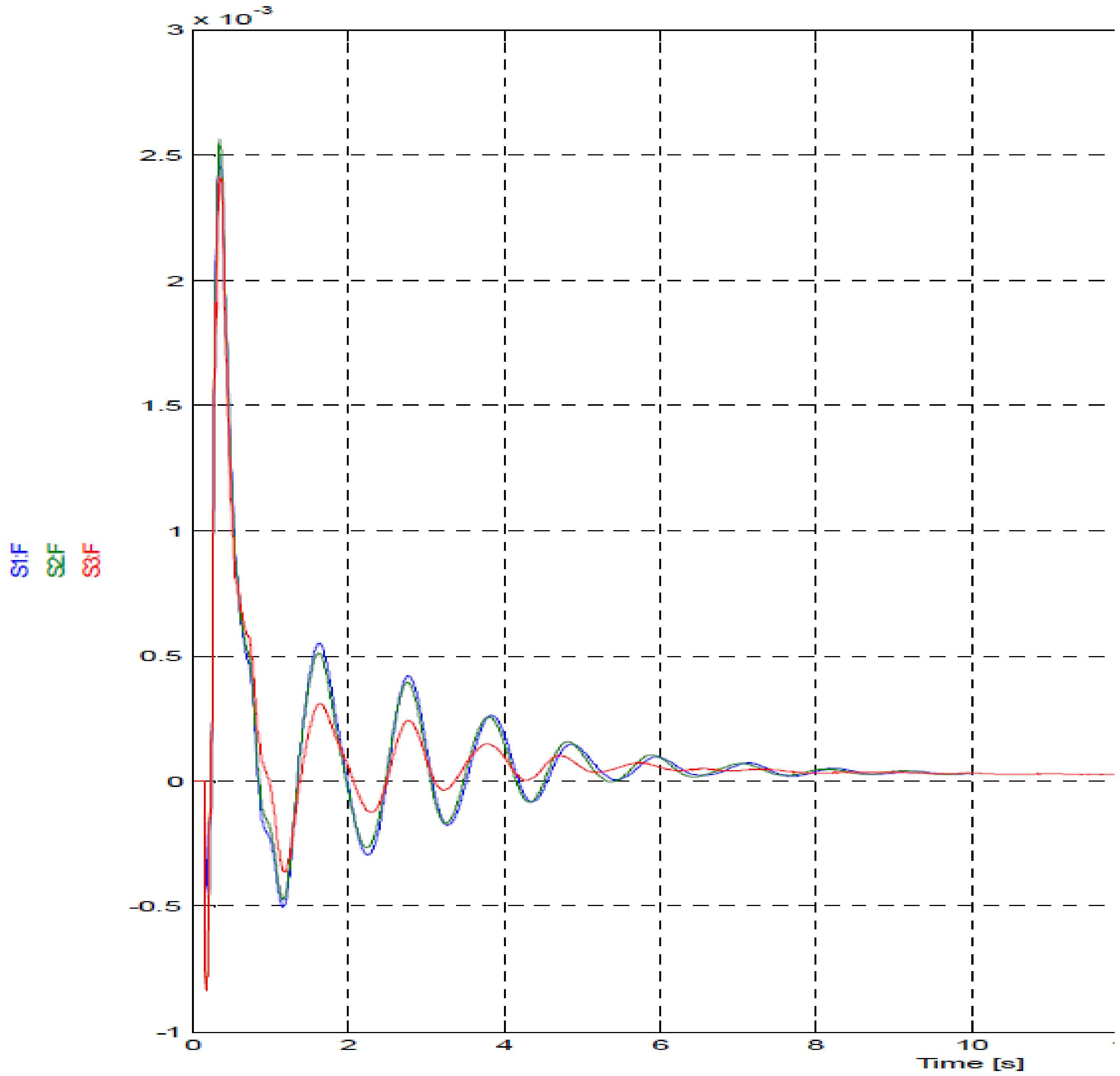
- Frequency deviation as an input
- An output is a contribution to the SVC voltage reference
  - K is important to test and tune for optimal performance
  - T1, T2, and T3 can be adjusted as needed
- POD tuning to strike a balance between frequency damping and voltage response



