SIW21-95:

Hybridizing Synchronous Condensers with Grid-Forming Battery Energy Storage Systems

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Main Reliability Challenges in Evolving Grid

- Degrading grid strength with high levels of inverter-based resources (IBRs):
  - Impact on stability
  - Impact on transient performance
  - Impact on protection.
- Degrading synchronizing torque, reduced inertia
- What provides grid forming (GFM)?
- Reliability services, wide-area stability services
- Resilience and black-start with GFM IBRs:
  - What is providing inrush current?

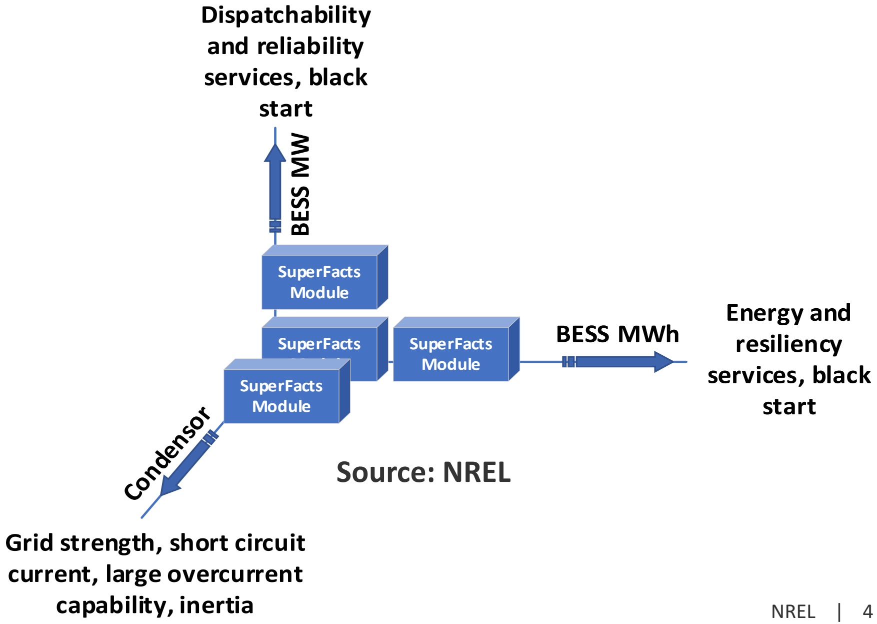
Importance of Grid Strength

A power system with low system strength is expected to exhibit the following behavior:

- Undamped voltage and power oscillations
- Degradation in the IBRs' fault ride-through capabilities
- Protection system malfunctioning due to reduced levels of short-circuit current
- Longer voltage recovery after voltage faults and disturbances
- Larger transient voltage steps caused by switching capacitor or inductor banks
- Dynamic voltage control stability issues
- Increased levels of harmonic distortion in the grid
- Deeper voltage dips and higher overvoltages during transients
- More severe transient characteristics of the system (much deeper or much higher voltage events).

Hybrid Concept

- Super flexible AC transmission system (**SuperFACTS**)
- Combination of mature technologies a scalable module under central control
- Hybrid approach:
  - **SuperFACTS** = SC + GFM BESS + Smart integrated control
  - Research project funded by U.S. Department of Energy (Office of Electricity Transformer Resilience and Advanced Components program).
- What makes it different from prior battery energy storage system (BESS)-synchronous generator hybrid work?
  - Prior work was focused on limited sets of services (gas-battery peakers) of synchronous condensers with grid-following (GFL) BESS.*
  - SuperFACTS has controls that can provide a full spectrum of grid services.
- Scalability:
  - Grid strength, inertia, and fault current
  - Energy services and resilience services
  - Reliability services
  - Black-start services.



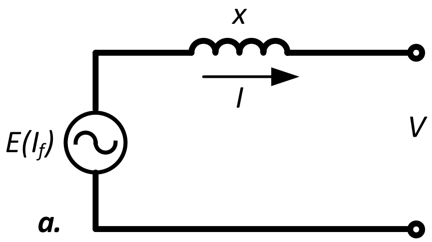
* M. Nuhic and G. Yang, "A Hybrid System Consisting of Synchronous Condenser and Battery – Enhanced Services in Weak Systems," presented at the 2019 IEEE PES Innovative Smart Grid Technologies Europe, September 29, 2019.

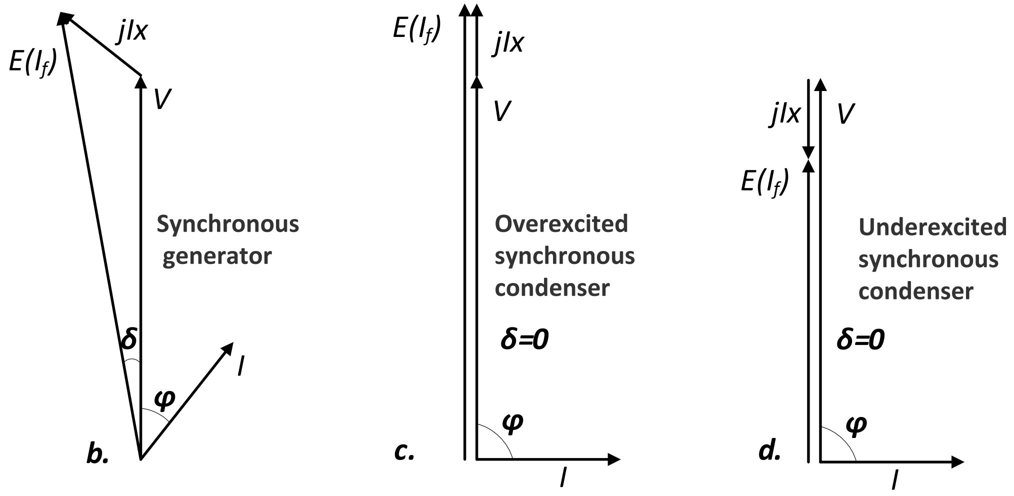
SuperFACTS Hybridization Benefits

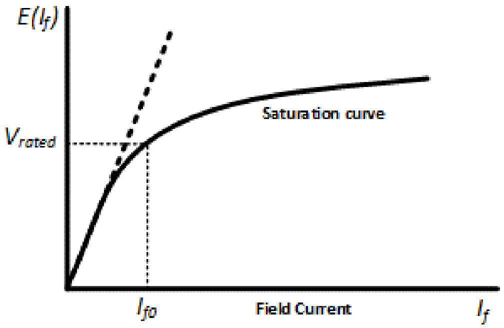
Challenge	BESS	Synchronous Condensers	SuperFACTS
Various forms of grid services based on active power control	Yes	No	Yes
Inertial response	Synthetic, depends on BESS operation point	Yes, real rotating inertia	Enhanced
Steady-state and dynamic reactive compensation, voltage support	4-quadrant	2-quadrant (limited by stability and thermal constraints)	Enhanced
Grid strength enhancement	No	Yes	Yes
Overcurrent capability	No	Yes (up to 300% for 2–3 seconds)	Yes
Short-circuit current	No	Yes, very high	Yes
Black-start capability	Yes (only for BESS with GFM inverters)	No	Yes
Transient and fault ride-through performance	Yes (can control levels of fault current within inverter rating)	Yes (no control over levels of fault current)	Enhanced
Controls to mitigate undesirable interactions with other components on the grid	Yes	Yes (but limited)	Enhanced
Cost	Moderate	Moderate	Lower (compared to same performance by BESS or condenser only)

Synchronous Condenser Limitations

Simplified model of synchronous machine







Rotor thermal limit

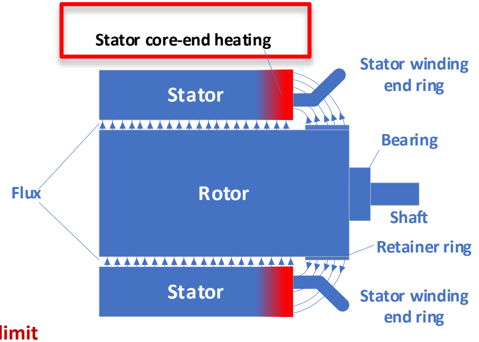
Stator thermal limit

$Q_{cond} = 3\frac{V}{X}[E(I_f) - V]$, $I_{cond} = \frac{E(I_f)-V}{X}$, $I_{cond} \leq I_{max}$

