Super-Flexible and Robust AC Transmission System Devices (SuperFACTS)

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The Numbers

- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- FUNDING OPPORTUNITY:
  N/A
- LOCATION:
  NREL, Golden, CO
- PROJECT TERM:
  10/01/2020 to 6/30/2023
- PROJECT STATUS:
  Nearing completion
- AWARD AMOUNT (DOE CONTRIBUTION):
  $800,000
- AWARDEE CONTRIBUTION (COST SHARE):
  $0
- PARTNERS: no paid partners
  ABB (advisory role)

Project Summary

- SuperFACTS concept proposes a grid stability enhancing solution that combines mature grid supporting technologies under central advanced control system capable of addressing all main grid integration challenges for variable generation and improve reliability of power grids.

- SuperFACTS scalable concept combines grid forming battery energy storage (GFM BESS) and synchronous condenser (SC) functionality in a single system that depending on use case can be controlled to provide fully dispatchable and flexible operation using energy storage component, provide a full range of existing and future ancillary and reliability services to the grid (similar or better than conventional sources), maintain adequate levels of grid strength and inertia, and provide fault current for proper operation of protection systems.

- The main objective of this project is to develop a validation platform and demonstrate the SuperFACTS system at scale and develop models and conduct simulations to demonstrate benefits at system level.

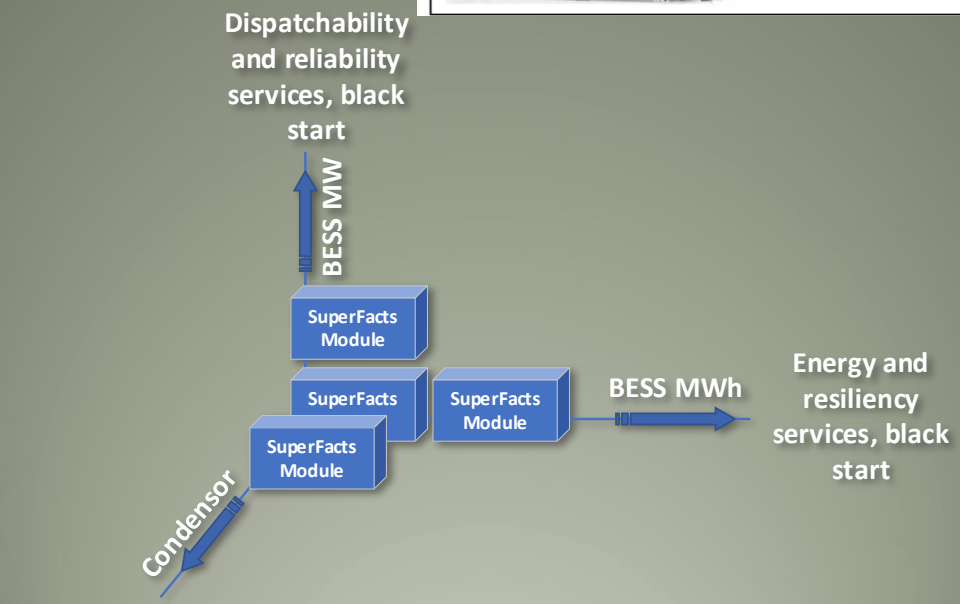
Project Summary (continued)

SuperFACTS benefits

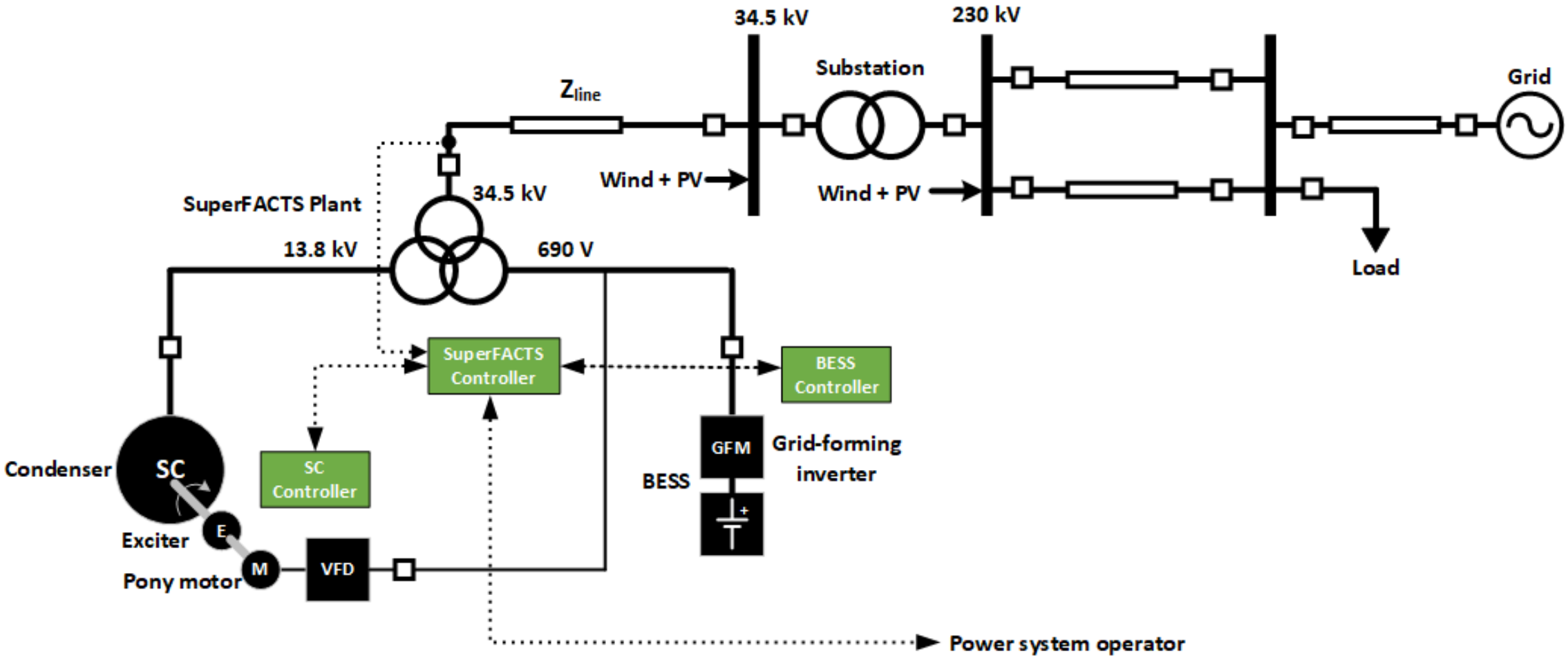
Challenge	BESS	Synchronous Condensers	SuperFACTS
Various forms of grid services based on active power control	Yes	No	Yes
Inertial response	Synthetic, depends on BESS operation point	Yes, real rotating inertia	Enhanced
Steady-state and dynamic reactive compensation, voltage support	4-quadrant	2-quadrant (limited by stability and thermal constraints)	Enhanced
Grid strength enhancement	Depends	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)

