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Potential of Solid-State Transformers to Improve Grid Resilience*

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***Abstract*— A methodology for the design of control systems for wide-area power systems using solid-state transformers (SSTs) as actuators is presented. Due to their ability to isolate the primary side from the secondary side, an SST can limit the propagation of disturbances, such as frequency and voltage deviations, from one side to the other. This paper studies a control strategy based on SSTs deployed in the transmission grid to improve the resilience of power grids to disturbances. The control design is based on an empirical model of an SST that is appropriate for control design in grid level applications. A simulation example illustrating the improvement provided by an SST in a large-scale power system via a reduction in load shedding due to severe disturbances are presented.**

***Index Terms*—solid state transformers, power system dynamics, small-signal stability, inter-area oscillations, power grid resilience.**

I. Introduction

The electrical grid comprises thousands of distributed three-phase 60 Hz AC generation assets, all of which must be kept precisely synchronized in frequency and phase. This synchronization requirement is what makes large AC electrical grids vulnerable to cascaded failure, such as the August 1996 Western Interconnection (WI) blackout that left 10 million people in the western U.S. without power [1], and the August 2003 Eastern Interconnection (EI) blackout that left 50 million people in the eastern U.S and Canada without power [2]. Such cascaded failures have historically been the result of unintentional events. Our transition to an ever more interconnected and "smarter" grid has made our electrical grid vulnerable to major weather events and climate scenarios [3],[4] and cyber-attacks [5]. This demonstrates that the threats are significant and that our computer and control systems are vulnerable. New technology based on solid-state transformers (SSTs) have been proposed to significantly reduce the magnitude of the effects of any attack or disaster to the electrical system [6].

It has long been understood that replacement of conventional AC-AC transformers with AC-DC-AC transformers that provide phase/frequency decoupling would provide a potent remedy for cascaded failure [7]. Accordingly, such devices, commonly referred to as solid-state transformers, have been the subject of increasing research during the past decade [8],[9]. Solid-state transformers devised to date comprise a very large number of semiconductor switches and bulky reactive components, and fall far short of the required 99% transformer efficiency. Current research is focused on constructing a fundamentally new class of bidirectional inverter topology based on temporally weighted nonlinear rectification that meets all the above requirements. This novel inverter topology would allow the construction of low-parts-count, highly efficient solid-state transformers, and should be ideally suited to interfacing of direct current grid assets (solar PV, grid storage batteries, electric vehicles) and variable frequency-AC generation grid assets (wind).

The primary differences between conventional transformers and solid state transformers can be summarized as follows:

Features of conventional transformers:

- Passive devices.
- Approx. 99% efficient.
- Can introduce harmonics.
- Pass disturbances along.
- Require a year or more lead time for replacement.

Features of 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, e.g., PV, energy storage.
- Frequency insensitivity enables natural integration of variable frequency AC sources, e.g., wind.

The use of SSTs in wide-area power grid control is focused on development of power system models with SSTs to study their ability to guard against cascaded failures. To do so, we first create appropriate component models of SSTs for use in General Electric's Positive Sequence Load Flow (PSLF) software. We then use these component models in existing large scale power system models to assess their behavior and quantify their impacts for significant grid disruptions. As part of our current research, the ancillary benefits of SSTs will be quantified. These benefits include the ability to provide voltage support and power factor correction, the efficacy of larger spare inventories given the

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reduced capital expense of these devices, and the reduced recovery time resulting from decreased replacement times resulting from greatly reduced size. For brevity, in this paper, we focus on the potential benefits of SSTs in improving small signal stability, e.g., improved damping of power system oscillations, for wide-area power grids. It should be noted that the lack of small signal stability was a contributing factor to the cascading failures in the 1996 WI outage [1].

For power systems modeling, we use dynamic component models of the SSTs. We leverage high-fidelity, vetted Western Electricity Coordinating Council (WECC) or Northeast Power Coordinating Council (NPCC) PSLF power system models to make assessments of how the SSTs will perform in a broader system context. Specifically, we use these models together to quantify the ability of the SSTs to stave-off cascaded failures at varying levels of deployment. To do so, we investigate the introduction of a disturbance similar to the one that caused the northeast blackout of 2003. We note that it is expected that there will be ancillary benefits of SSTs, e.g., ability to improve system wide power factor via phase modulation and voltage support via fast, continuous (as opposed to discrete such as with current transformer tap changers) control of output voltage over a wider range. However, this paper focuses on the potential for SSTs to improve damping of power system oscillations.