$E(I_f) \rightarrow I_f \leq I_{f.max}$

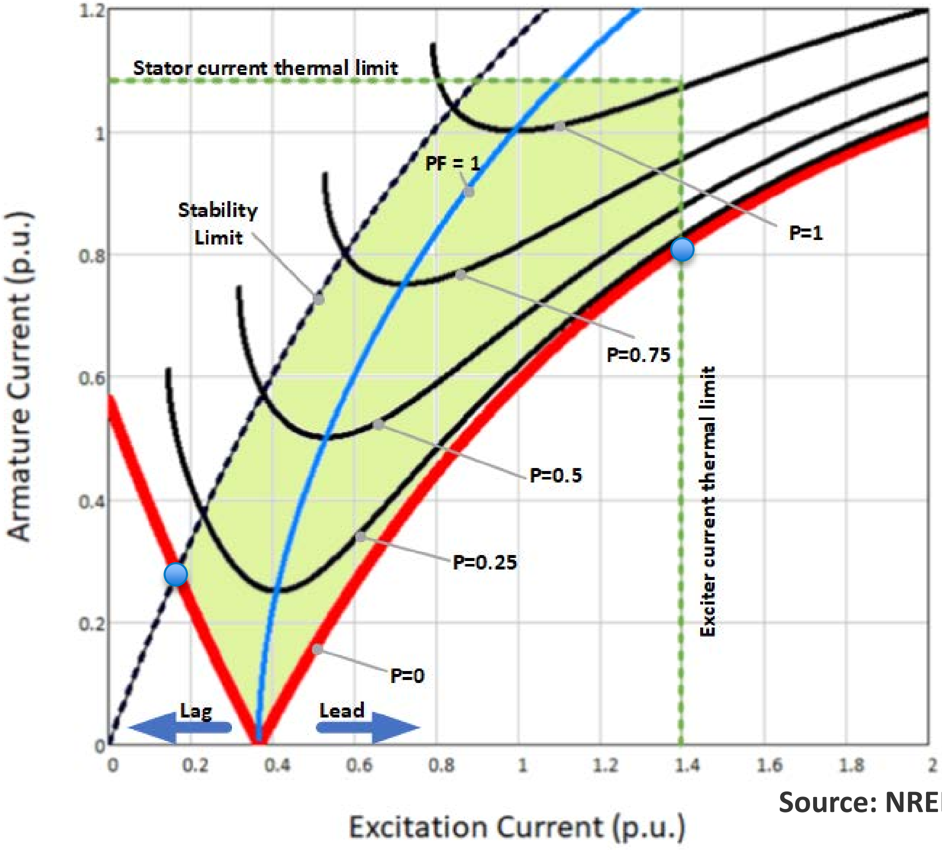
Excitation stability limit — $I(I_f) \leq \frac{E(I_f)}{X}$

Excitation stability limit



Source: NREL

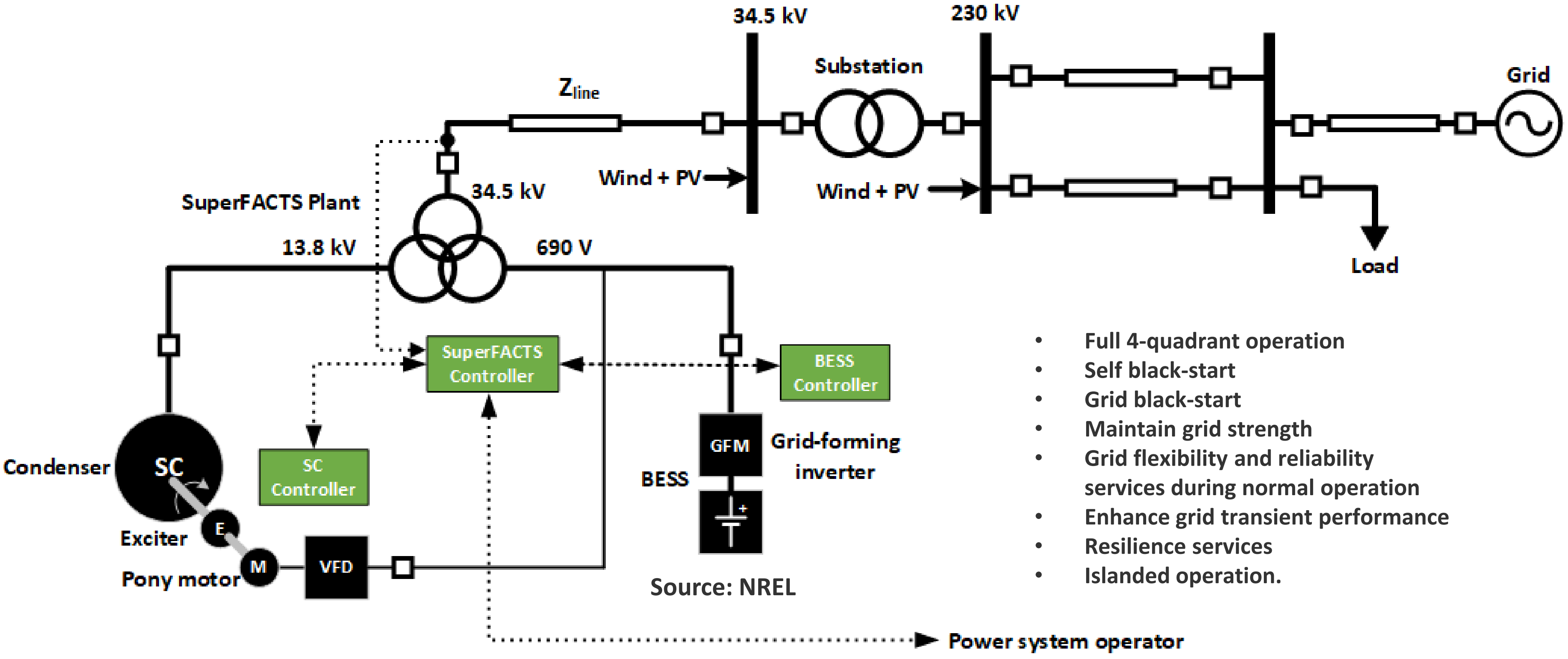
Reactive Capability of Small Synchronous Generator



Source: NREL

- The operational region of the synchronous condenser is restricted by several thermal and stability limitations.
- The reactive capability of the synchronous condenser is inherently nonsymmetric (the overexcited region is wider than the underexcited region).
- The operational ranges can be customized by design.