Simplified POD Block Diagram

Benson Lake SVC - POD

Example of frequency/rotor speed damping for a single minor event



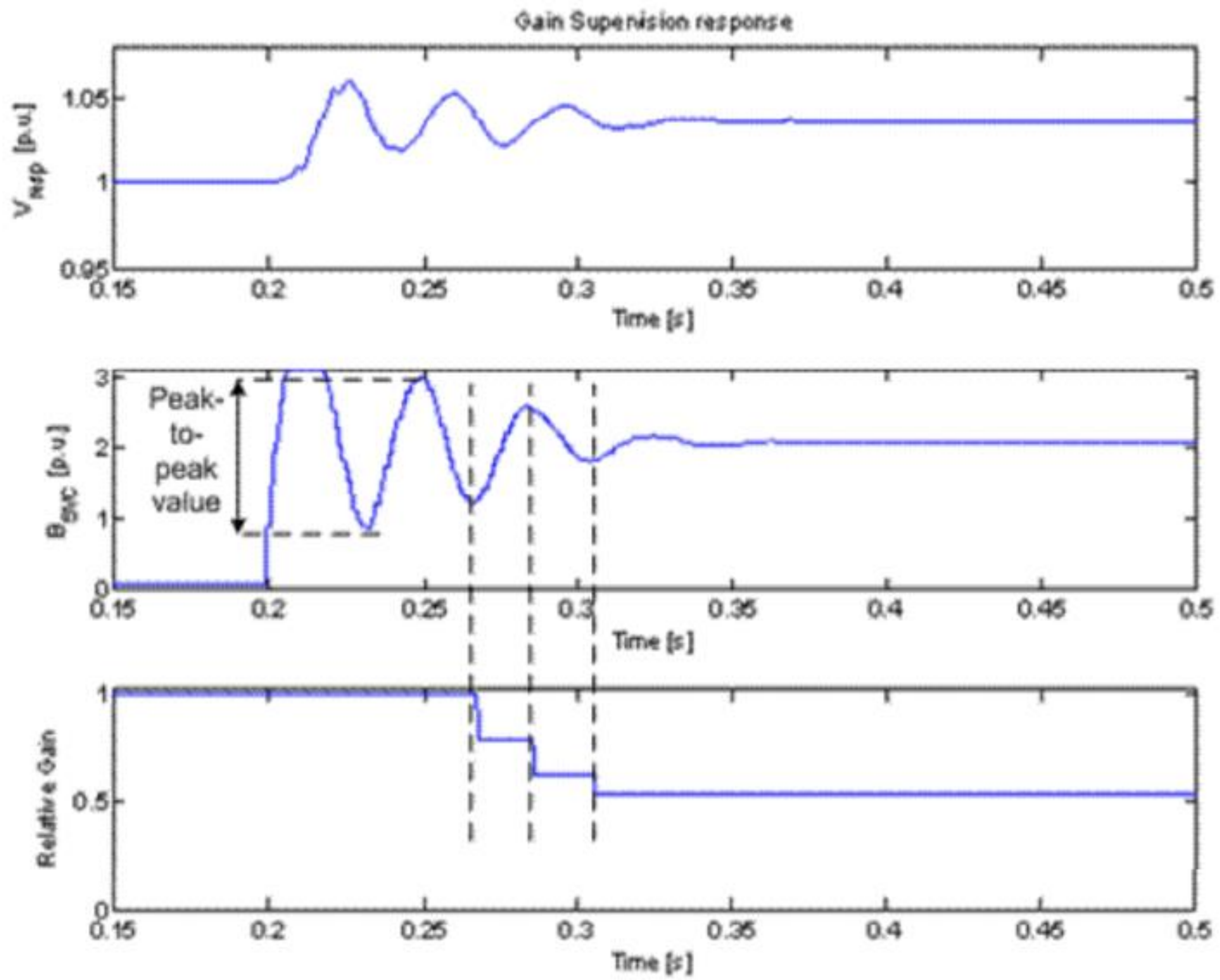
Blue is no SVC

Green is with SVC and no POD

Red is with SVC and POD

Benson Lake SVC – Gain Supervision, Optimizer, & Reset

- **Potential voltage oscillations in weakened grid**
- **Voltage regulator gain can be automatically adjusted**