SuperFACTS scalability:

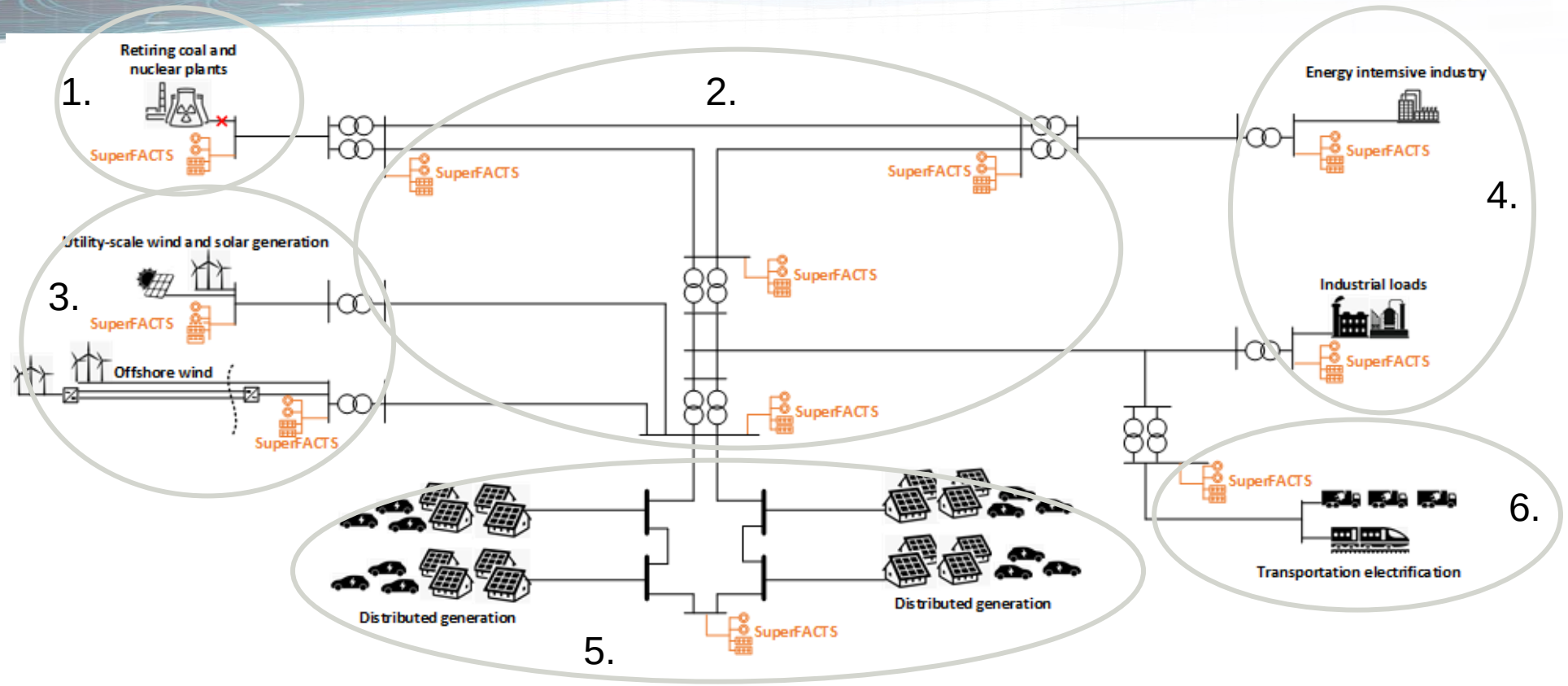
- Grid strength, inertia, and fault current
- Energy services and resilience services
- Reliability services
- Black-start services.



Technical Approach



SuperFACTS in the Grid



1. Replacing retiring conventional plants (taking advantage of existing infrastructure) for active and reactive power control services, maintaining grid strength and protection adequacy
2. Transmission services (power flow control, voltage support, black start etc.)
3. Integrating variable generation (dispatchability, grid strength, enhanced transient performance, black start, etc.)
4. Services to large industrial loads (power quality, islanded operation, black start. Etc.)
5. Distribution level services (increase hosting capacitates of distribution systems, islanded operation, black start, protection adequacy, etc.)
6. Maintaining grid strength, SCR and transient performance for heavy-duty EV charging stations
7. Islands

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Milestones

3.1: Task 1: Identify all use cases for SuperFACTS concept, develop a test plan	**100%**
3.2: Task 2: Develop control theory for SuperFACTS concept	**100%**
3.3: Task 3: Develop SuperFACTS Controller	**100%**
Task 4: Deploy controller and conduct initial testing	**100%**
Task 5: Demonstrate ability to provide reliability services on transmission level	**100%**
Task 6: Demonstrate ability to provide blacks start services	**100%**
Task 7: Demonstrate benefits of SuperFACTS operation in a large power system	**100%**
Task 8: Demonstrate benefits of SuperFACTS in islanded grids	**100%**
Task 9: Impedance-based stability testing and evaluation of SuperFACTS system	**100%**
Task 10: Development of power system stabilizer (PSS) controls for SuperFACTS	**100%**
Task 11: Testing SuperFACTS with GFL BESS configuration	**100%**

