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Wide-Area Controls Using Solid-State Transformers to Improve Grid Resilience

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Overview of Presentation

1. Background on Solid State Transformers (SSTs)
2. SSTs as an actuator to improve grid reliability and resilience
3. Modeling of SSTs
4. Control design methodology for SSTs
5. Simulation example comparing SSTs to conventional transformers in providing transient stability under severe contingencies

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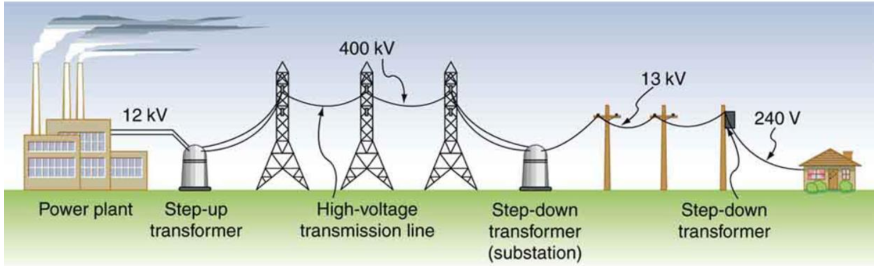
Background

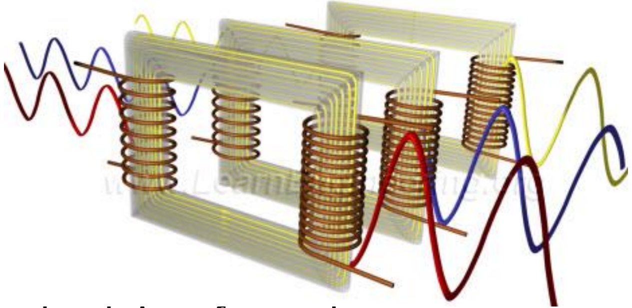
- The current power system depends on thousands of generators working in unison (phase and frequency must match) to meet ever-increasing power demands.
- This synchronization requirement is what makes large AC grids vulnerable to cascading failures.
- The transition to a more interconnected “smarter” grid has made it vulnerable to cyberattack.
- Sudden perturbations can trigger instability, cascaded failure.
- During a fault, attempted corrective actions can easily backfire.
- Increasing reliance on software = increasingly attractive target.

It has long been hypothesized that Solid-State Transformers (SSTs) have the potential to prevent/reduce cascading failures.

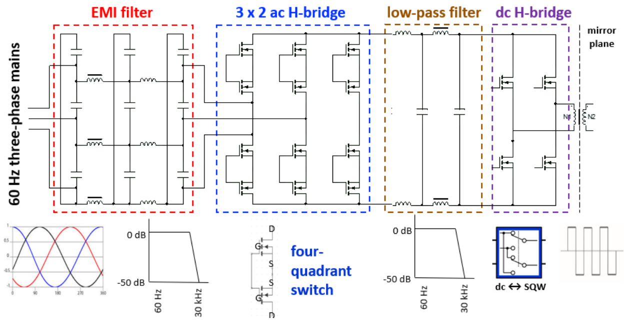


Conventional Transformers vs. Solid-State Transformers

The primary job of a transformer is to convert between voltage levels on the grid



- Conventional transformers
  - Passive devices
  - ~99% efficient
  - Can introduce harmonics
  - Pass disturbances along
  - EHV Transformers are large, expensive, and require a year or more lead time for replacement



- Solid-State Transformers
  - Phase & frequency decoupling
  - Reactive power control (VAR support, power factor correction)
  - Power quality management
  - Reduced footprint, deployment burden, and inventory overhead
  - Potential for correction of certain kinds of phase imbalance
  - “DC in the middle” enables natural integration of DC power sources (PV, storage)
  - Frequency insensitivity enables natural integration of variable frequency AC sources (Wind)

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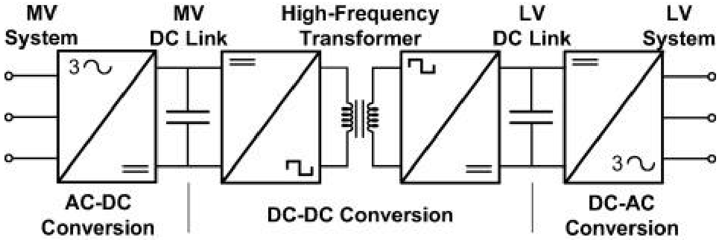
Objectives of Solid State Transformer Technology