SuperFACTS Conceptual Diagram



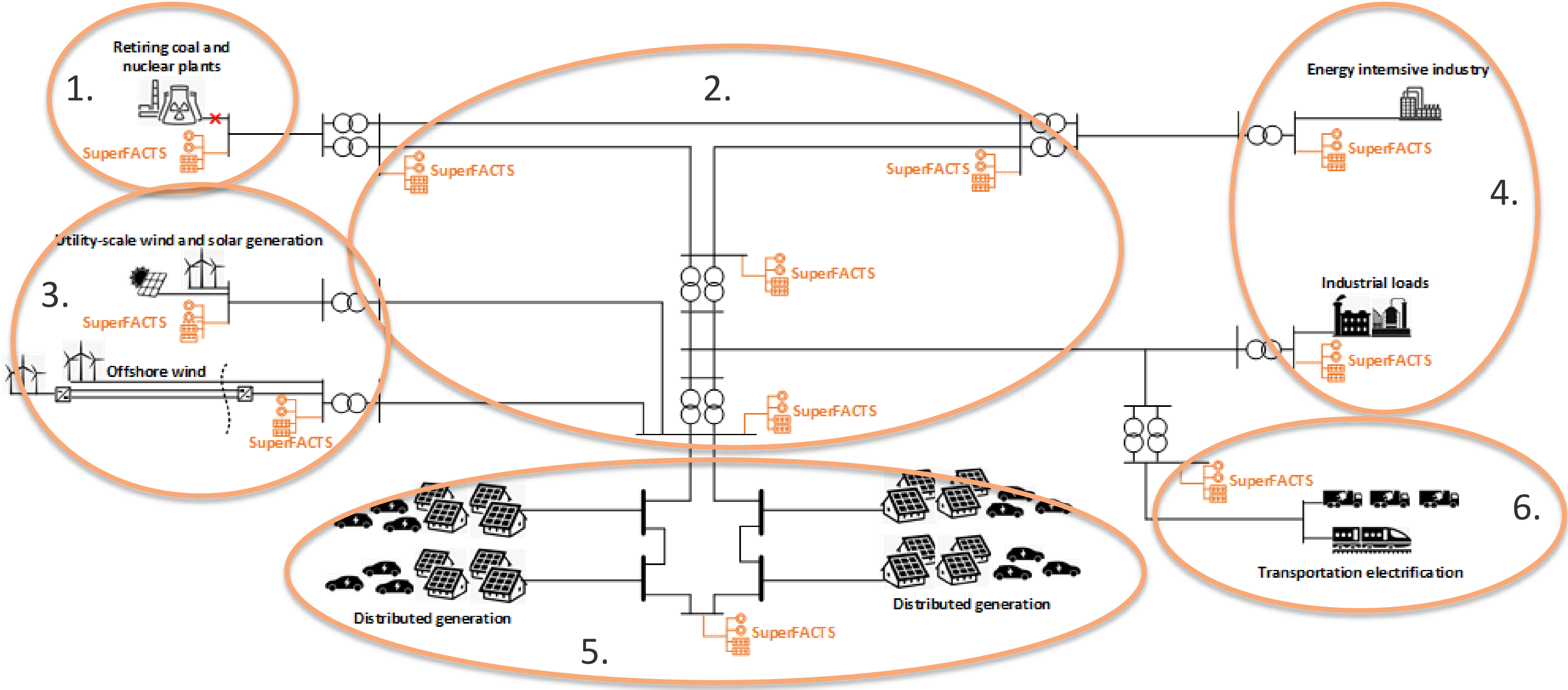
Source: NREL

- Full 4-quadrant operation
- Self black-start
- Grid black-start
- Maintain grid strength
- Grid flexibility and reliability services during normal operation
- Enhance grid transient performance
- Resilience services
- Islanded operation.

SuperFACTS Use Cases

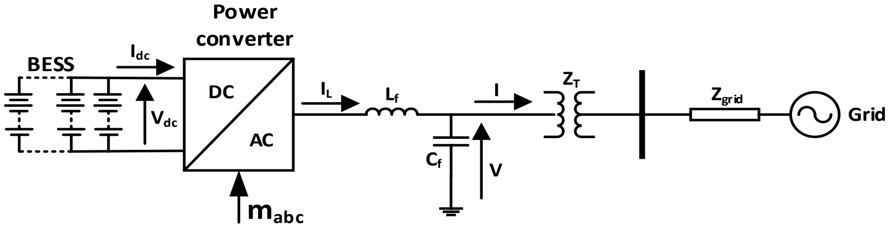
- Provision of combined real and configurable virtual inertias
- Provision of synchronizing torque
- Short-circuit current contribution
- Increased grid strength and short-circuit ratios
- High overcurrent capability (several seconds)
- Grid topology-independent smart voltage recovery contributor/flexible fault response provider
- Provision of enhanced voltage and reactive power control with wide dynamic ranges
- Provision of all forms of active power controls
- Provision of dispatchable operation and flexibility services for variable generation
- Provision of all essential reliability services (better and faster than conventional generation)
- Black-start and stand-alone operation
- Enabler for economic renewable technology hybridization (can be colocated with solar and wind generation)
- Provision of active and reactive power flow controls
- Full 4-quadrant reactive power capability
- High bandwidth for power system oscillations damping
- Superior transient and grid fault ride-through performance
    - Control of negative-sequence voltages for phase rebalancing might be possible for advanced BESS inverters.
- Less than 1-ms response times for damping instabilities caused by control interactions between inverter-coupled variable power generation and the grid
- Stabilizing power systems with any desired ratios between GFM and GFL inverters
- Fully scalable and modular topology for grid-connected, microgrid, and stand-alone operation
    - The same SuperFACTS building blocks will allow deployment in numbers to achieve the desired design parameters (MVA capacity, MWh capacity, inertia, short-circuit ratio and grid strength levels, ability to provide overcurrent during system faults and inrush currents during black starts, etc.).
    - The same basic SuperFACTS building blocks can be used to provide services at the transmission, sub-transmission, and distribution levels, can help operating microgrids and islanded grids, and can provide black-start services for all of the above.
- Can be controlled for electric loss minimization in transmission and distribution grids.