The contributions and organization of this paper are as follows: model creation and control design for an SST that is appropriate for small signal stability improvement of a large power system in Sec. II, and simulation results demonstrating such improvement on a multi-area power grid example in Sec. III. The paper provides concluding remarks and avenues for future research in Sec. IV.

II. Modeling and Control of Solid State Transformers

In grid simulations, the SST is modeled as a back-to-back inverter generator. There is a "leader" side and a "follower" side to the back-to-back inverter generator. The leader reacts to the changing system. The follower side reacts to the changing leader. The output of both sides of the back-to-back inverter generator are equal but opposite.

For control design, however, an empirical approach is taken. Through experimentation, the transfer function of an SST can be modeled at a high level (appropriate for control design in grid stability studies but not for analysis of device physics) as a critically damped 2nd order lag system without zeros

$$SST(s) = (K_{DC}\,\omega_n^2)/(s^2+2\zeta\,\omega_n s + \omega_n^2) \qquad (1)$$

where K_{DC} is the DC gain, ζ is the damping ratio, ω_n is the natural frequency = $1/\tau$, where τ is the time constant. Nominal parameter values for the SST in our grid simulations are: $K_{DC} = 1$, $\zeta = 1$ (critically damped), $\tau = 100$ µs, and $\omega_n =$ 10,000 rad/s. In Fig. 1, the open loop response (blue curve) of (1) is shown along with the closed loop response (red curve) based on a lead-lag compensator design. The closed loop response in this case has a 30% faster rise time than the open loop response while maintaining no overshoot. This type of controller was chosen because of its potential to improve SST response during a disturbance. The control design is anticipated to decrease the amount of load shedding needed during a severe disturbance as well as reduce the frequency nadir during such an event.

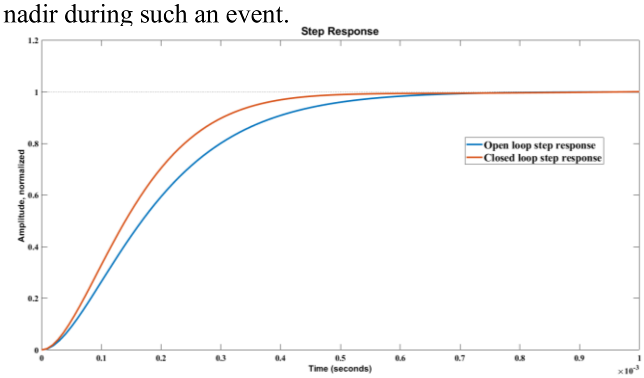

Figure 1. Plots of open and closed loop responses of the SST modeled by (1).

For use in a large-scale power system, Fig. 2 depicts a high-level block diagram for control implementation. In Fig. 2, the SST is inserted between two areas of the power system. Because of its ability to isolate the phase/frequency of each area, the inputs/outputs of the SST for control deployment can be a combination of real and reactive power, voltage and phase/frequency. For small signal stability, the inputs to the controller will be frequency of each area, and the output will be real power to Area 2. This represents a type of frequency-Watt control. Based on the frequency difference between the two areas, the real power flow through the SST, P_{SST}, is controlled by

$$P_{SST} = K(f_1 - f_2) \qquad (2)$$

where f_1 and f_2 are the frequencies in Hz of areas 1 and 2, resp., and the compensator block, denoted by K (not necessarily a constant gain but can be a dynamic function), is chosen based on the lead-lag compensator used in Fig. 1. In this case, the compensator is modeled as

$$K(s) = (s + \alpha)/(s + \beta) \qquad (3)$$

where α and β are constants chosen such that $\beta \approx 1 \ll \alpha$.

The control law is then scaled to the parameters representing a grid implementation of an SST.