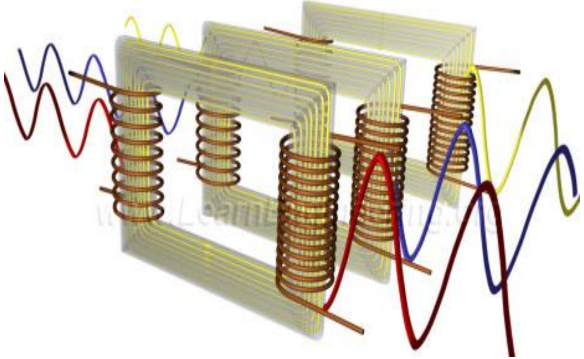
Solid State AC-DC-AC Transformer



NOTE: Internally generated dc power is not transmitted any distance; voltage ratings of semiconductors need not be unreasonably high.

Provides required galvanic isolation
Asynchronous generation assets welcome
Generator phasing is incidental and innocuous
Generation assets decoupled but fully accessible
VAR support (active injection of leading power)
Distant reactive loads are nonexistent
Drop-in replacement for existing transformers
Hypothesized to be cost competitive

Conventional Transformer



Provides required galvanic isolation
Generation assets must all be phase-locked
Loss of phase-locking can be catastrophic
Islanding of nodes = no load sharing = unstable
Provides no VAR support
Distant reactive loads are a serious liability
Drop-in replacement for existing transformers
Known to be cost competitive

Advances in high-speed, high-power MOSFET & IGBT technology has opened a new frontier.

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SST Model

- The SST is modeled as a back-to-back inverter generator.
- There is a “master” side and a “slave” side to the back-to-back inverter generator.
- The master reacts to the changing system, the slave side reacts to the changing master.
- The output of both sides of the back-to-back inverter generator are equal but opposite.

SST Controls

- A modified Frequency-Watt control:

$$P_{SST} = K(f_1 - f_2)$$

- Based on the frequency difference between the two sides, the real power flow through the SST is changed.
- Gain, *K*, selection is difficult, and more advanced controls are needed for actual SST implementation.

Methodology for SST Controls

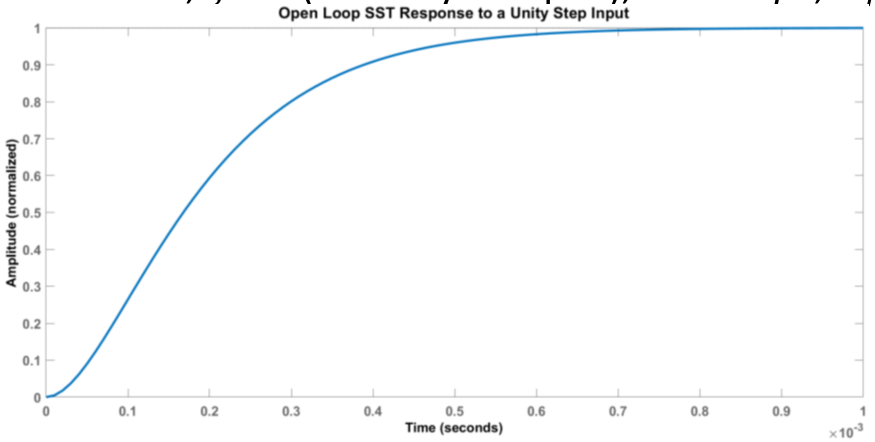
1. Develop High-level Control Model for SST (in Matlab)

Grid-level transfer function of SST is a critically damped 2nd order lag system (no zeros):

$$\frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

where K = DC gain, ζ = damping ratio, ω_n = natural frequency = $1/\tau$, τ = time constant

Nominally for the SST: K = 1, ζ = 1 (critically damped), τ = 100 μs, ω_n = 10,000 rad/s



Methodology for SST Controls (cont.)