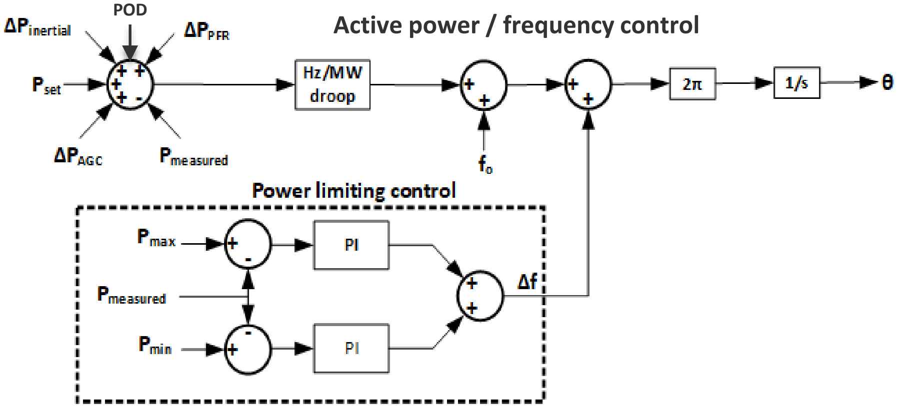
SuperFACTS Use Cases



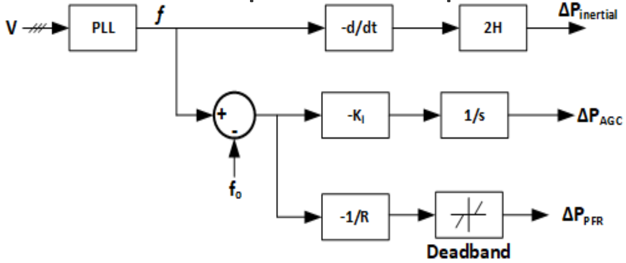
Adopted from ABB image

GFM BESS Model with Current Limiting

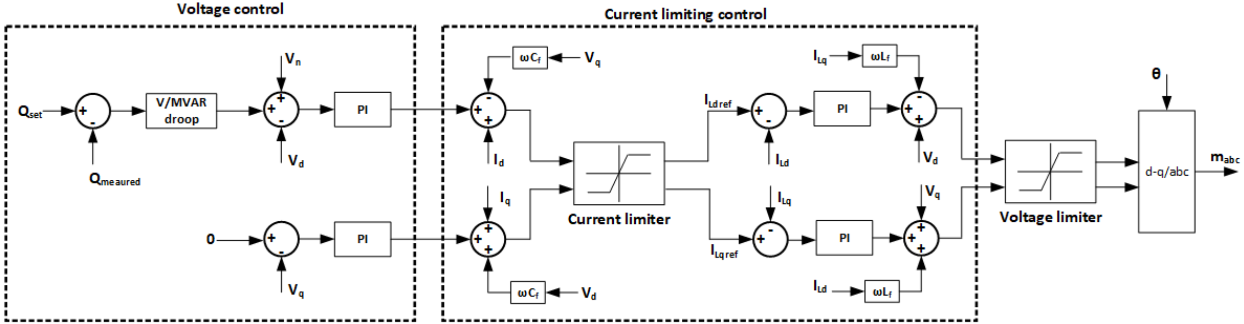




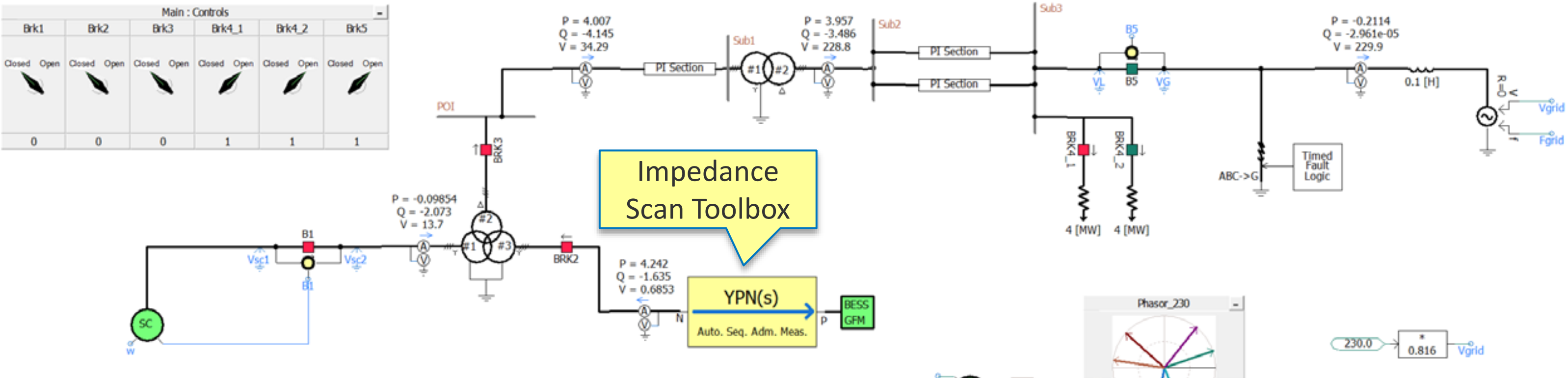
Components of active power control



Voltage control with current limiting



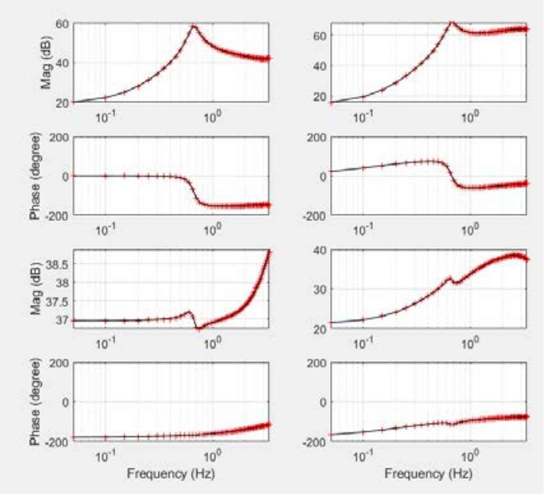
Stability Analysis Using Impedance Scan Toolbox



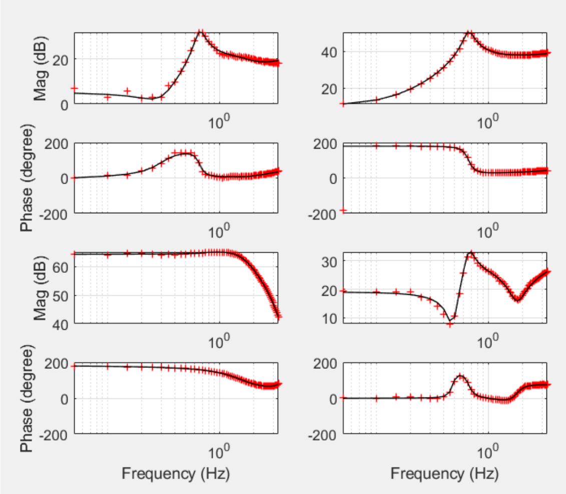
- Impedance scans are performed for different droop settings to understand the interactions between BESS and synchronous condensers.
- Extended to a 39-bus system for evaluating stability in the presence of multiple SuperFACTS devices.

Impedance Analysis for Droop Gain: 50 mHz/MW

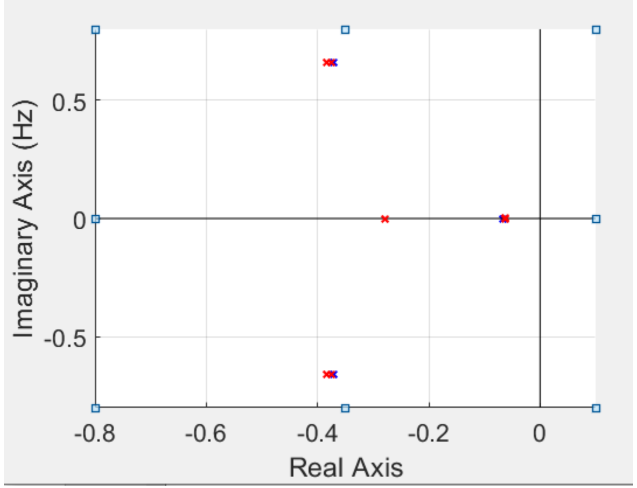
BESS DQ Admittance



Network DQ Admittance



System Dominant Poles



Red cross: measurements

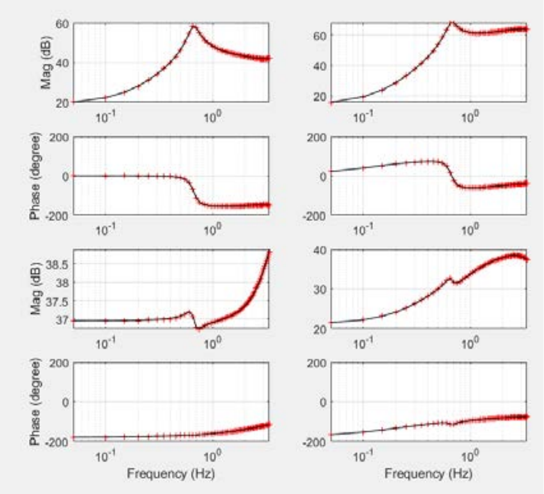
Black lines: analytical fitting

Blue: without BESS; Red: with BESS

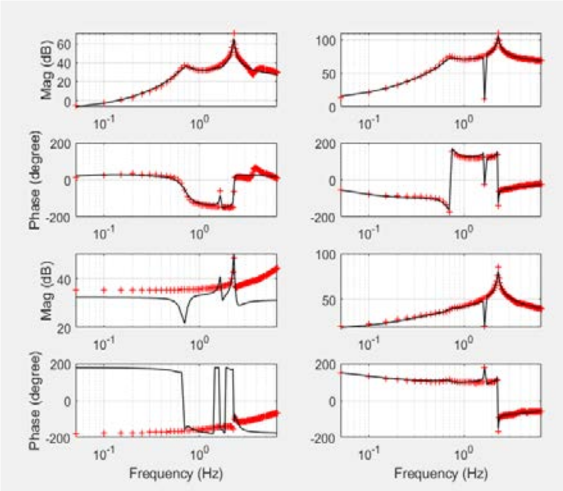
- Result: BESS with droop of 50 mHz/MW does not affect the synchronous condenser mode at 0.7 Hz.

Impedance Analysis for Droop Gain: 5 mHz/MW

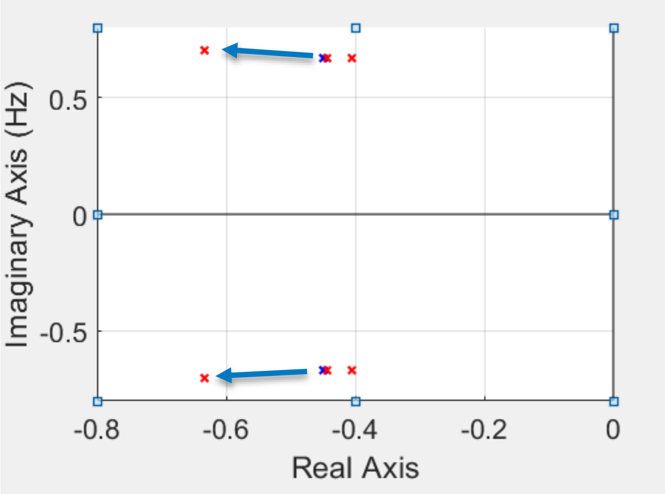
BESS DQ Admittance (50 mHz/MW)



BESS DQ Admittance (5 mHz/MW)