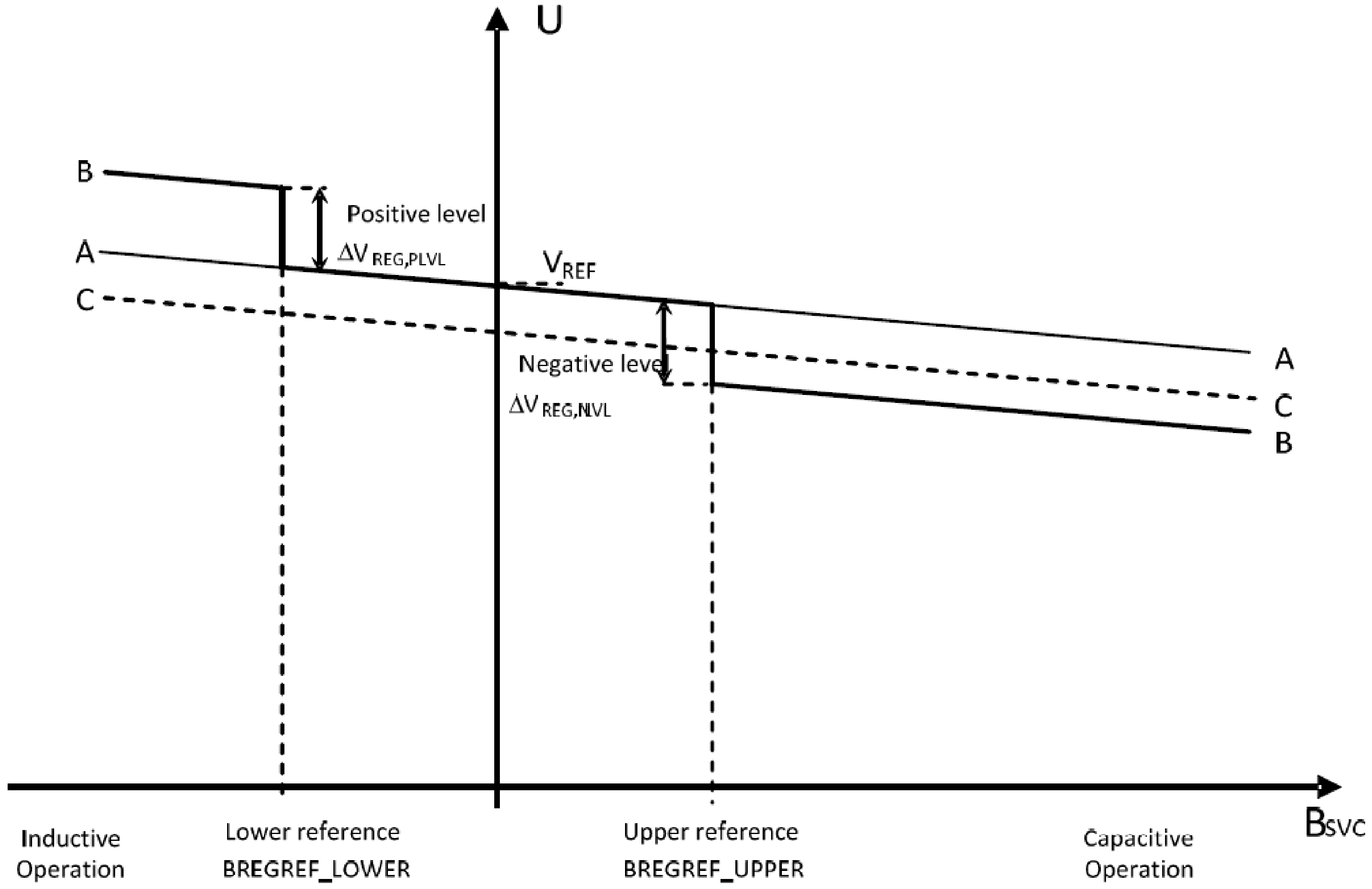


Simplified Example of Gain Adjustment

Courtesy of ABB

Benson Lake SVC – Slow Reactive Power Control

- Steady state voltage control should be shared across devices
- Desirable to maintain dynamic response of the SVC
  - Off is line A in steady state
  - On is line B in steady state
  - Line C represents dynamic resp