Ongoing activities:

- **Drafting final project report**
- **Paper to be presented at 2023 IEEE PES GM, US**
- **Paper to be presented at 2023 Wind&Solar International Workshop, Europe**
- **ESIG presentation being planned**

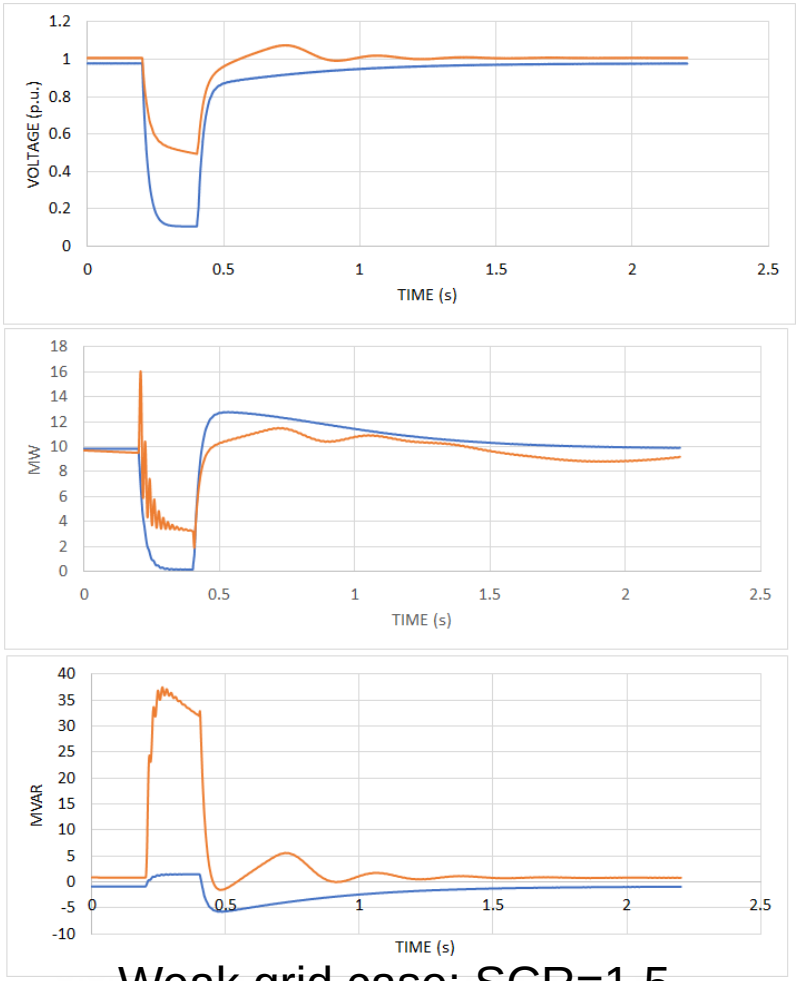
Accomplishments: Demonstrated Use Cases

- Combination of SC with GFM BESS provides much better transient performance
- This is because of significant grid strength increase provided by SC

SuperFACTS services:

- Provision of combined real and configurable virtual inertias √
- Provision of synchronizing torque √
- Provision of short circuit current contribution √
- Increased grid strength and short-circuit ratios √
- High overcurrent capability √
- Grid topology-independent smart voltage recovery contributor/ flexible fault response provider
- Provision of enhanced voltage and reactive power control with ultra-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 √
- Ability to provide inrush current-free energization of transformers, cables and motors √
- Enabler for economic renewable technology hybridization (can be co-located 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 √
- Less than 1ms response times for damping instabilities caused by control interactions between inverter-coupled variable power generation and grid √
- Stabilizing power systems with any desired ratios between grid-forming and grid-following inverters √
- Fully scalable and modular topology for both grid-connected, microgrid and stand-alone operation √

  - Same SuperFACTS building blocks will allow deployment in numbers to achieve desired design parameters (MVA capacity, MWh capacity, inertia, SCR 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 transmission, sub-transmission and distribution levels, cam help operating microgrids and islanded grids, and provide black start services for all above.
- Can be controlled for electric loss minimization in transmission and distribution grids
- Control of negative sequence voltages for phase rebalancing may be possible for advanced BESS inverters