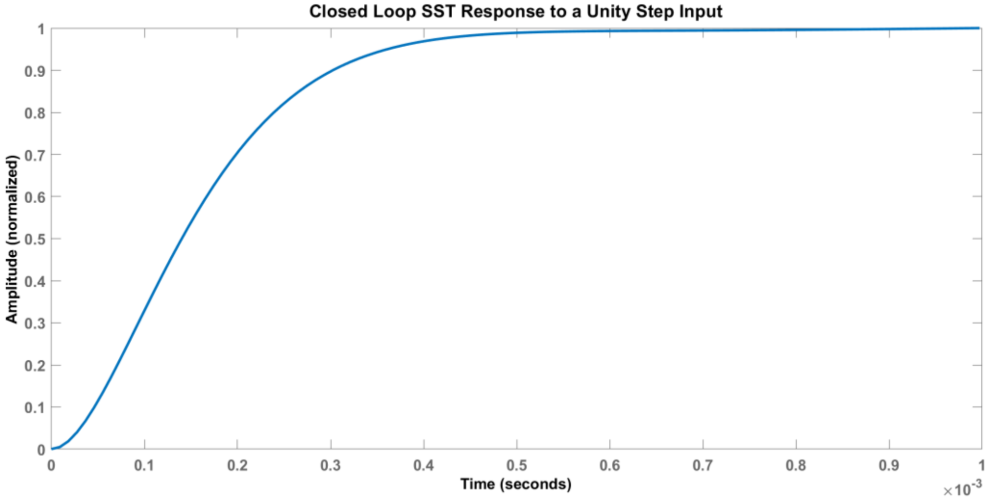
2. Design PI compensator for SST (in Matlab)

PI compensator transfer function:

$$K_p + \frac{K_I}{s}$$

where K_p is the proportional gain and K_I is the integral gain

Nominally for the SST: K_p = 0.3 and K_I= 10

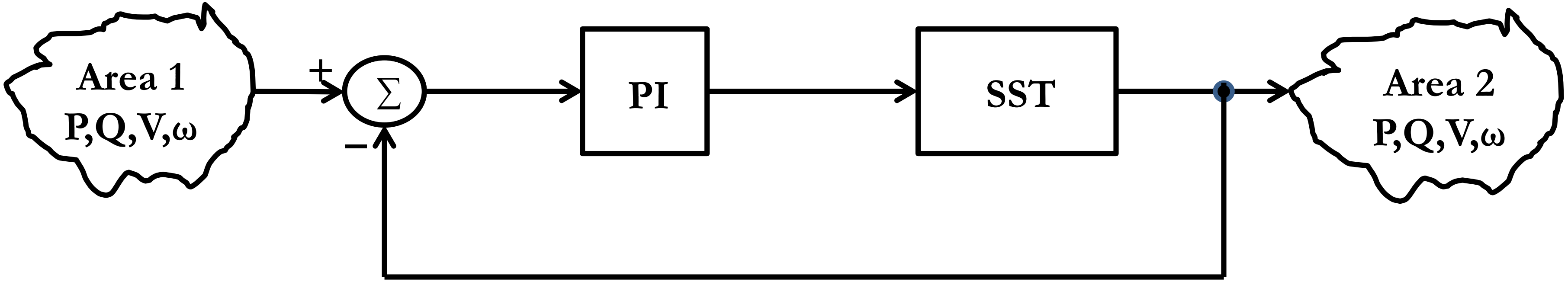


Compared to open loop response, closed loop response has a 30% faster rise time while maintaining no overshoot.

Methodology for SST Controls (cont.)

3. Implement PI compensator for SST (in PSLF)
4. Iterate PI compensator design for SST between Matlab and PSLF to obtain desired performance

Grid-level block diagram of closed-loop control



Evaluation of SST vs. conventional transformer under severe contingencies

Two cases for evaluation:

1. Base case system (RTS-96 system with conventional transformer)

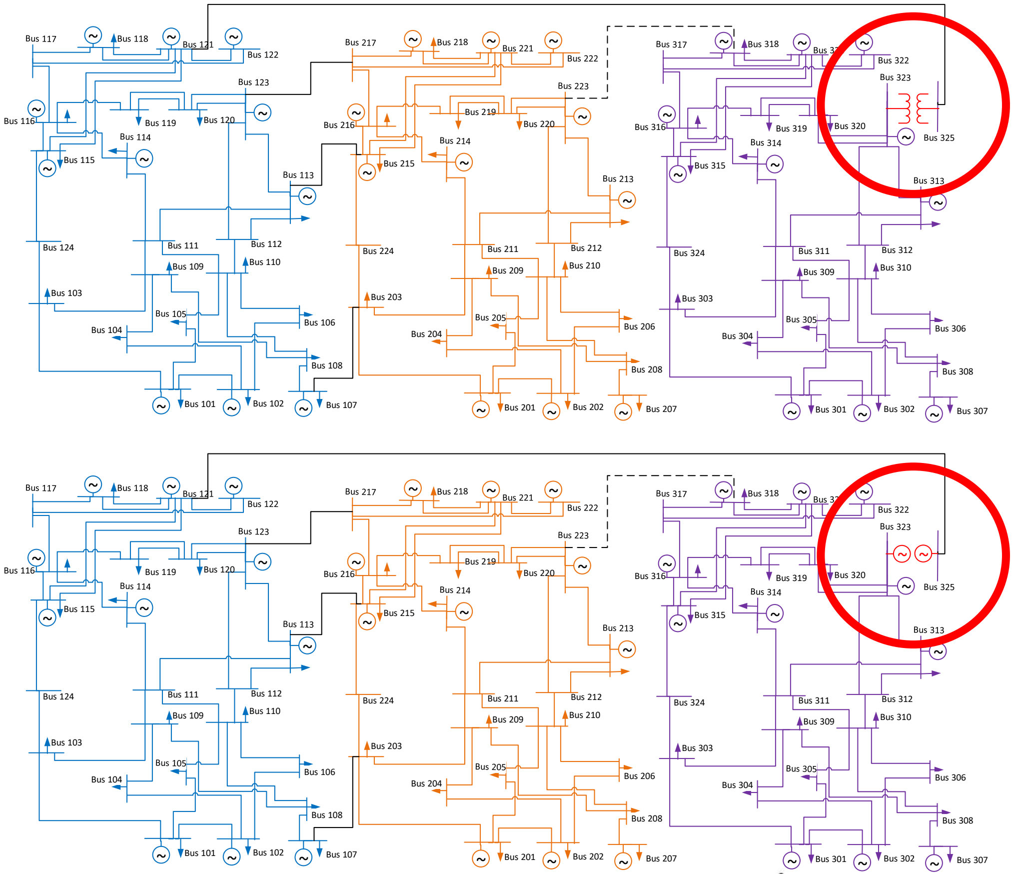
   Note: Area 3 is connected to Area 1 through a single conventional transformer, and is otherwise isolated.

2. SST with frequency-watt controls replaces conventional transformer.

Two contingencies for evaluation all in Areas 1 and 2:

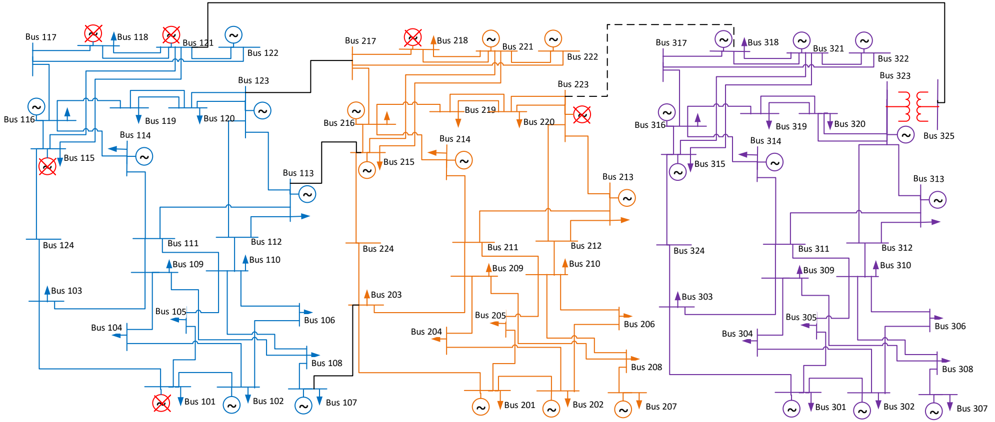
1. Severe generation trip contingency.
2. Catastrophic load trip contingency.