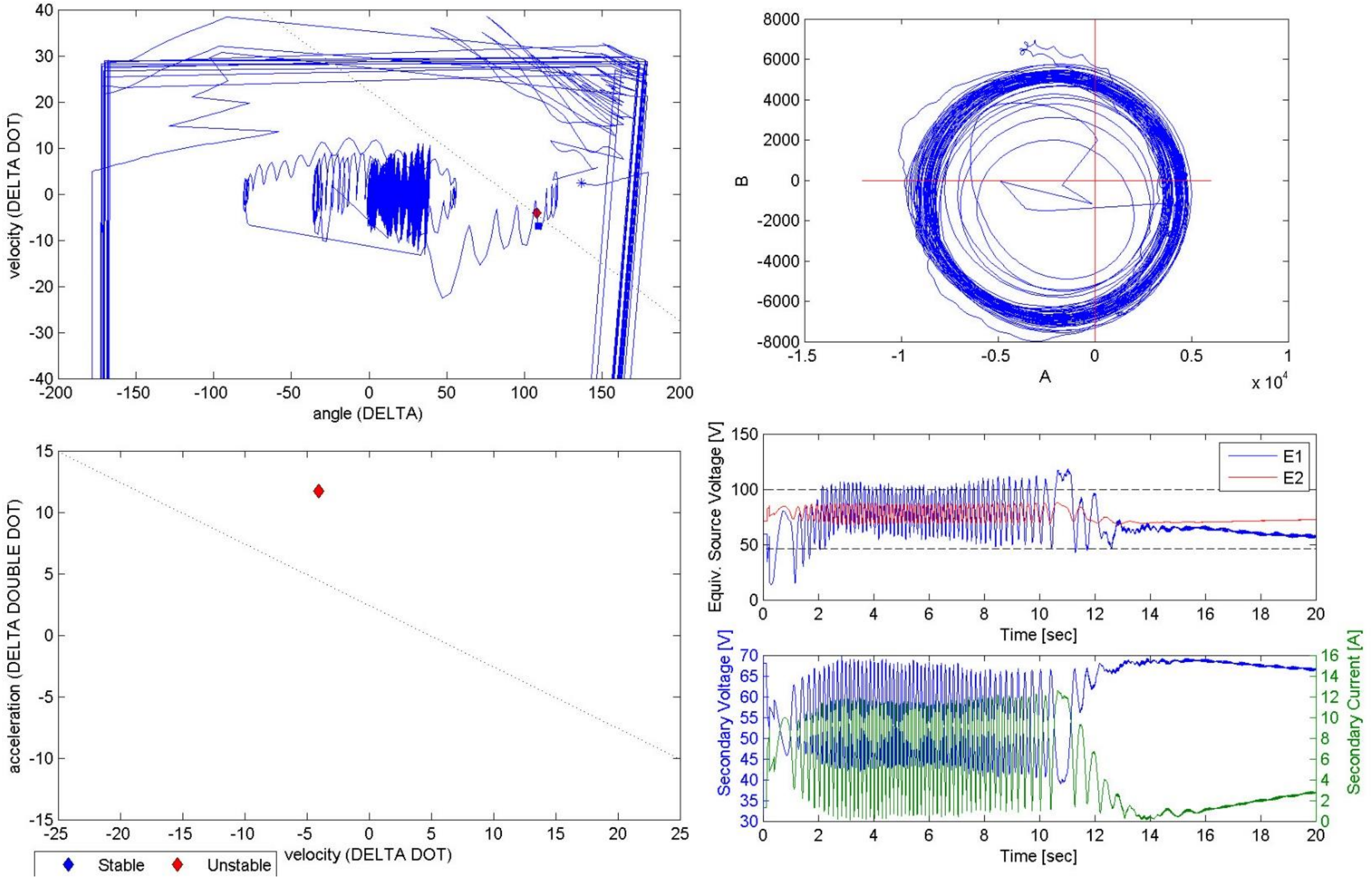


SRPC Example

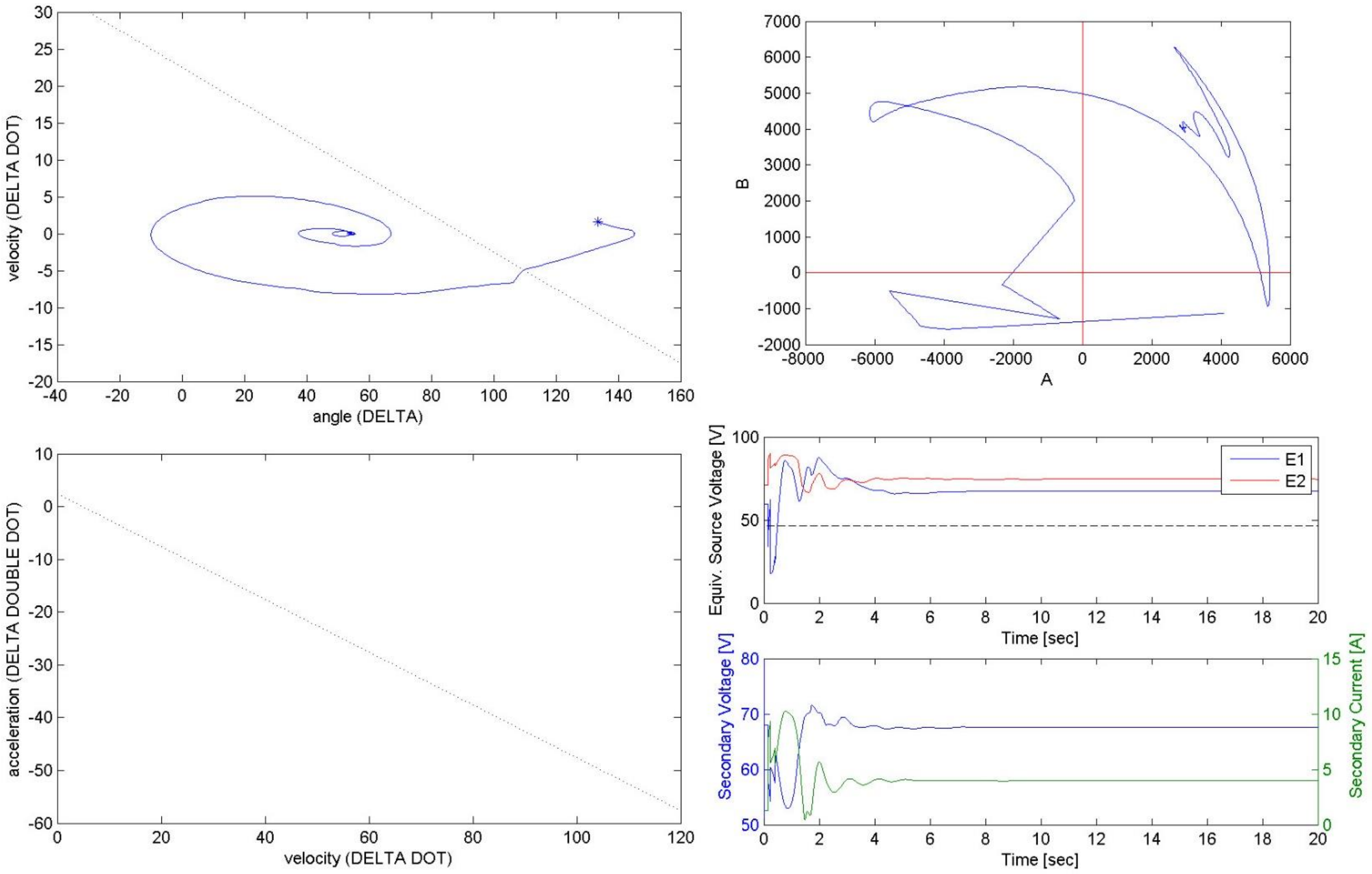
Courtesy of ABB

Benson Lake SVC

System Dynamics – No SVC



Improved System Dynamics – SVC with POD



Benson Lake SVC – Other Thoughts

- Important to test the device across a wide range of cases and faults
  - Extreme cases, expected real-time cases, load levels, dispatches, etc.
- Test and compare across multiple platforms
  - Ex. PSS/E Dynamics, PSCAD, & RTDS
- Detailed modeling of area loads, motors, etc. is important
- Verifying against real-world data via post-event analysis, PMU data, etc.
  - Ex. Verification of POD performance with PMU measurements