Weak grid case: SCR=1.5

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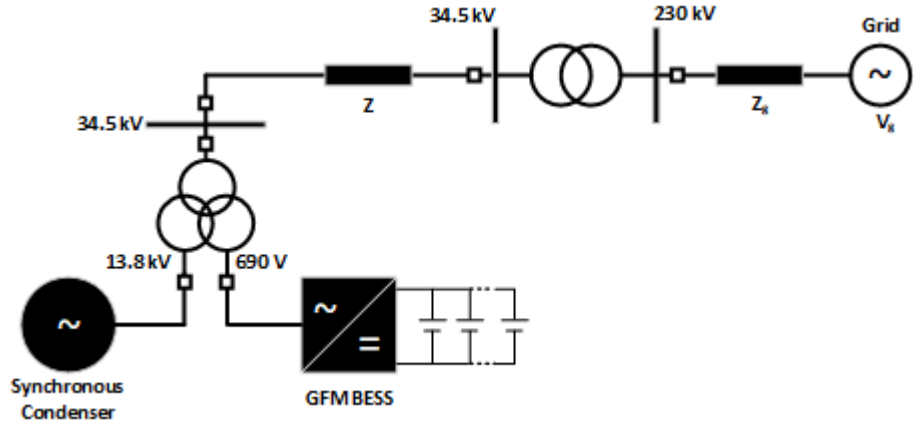
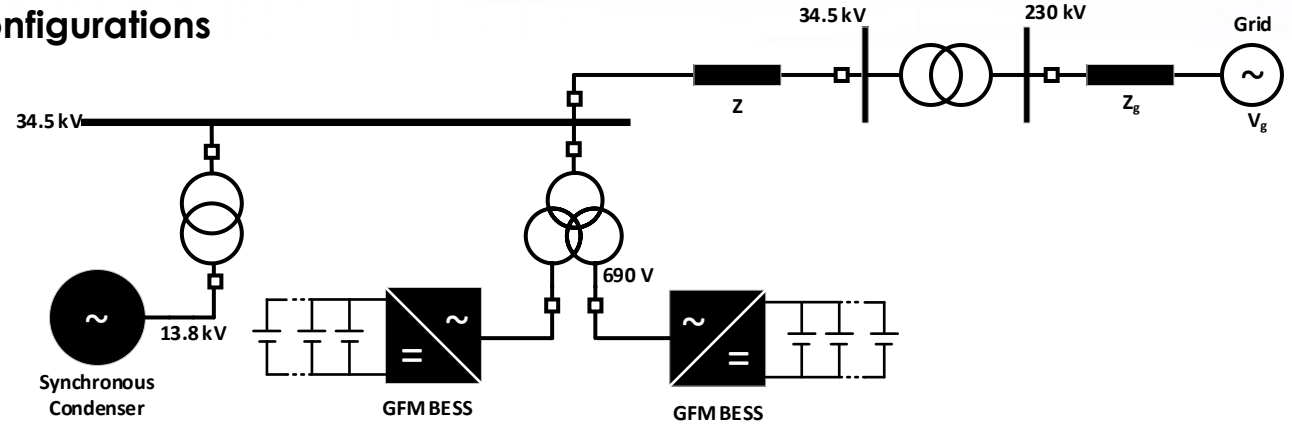
SuperFACTS configurations

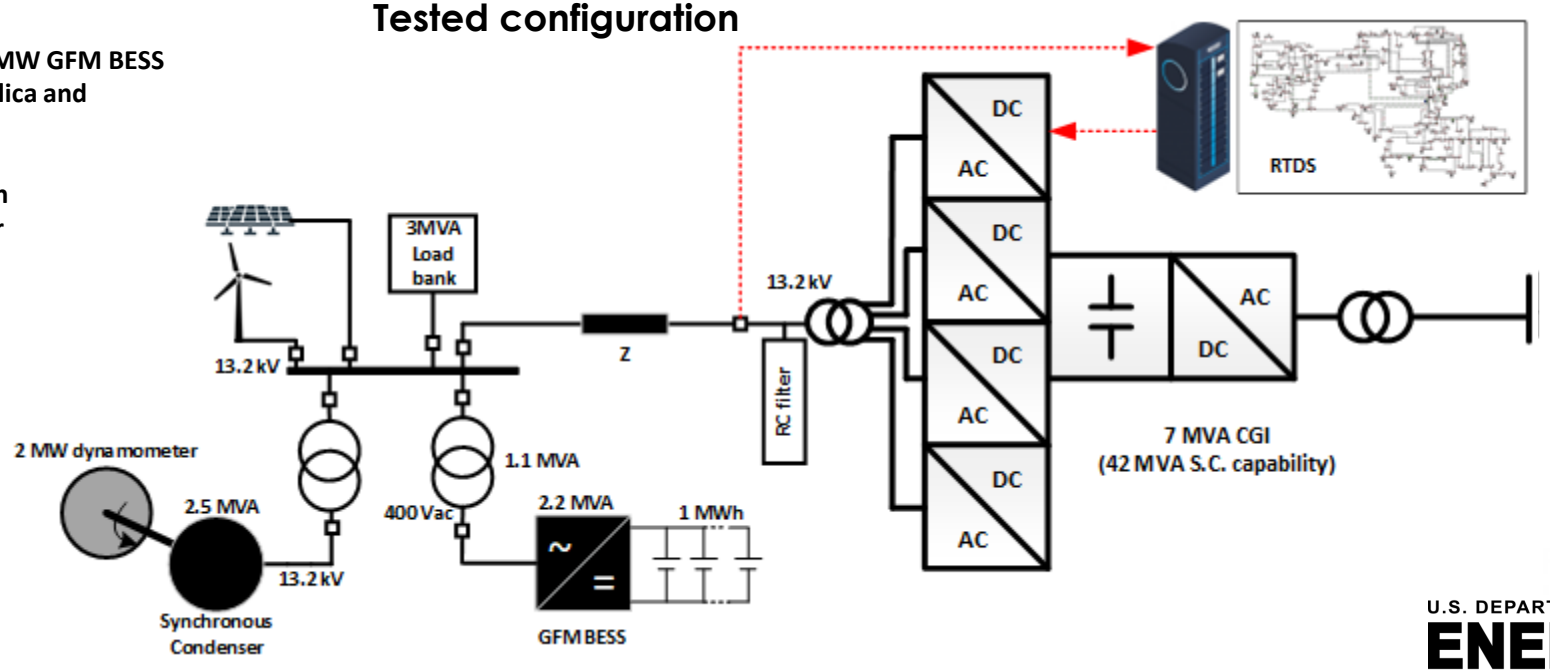
Modeled configurations





Tested configuration

- 2.5 MVA SC combined with 1 MW / 1MW GFM BESS
- 2 MW dynamometer: pony motor replica and enhanced mechanical inertia
- Controlled MV grid emulation
- Islanded and grid connected operation
- Parallel operation with wind and solar
- Multiple black-start scenarios