System Dominant Poles



Red cross: measurements

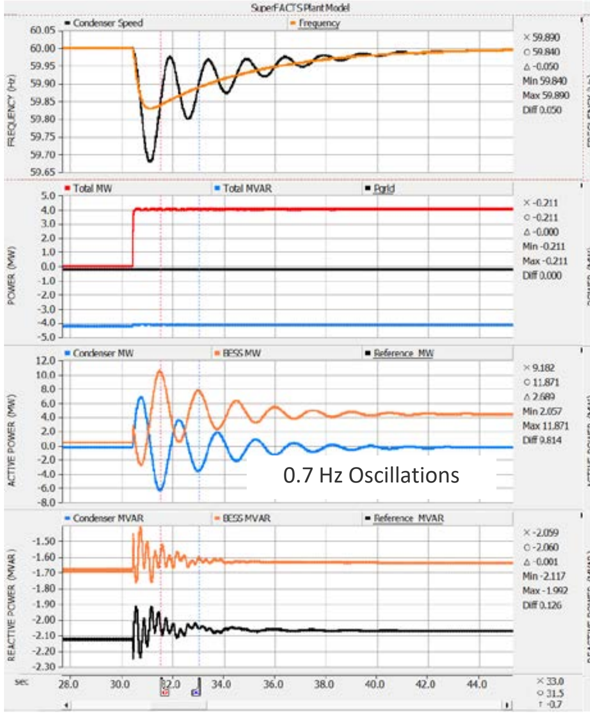
Black lines: analytical fitting

Blue: without BESS; Red: with BESS

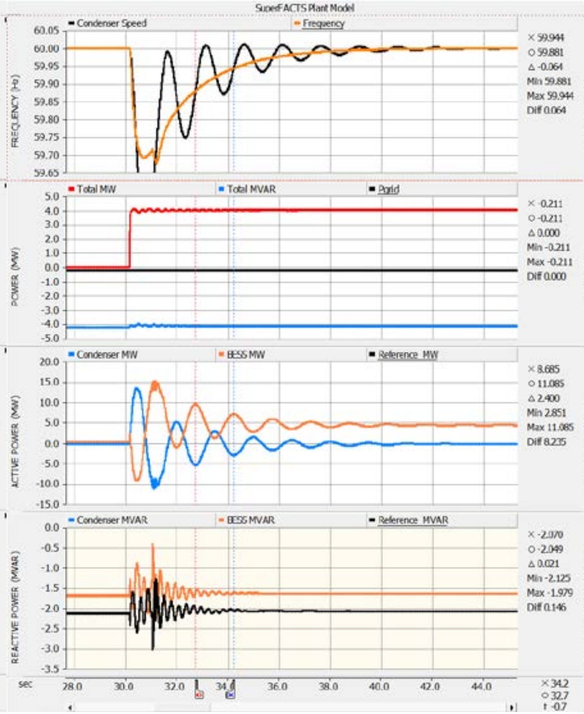
- Result: BESS with droop of 5 mHz/MW damps the oscillations at 0.7 Hz.