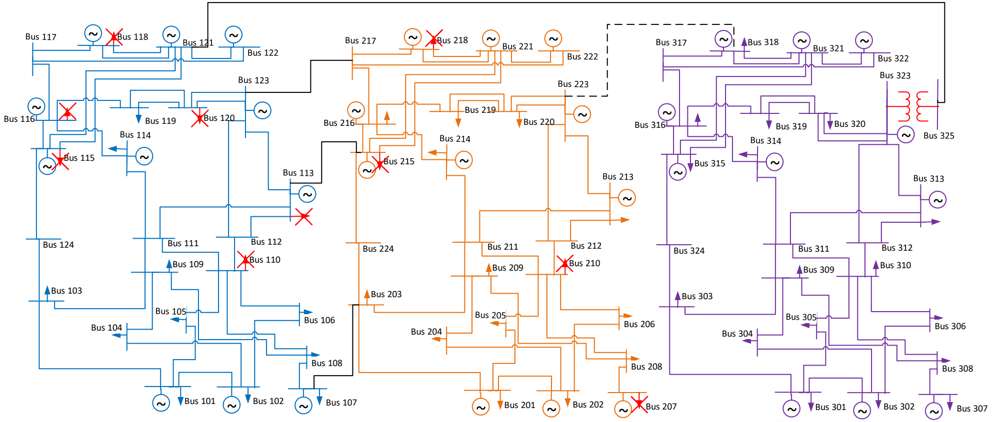
- IEEE Reliability Test System – RTS-96 system is grid model under study.
- Modified by removing one connection between areas 2 & 3.
- Area 3 has only one connection point to the rest of the system.
- Solid-State Transformer is modeled as back-to-back inverter generation with closed-loop controls.



Two severe contingencies are simulated:

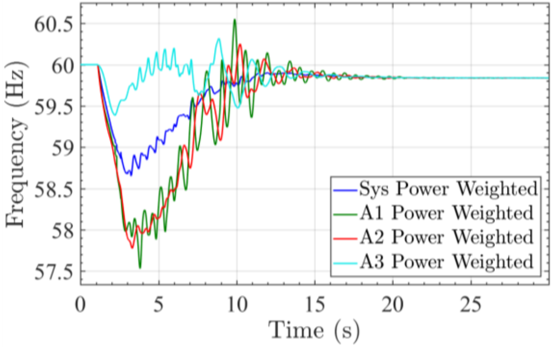
1. Severe Generation Trip (top schematic)
2. Catastrophic Load Trip (bottom schematic)

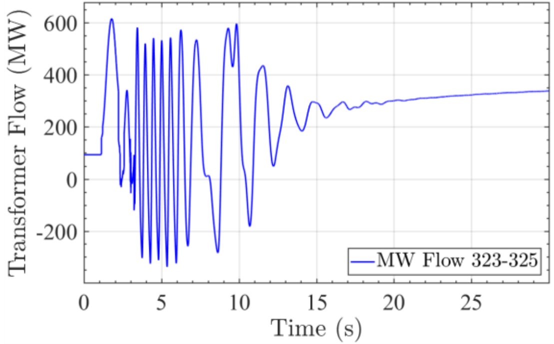




Severe Generation Trip in Areas 1 & 2

Base Case





Base case:

- Weak connection between Area 3 and Areas 1 & 2 causes oscillations during the severe generation trip.
- These oscillations lead to significant load shed.

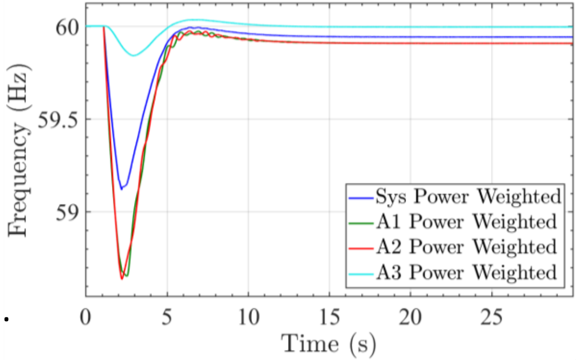
SST with controls:

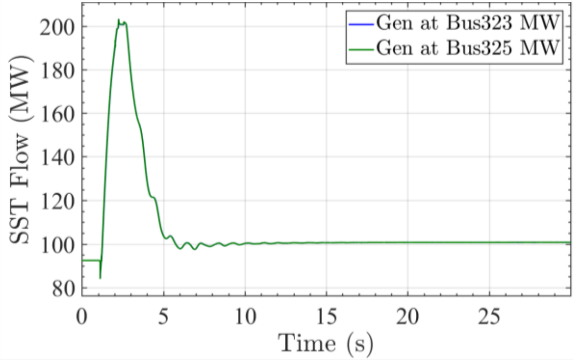
- Area 3 becomes asynchronous to Areas 1 & 2.
- Weak connection is greatly improved.
- Significant reduction in load shed.
- Elimination of oscillatory issues along with improved frequency nadir.