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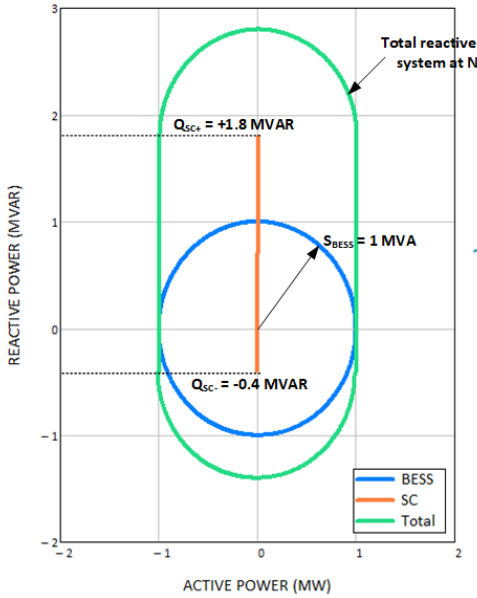
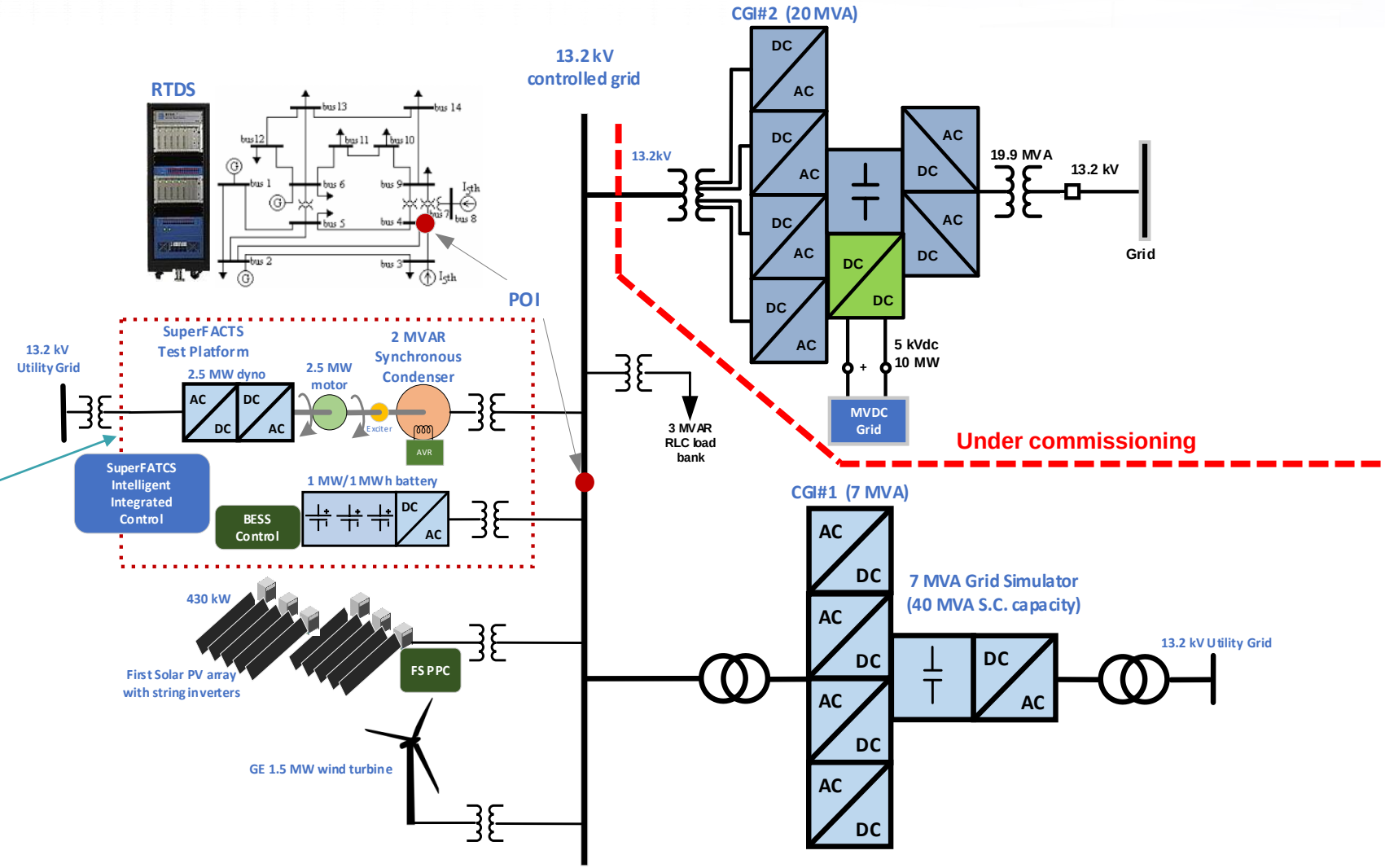
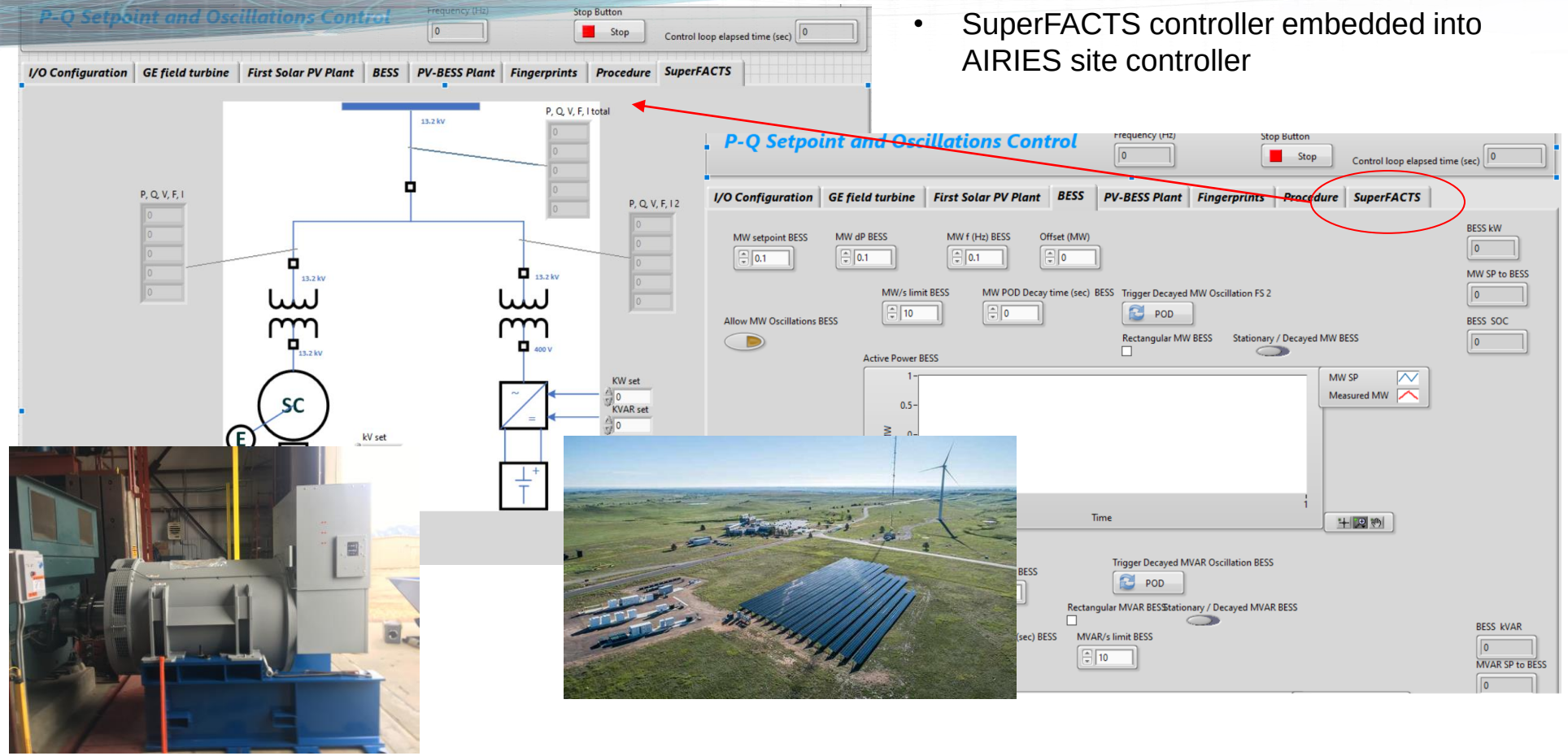
Demonstration Platform