Islanded Operation: 4-MW Load Step

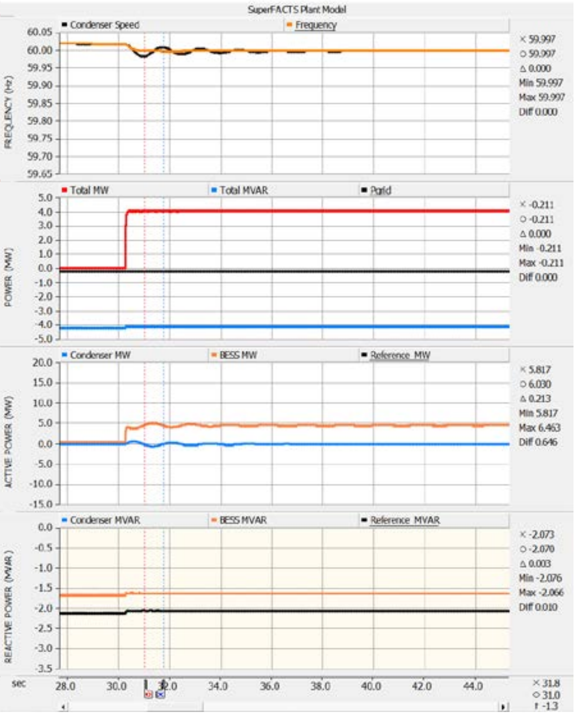
BESS Droop: 50 mHz/MW



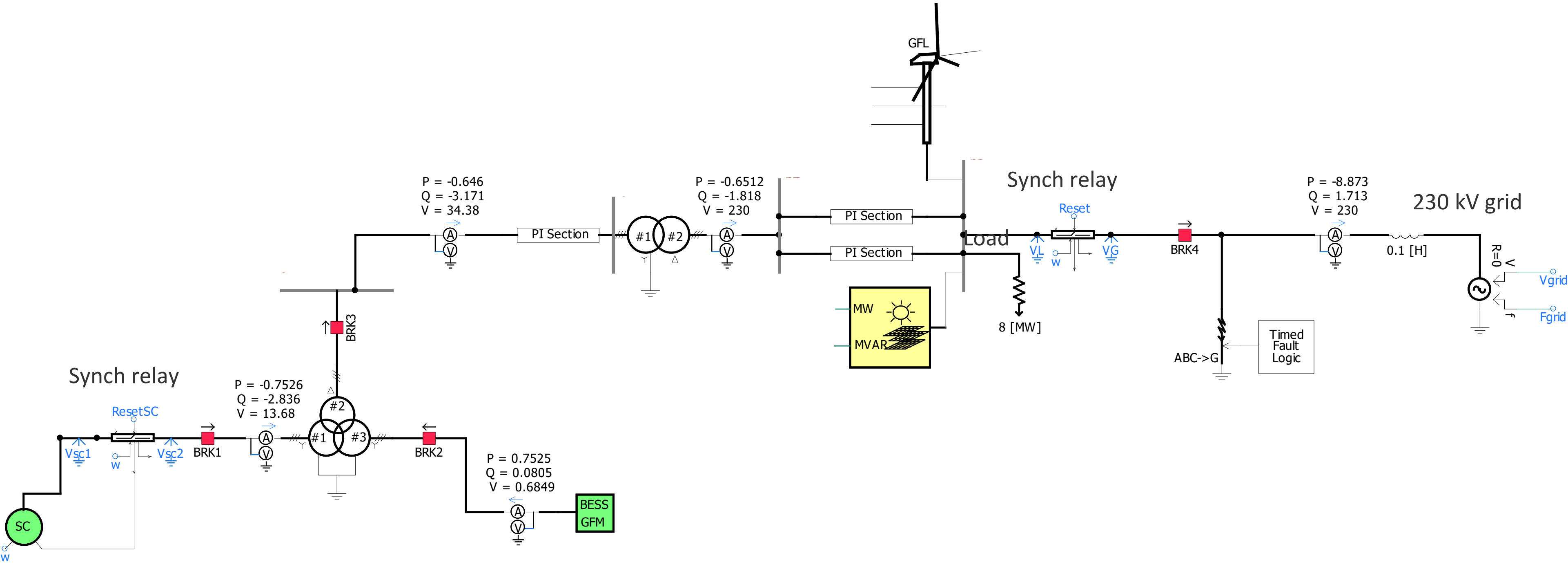
BESS Droop: 100 mHz/MW



BESS Droop: 5 mHz/MW



Black Start of Renewable Plants

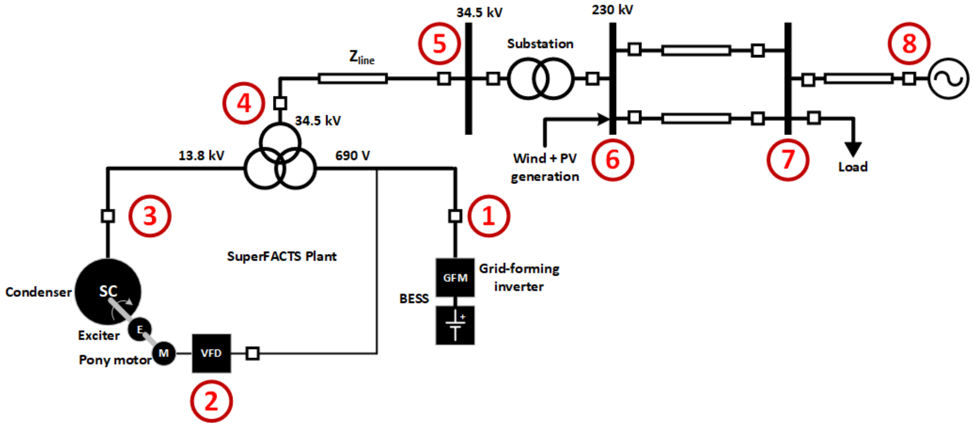


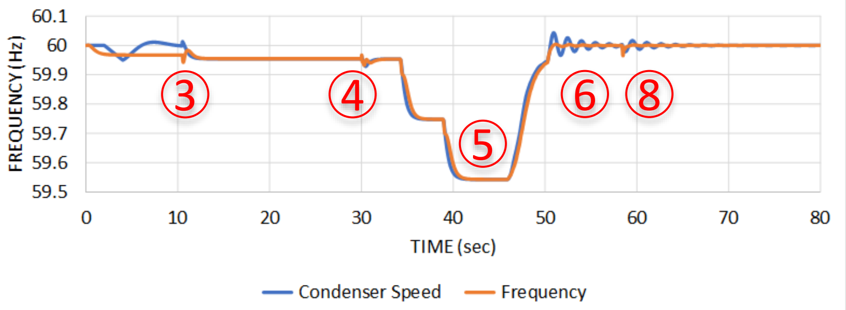
Synch condenser 60 MVA

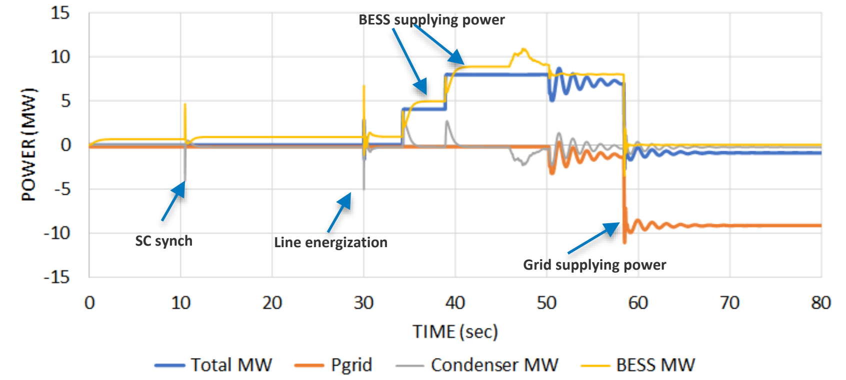
GFM BESS 15 MW

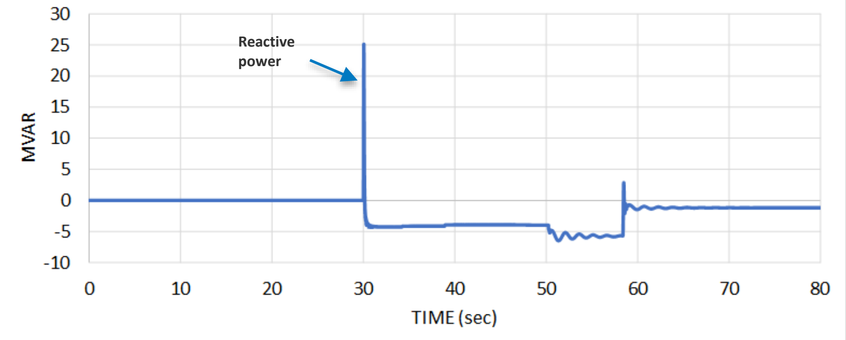
Black-Start Use Case

- Self black start:
  - Soft start by GFM BESS.
- Energizing lines and loads
- Staring PV and wind generation
  - Islanded operation.
- Synchronization with grid.