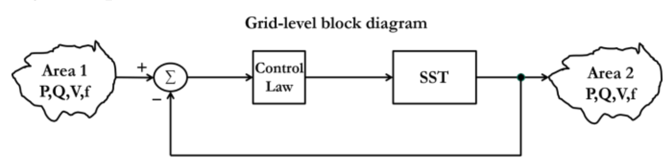

Figure 2. Block diagram for control of SST in a multi-area power system.

III. Simulation Example

The original 3-area IEEE Reliability Test System – RTS-96 system [10] shown in Fig. 3 is modified by removing one connection between Areas 2 and 3. Area 3 has only one connection point to the rest of the system. This is the base case for comparison. In the PSLF simulation, the SST is modeled as back-to-back inverter generation. This is the only connection from area 3 to the rest of the system. Two cases are compared in the simulation example:

1. The base case system using a conventional transformer. Note that Area 3 is connected to Area 1

through a single conventional transformer, and is otherwise isolated.

2. The base case system except for an SST using frequency-Watt control, as in (2) and (3), replacing the conventional transformer.

Three contingencies are evaluated in which disturbances occur in Areas 1 and 2:

a. A severe generation trip contingency in Areas 1 and 2.

b. A severe load trip contingency in Areas 1 and 2.

c. A catastrophic load trip contingency in Areas 1 and 2.

The results of the simulations are described below and summarized in Tables I-III. Figs. 4-15 show the system frequency plots and real power flow through the transformers for the base case with and without the SST and controller for all three contingencies, resp.

For the base case subjected to contingency (a), the weak connection between Area 3 and Areas 1 and 2 causes oscillations during the major generation outage event. These oscillations can lead to significant load shedding.

For the case of the SST with controller subjected to contingency (a), Area 3 becomes asynchronous to Areas 1 and 2. Therefore, the weak connection is greatly improved thus significantly reducing load shedding and eliminating oscillatory issues along with improved frequency nadir.

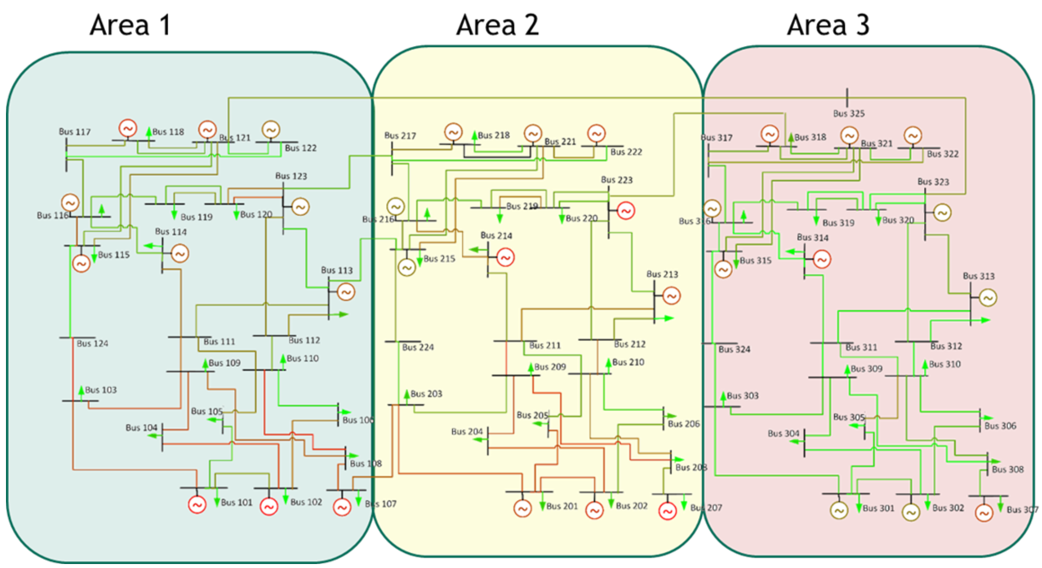

Figure 3. Schematic of IEEE Reliability Test System – RTS-96 system [10].

For the base case subjected to contingency (b), with the connection to Area 3, the generators have enough inertia to change quickly and match the load before the frequency becomes too high.

For the case of the SST with controller subjected to contingency (b), with the ability to control the SST, the system survives the contingency, and is still able to disconnect if need be.