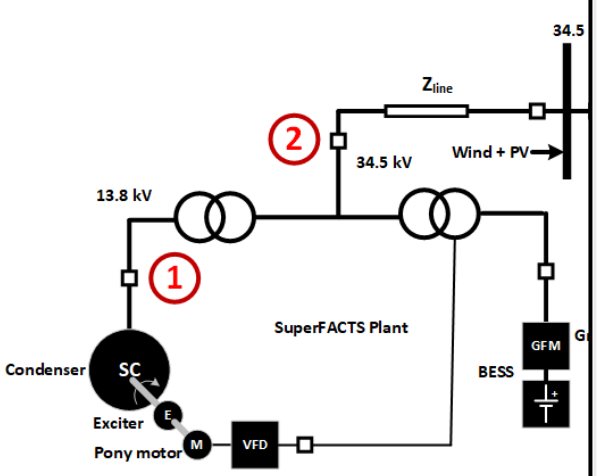
Controller Interface

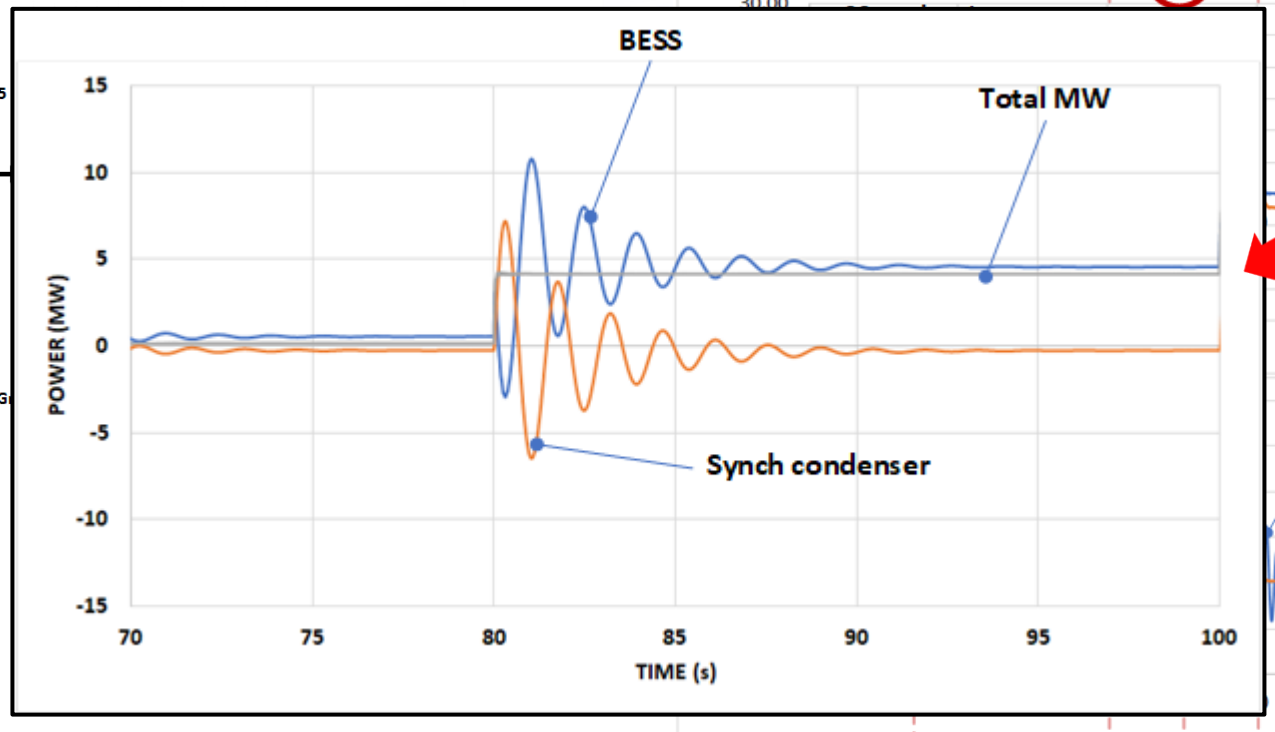


- SuperFACTS controller embedded into AIRIES site controller

- **Central SuperFACTS controller implemented in NI PXI RT hardware**
- **Can operate on operator setpoints, or setpoints coming from any interface or historic time series**
- **Modbus interface between PXI and BESS controllers**
- **CanBus interface between PCI and voltage regulator of synchronous condenser**