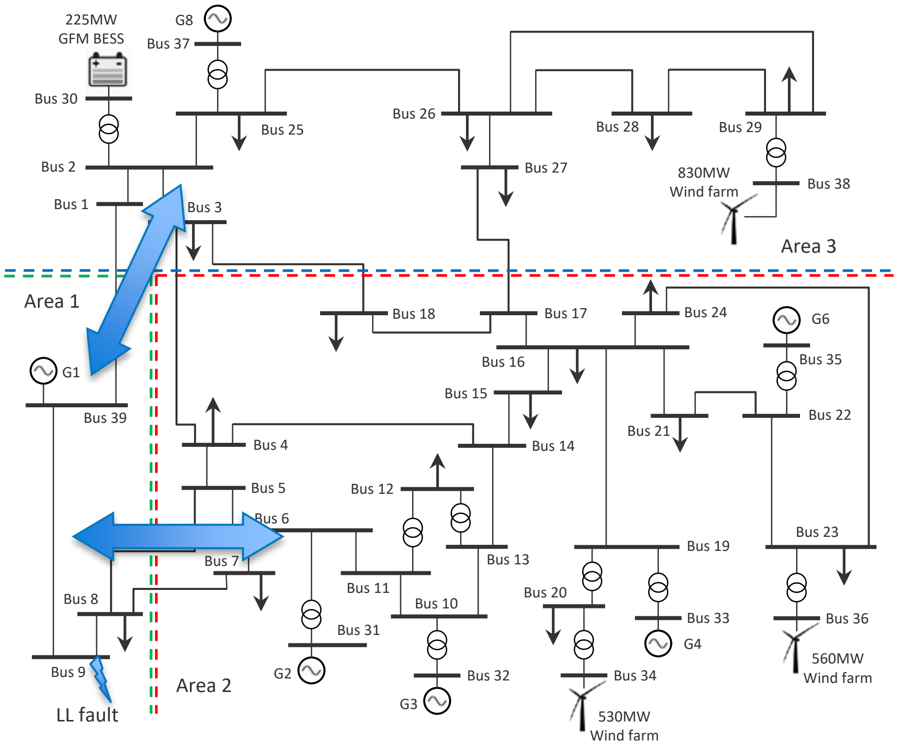


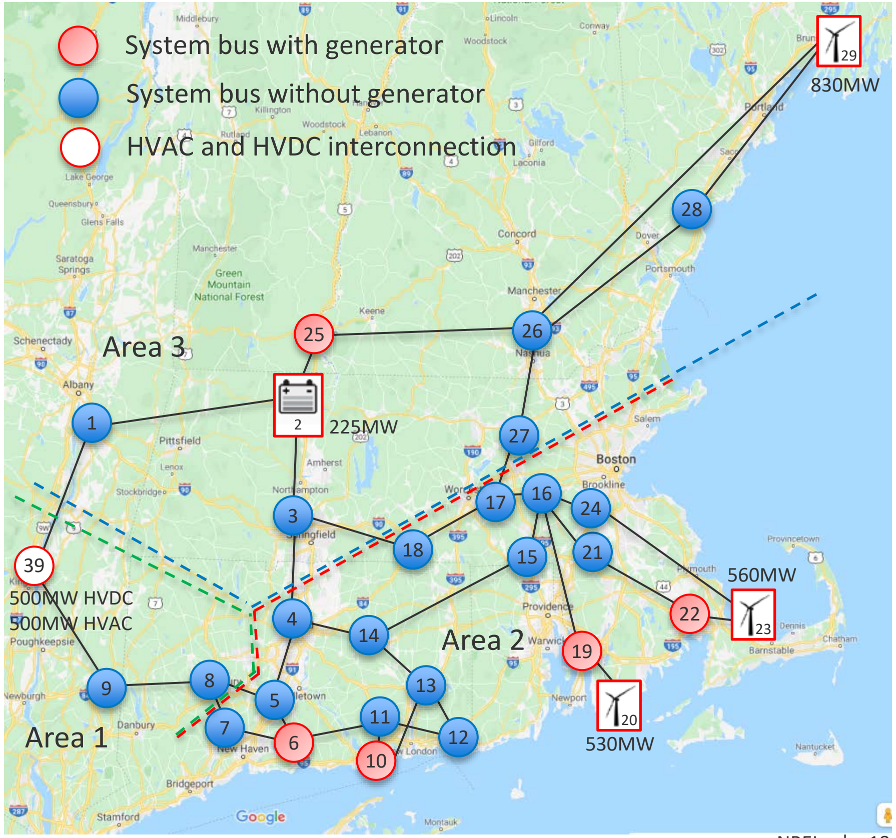






Oscillations in Modified IEEE 39-Bus Test Bed

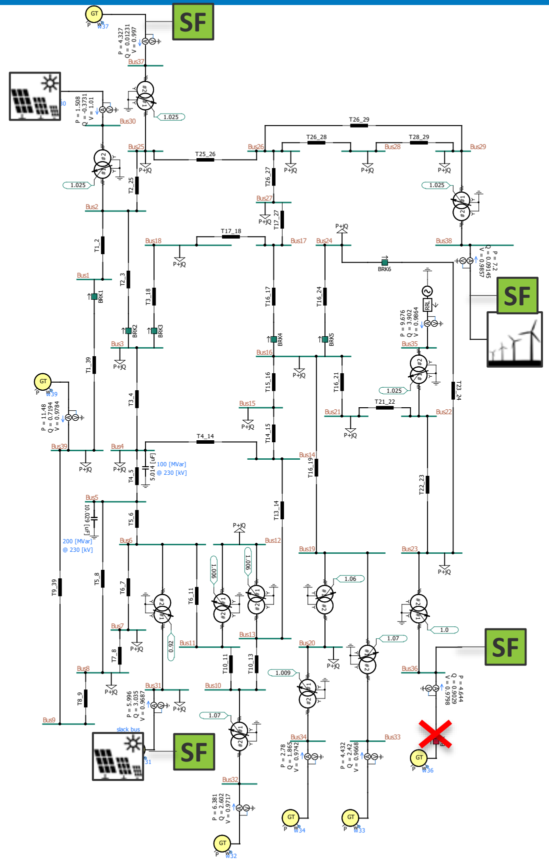


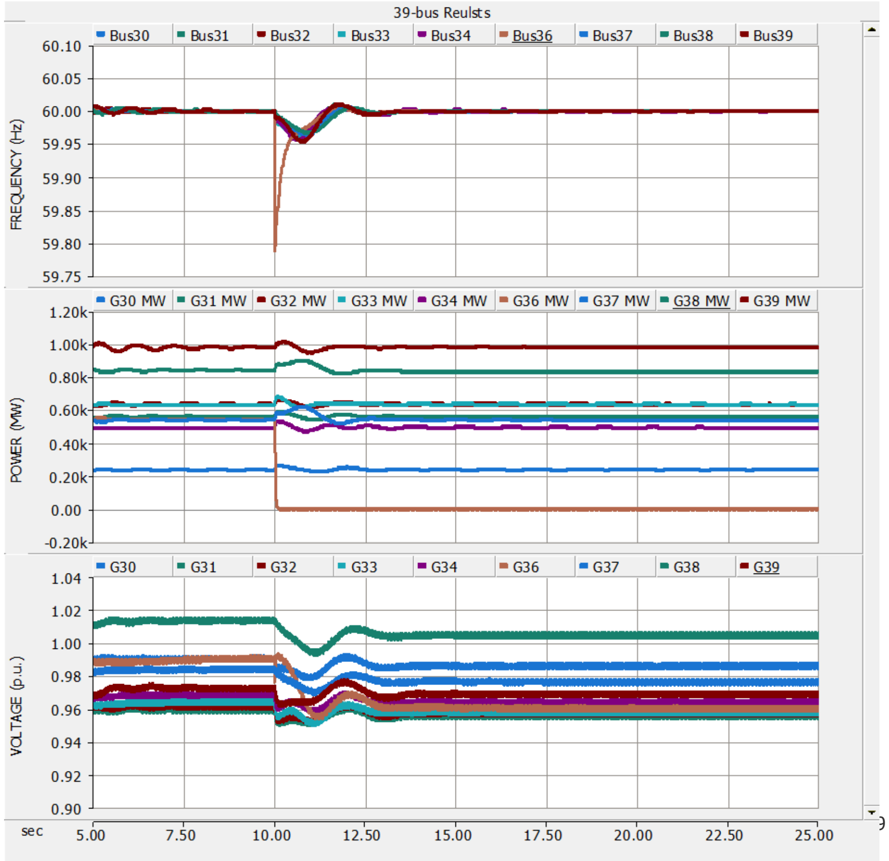


- Oscillation modes can be found between area 1 and area 3 and between area 2 and area 3.

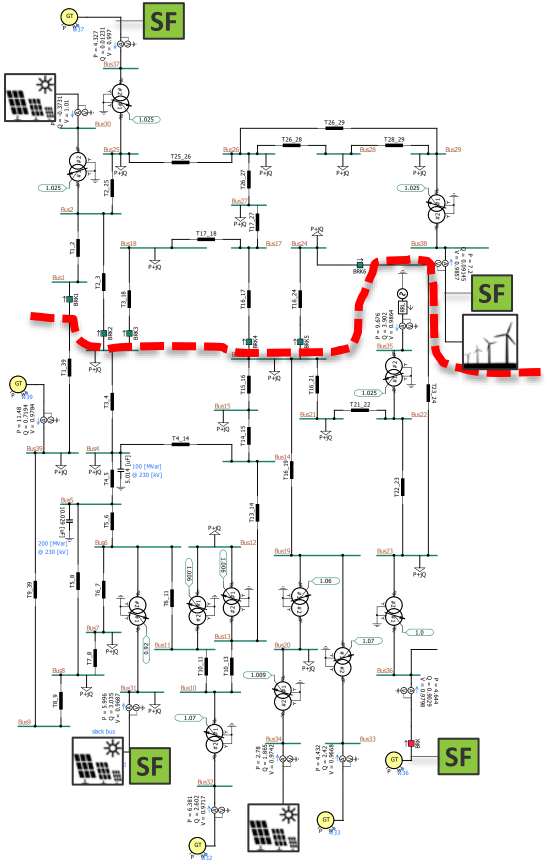
F. Wilches-Bernal, J. H. Chow, and J. J. Sanchez-Gasca, “A Fundamental Study of Applying Wind Turbines for Power System Frequency Control,” *IEEE Transactions on Power Systems* 31 (2): 1,496–1,505, March 2016.

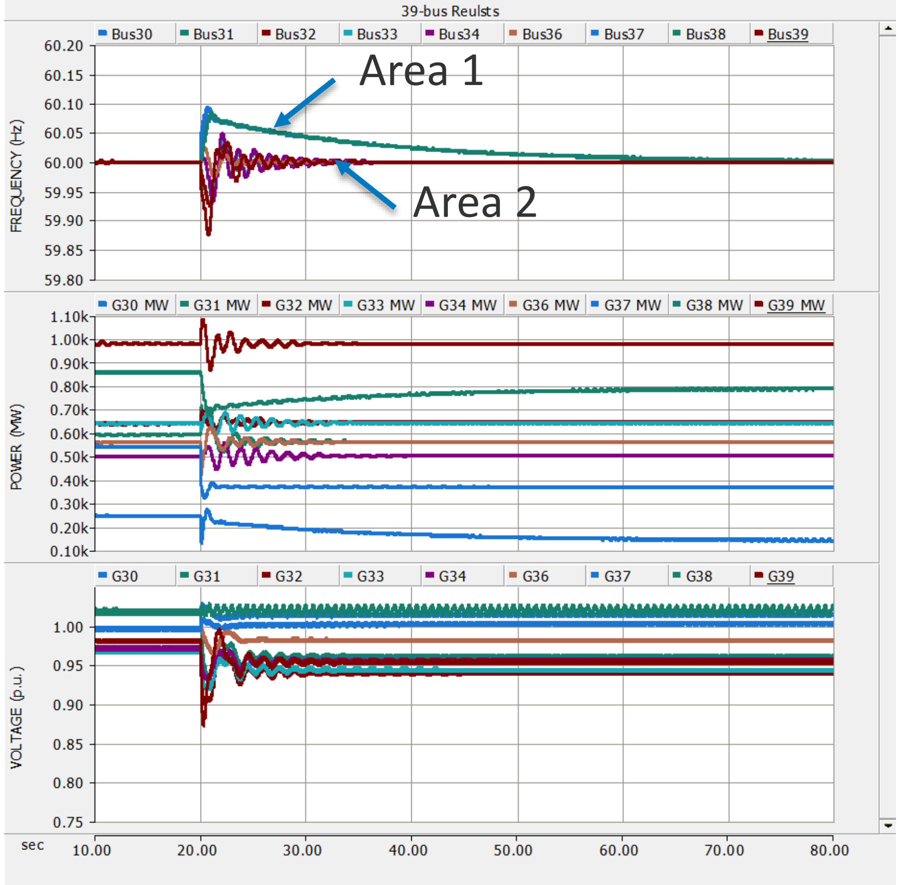
Case: Drop of 500-MW Generation, 830-MW Wind, 1,000-MW PV