For the base case subjected to contingency (c), the generators throughout the system are unable to change quick enough to account for the significant change in load. Therefore, generation trips offline because the frequency becomes too high which then triggers cascading outages.

For the case of the SST with controller subjected to contingency (c), since Area 3 is asynchronous from Areas 1 and 2 due to the SST, Area 3 experiences very little impact during the catastrophic event.

Table I. Summary of % load shed from a severe gen trip: Contingency (a)

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

Table II. Summary of % load shed from a severe load trip: Contingency (b)

	Area 1	Area 2	Area 3
Base (no SST)	38.9%	27.2%	0%
SST with controller	38.9%	27.2%	0%

Table III. Summary of % load shed from catastrophic load trip: Cont. (c)

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

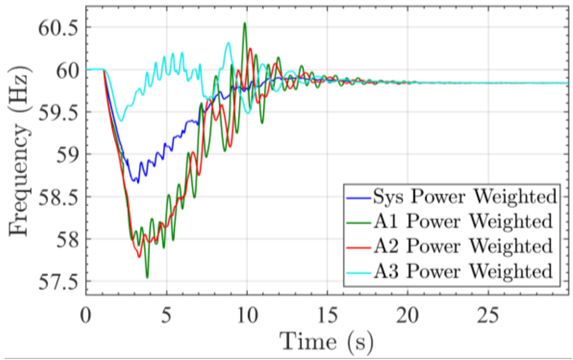

Figure 4. Plot of system frequency vs. time for the base case subject to a severe generation trip in Areas 1 and 2 – contingency (a).

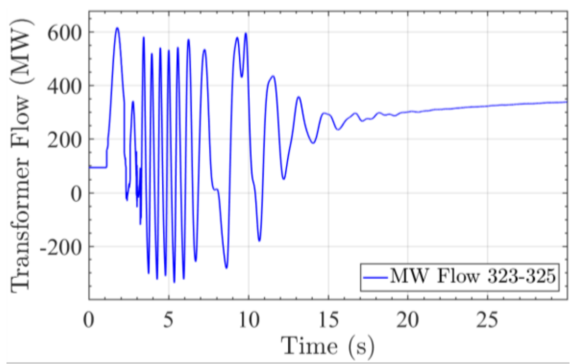

Figure 5. Plot of conventional transformer real power flow for the base case subject to a severe generation trip in Areas 1 and 2 – contingency (a).

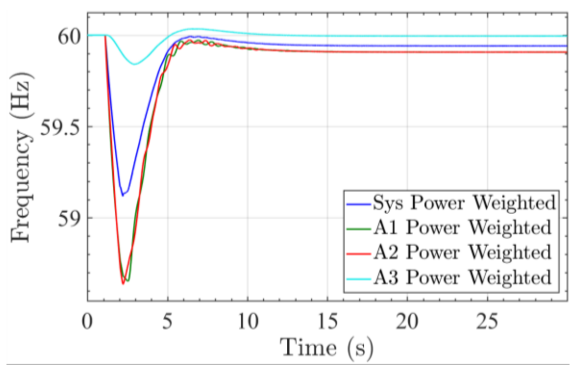

Figure 6. Plot of system frequency vs. time for the base case with SST and controller and a severe generation trip in Areas 1 and 2 – contingency (a).

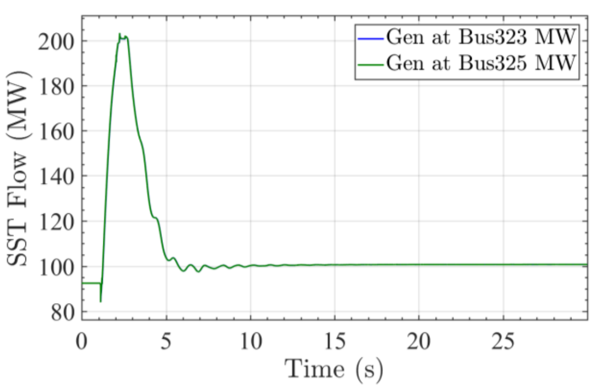

Figure 7. Plot of SST real power flow for the base case with SST and controller and a severe generation trip in Areas 1 and 2 – contingency (a).