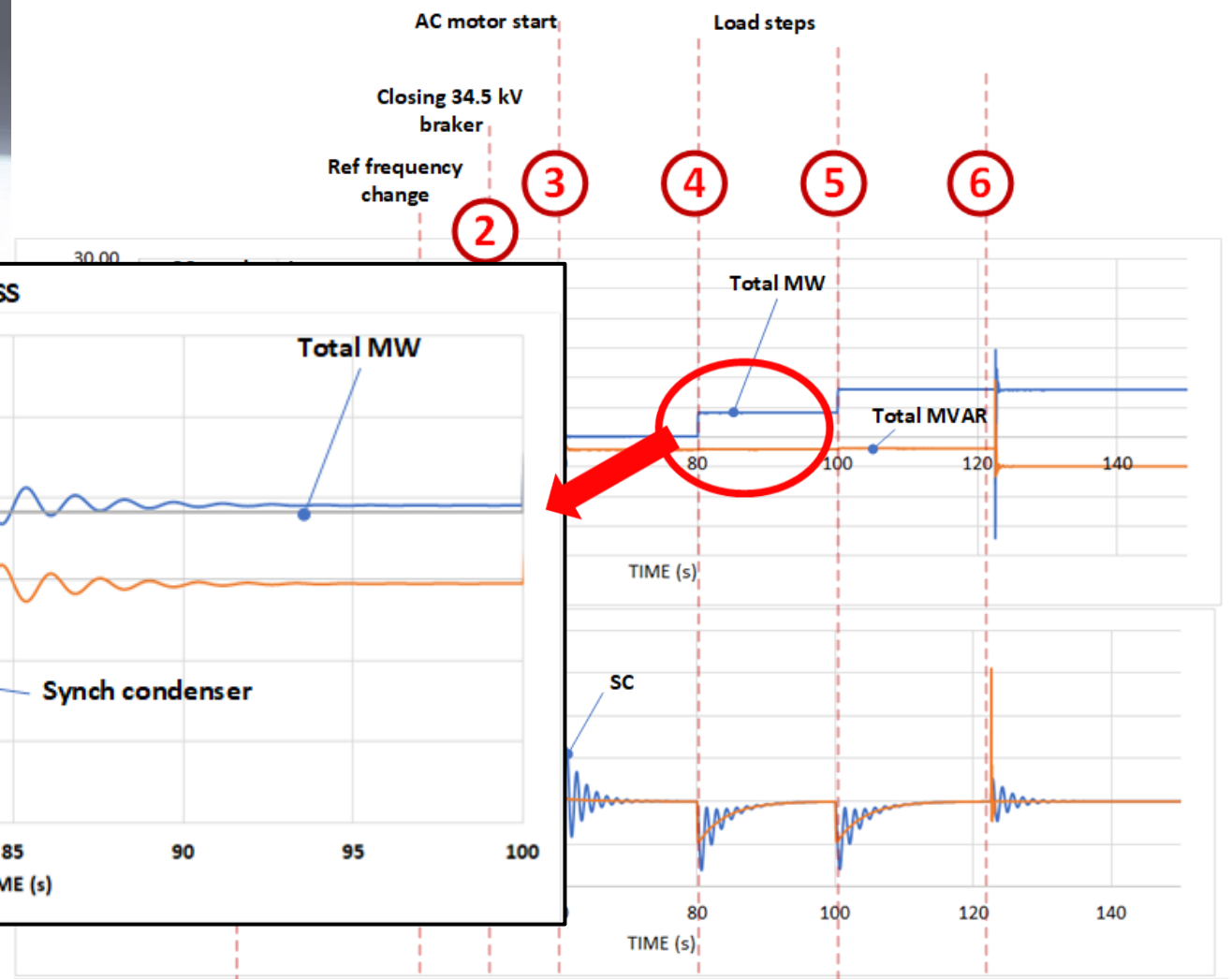
All stages of operation

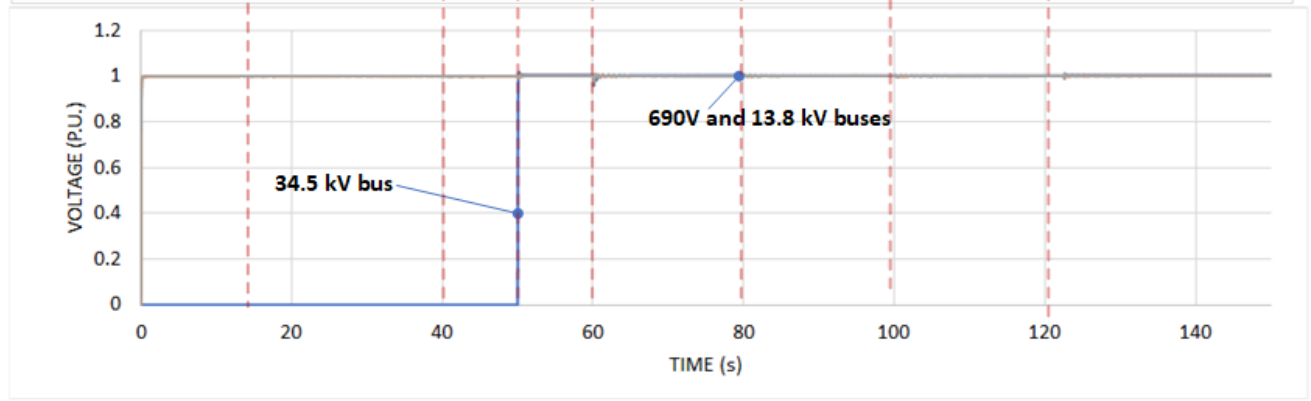




- Self black start
- Energizing transmission line
- Islanded operation of loads
- Resynchronization with grid