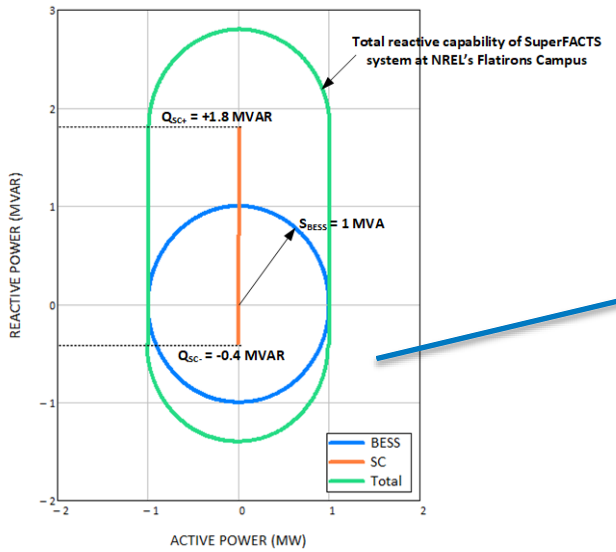
System Separation, Wind + Solar, SF Systems Deployed in Four Buses

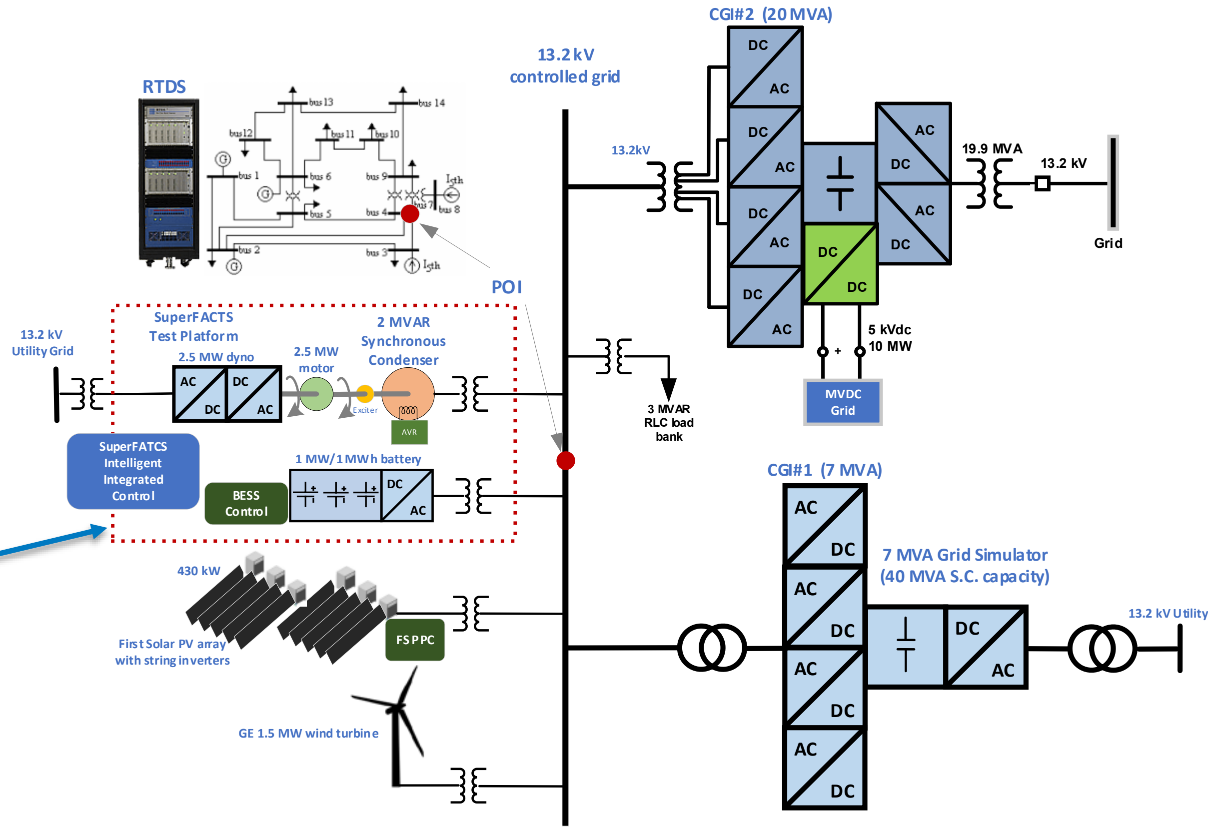




SuperFACTS Test Platform

Projected P-Q capability of SuperFACTS platform





Source: NREL

Conclusions and Future Plans

- Proposed SuperFACTS concept:
  - Useful tool for system operators and utilities to consider for addressing reliability challenges in IBR grids.
  - Provides scalable building blocks to address many integration and reliability challenges.
- Validation and demonstration testing in Fiscal Year 2022 at NREL:
  - Testing under grid fault conditions.
- SuperFACTS allocation optimization problem
- Levelized cost of energy and production cost analysis.

NREL test site. *Photo by NREL*

www.nrel.gov

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NREL/PR-5D00-81678

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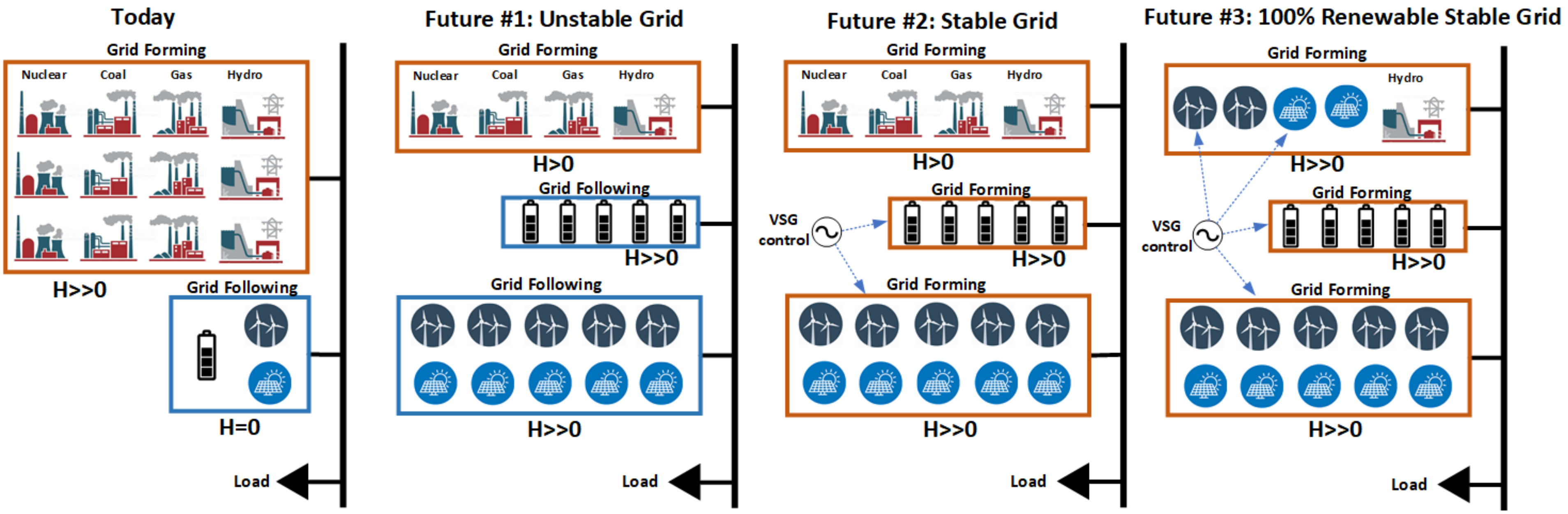

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