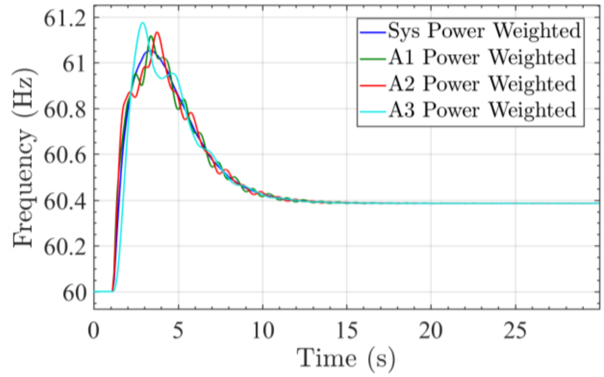

Figure 8. Plot of system frequency vs. time for the base case subject to a severe load trip in Areas 1 and 2 – contingency (b).

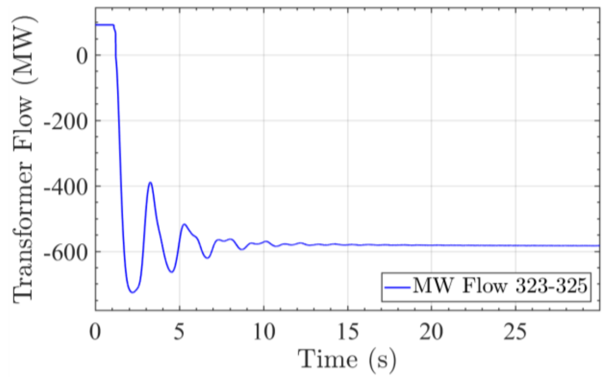

Figure 9. Plot of conventional transformer real power flow for the base case subject to a severe load trip in Areas 1 and 2 – contingency (b).

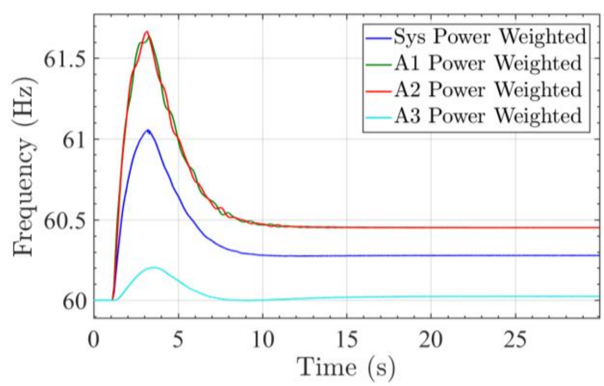

Figure 10. Plot of system frequency vs. time for the base case with SST and controller subject to a severe load trip in Areas 1 and 2 – contingency (b).

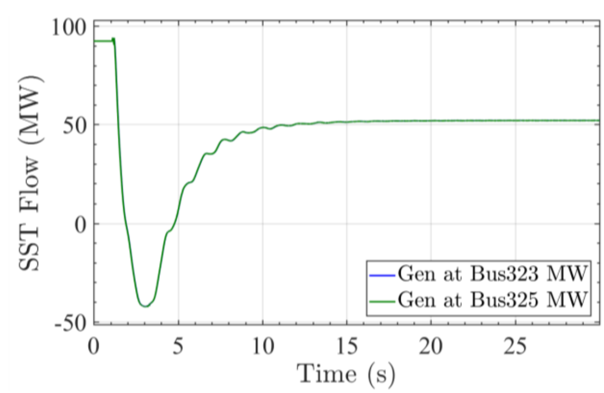

Figure 11. Plot of SST real power flow for the base case with SST and controller subject to a severe load trip in Areas 1 and 2 – contingency (b).

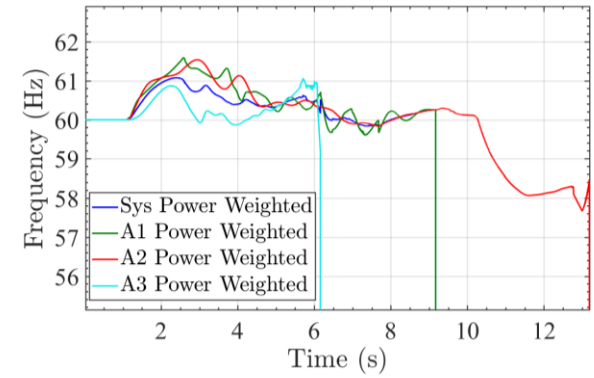

Figure 12. Plot of system frequency vs. time for the base case subject to a catastrophic load trip in Areas 1 and 2 – contingency (c).