Benson Lake SVC

October, 2016

November, 2016

Benson Lake SVC

December, 2016

January, 2017

Benson Lake SVC

February, 2017

March, 2017

Benson Lake SVC

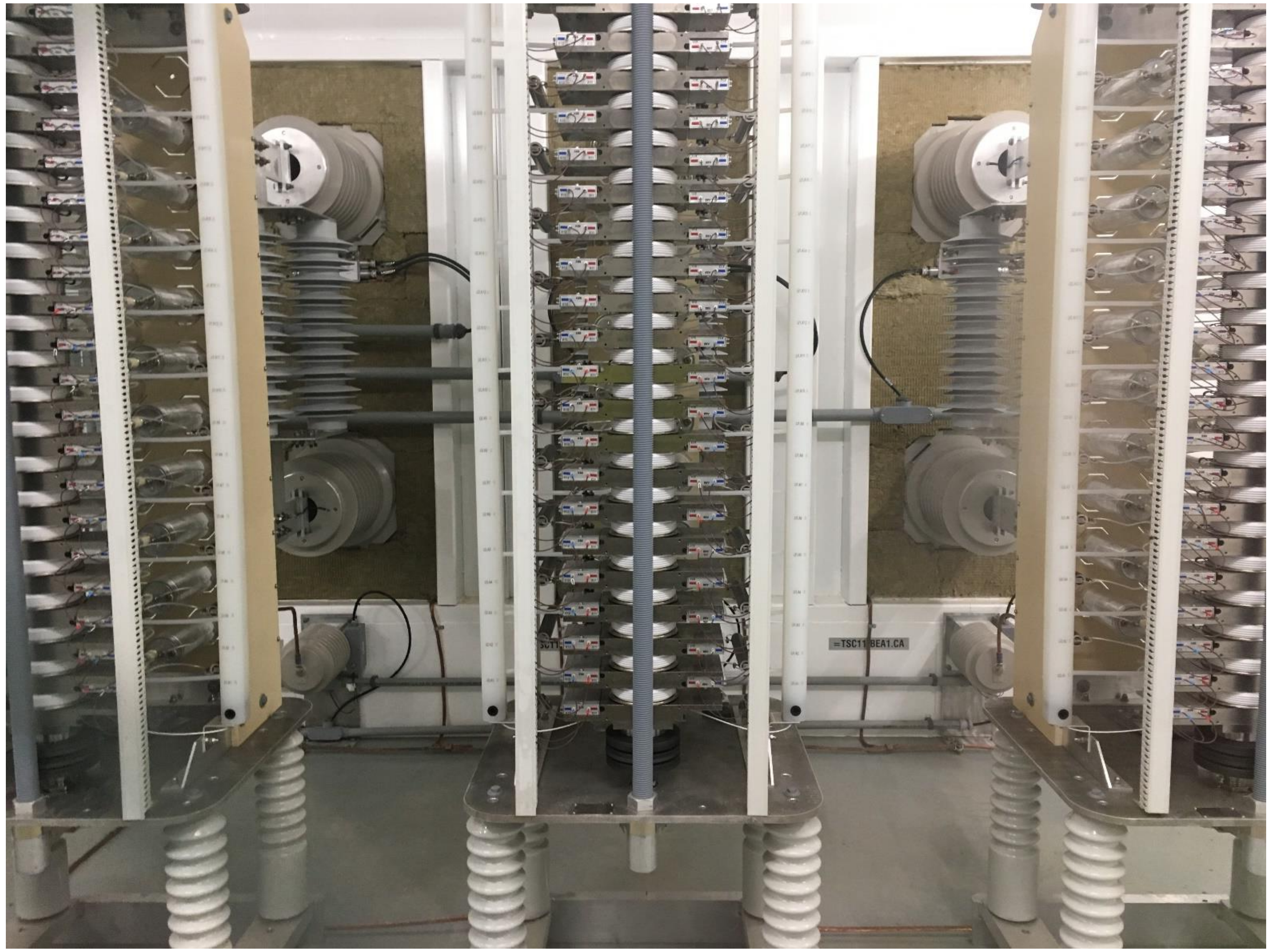
April, 2017

May, 2017

Benson Lake SVC

TCR Valve

TSC Valve



Thanks to the following

Dave Dickmander
Consulting Director
ABB Inc., Power Consulting
Raleigh, NC

Martin Wastljung
System Studies – Market Leads Support
ABB Inc, FACTS
Västerås, Sweden

Mike Marz
Principal Transmission Planning Engineer
American Transmission Company
Waukesha, WI

Questions?

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