Summary of % Load Shed by Area

	Area 1	Area 2	Area 3
Base Case (no SST)	46.8%	31.3%	0.1%
SST with controls	17.0%	17.4%	0%

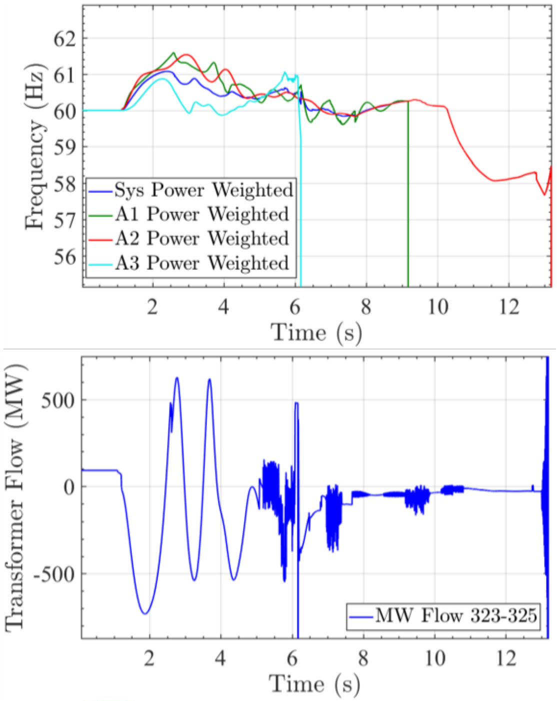
SST with controls





Catastrophic Load Trip Contingency in Areas 1 & 2

Base Case



<u>Base case</u>:

- Generators throughout the system are unable to change quickly enough to account for the significant change in load.
- Generation trips offline because the frequency gets too high which triggers cascading outages.

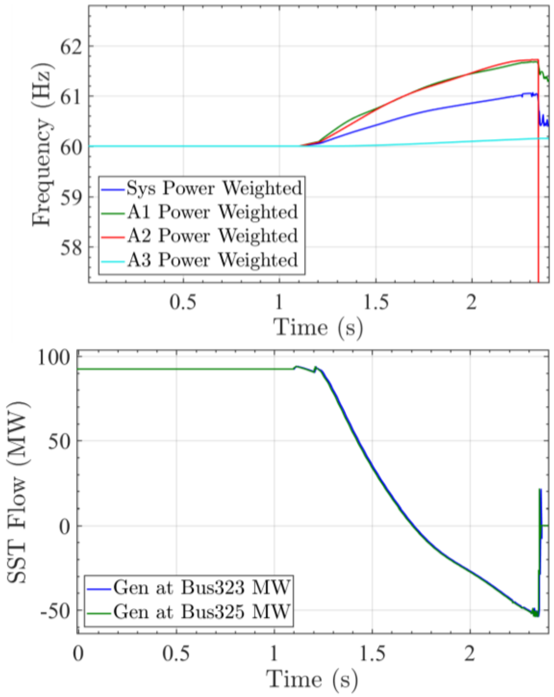
<u>SST with controls</u>:

- Area 3 is asynchronous from Area 1&2 due to the SST.
- Area 3 experiences very little impact during the catastrophic event.

Summary of % Load Shed by Area

	Area 1	Area 2	Area 3
Base Case (no SST)	100%	100%	100%
SST with controls	100%	100%	**0%**

SST with controls



Conclusions

- The SST is an important step to creating a more resilient power grid to disturbances caused by multiple threat vectors, e.g., cyber-attacks and natural disasters.
- An SST modeling and control design methodology was presented
- A simulation example based on the IEEE RTS-96 system was used to compare a base case with no SST and the same base case with an SST using the control design methodology.
- The base case illustrated a weak connection between Area 3 and Areas 1 and 2 due to the severe disturbances leading to significant load shedding.
- The base case with an SST showed significant improvements in reducing load shedding and improving frequency nadir for the same disturbances.
- Future work will focus on:
  - Optimization strategies using SSTs to maximize grid resilience
  - Robust control designs given parameter uncertainties and measurement noise