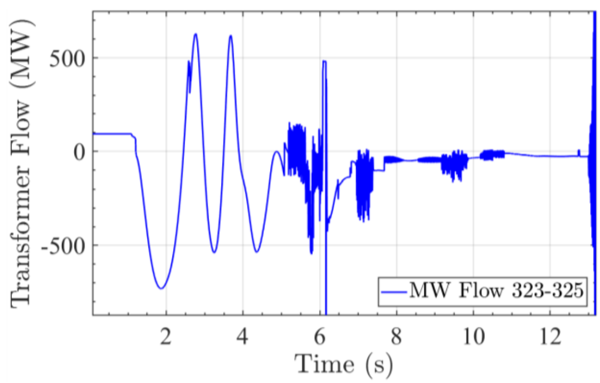

Figure 13. Plot of conventional transformer real power flow for the base case subject to a catastrophic load trip in Areas 1 and 2 – contingency (c).

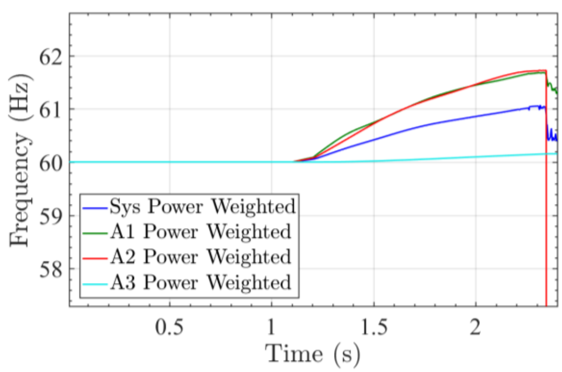

Figure 14. Plot of system frequency vs. time for the base case with SST and controller and a catastrophic load trip in Areas 1 and 2 – contingency (c).

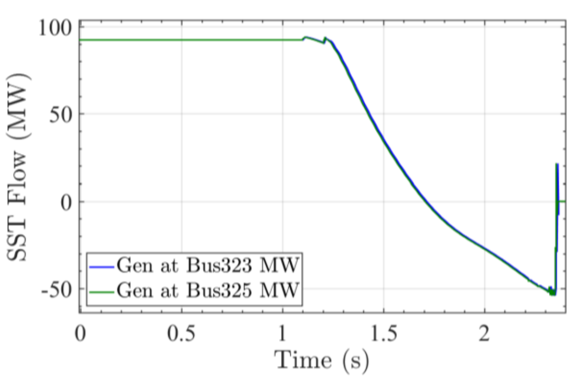

Figure 15. Plot of SST real power flow for the base case with SST and controller and a catastrophic load trip in Areas 1 and 2 – contingency (c).

IV. Conclusions and Future Research

The SST is an important step to creating a more resilient power grid that is more robust to disturbances caused by multiple threat vectors, e.g., cyber-attacks and natural disasters. SST models and control designs will be essential to develop an optimization capability that can be used to design resilience-optimal deployment strategies of SSTs in future grid resilience work. They will also provide an analysis of the cost/benefit landscape of SST deployment.

In this paper, a model and control design were synthesized for implementation of an SST to improve damping of power system oscillations. An example was chosen based on the IEEE RTS-96 system. Two cases are compared, the base case with no SST and the base case with an SST using frequency-Watt control as in (2) and (3). Each case is subjected to the same disturbances. The base case illustrated a weak connection between Area 3 and Areas 1 and 2 due to the severe disturbances. This weak connection led to inter-area oscillations that then led to significant load shedding. The case with an SST using (2) and (3) showed improvements both in load shedding and frequency nadir.

Future work will focus on models and control designs for more robust control performance given parameter uncertainties and measurement noise. Additional focus on optimal control strategies and the use of SSTs for other types of grid services will also be ramped up.

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