- Control mode: smooth power
- BESS is controlled to compensate any oscillations by SC





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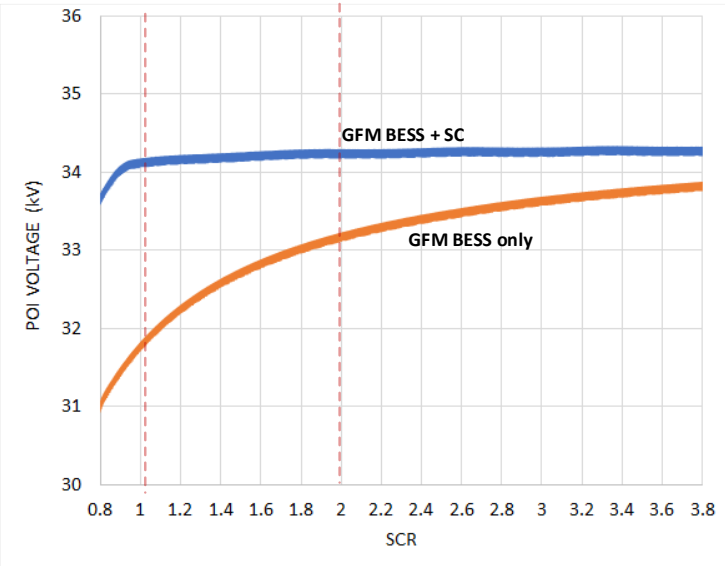
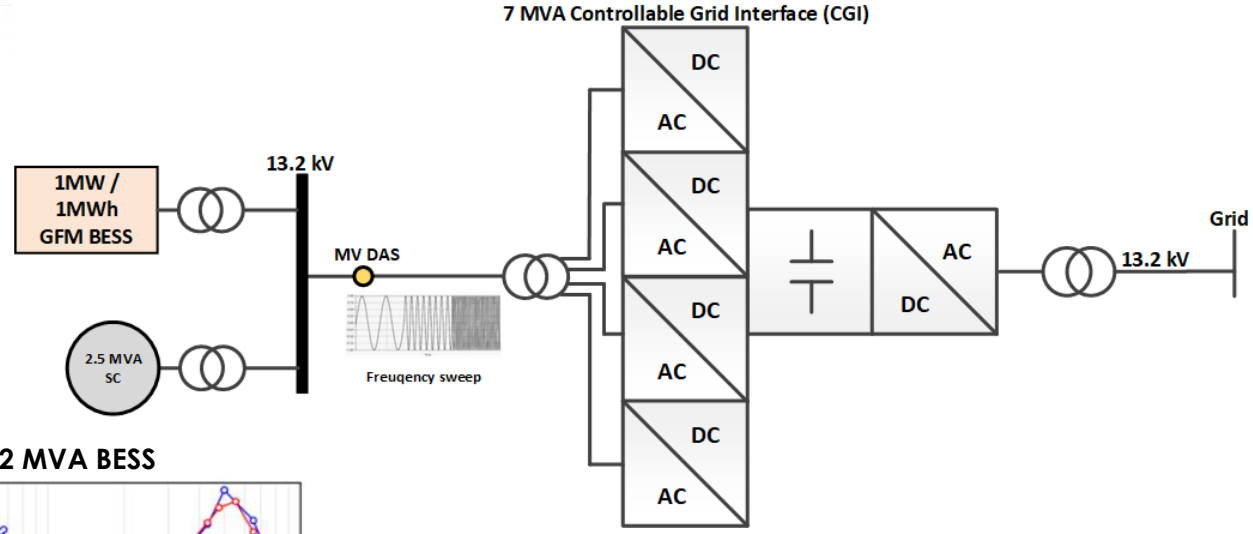
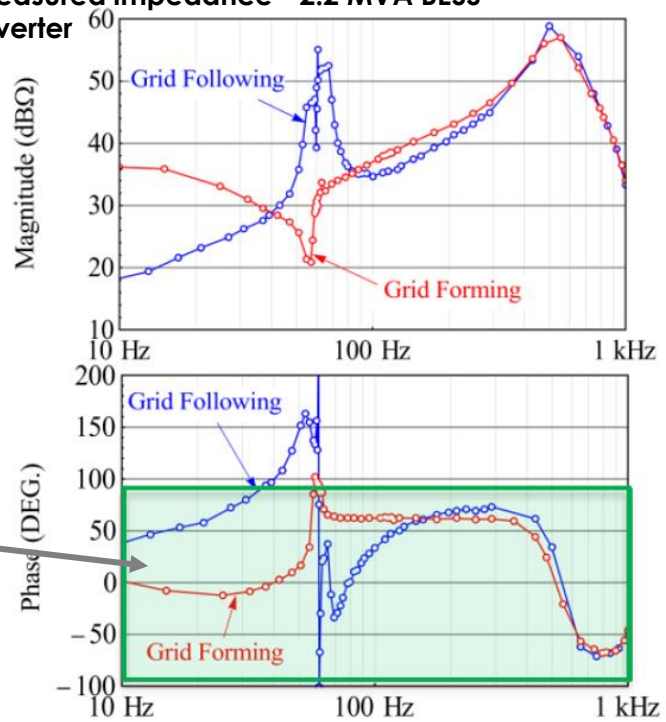
Weak Grid Operation and Stability

Operation at very low SCR possible

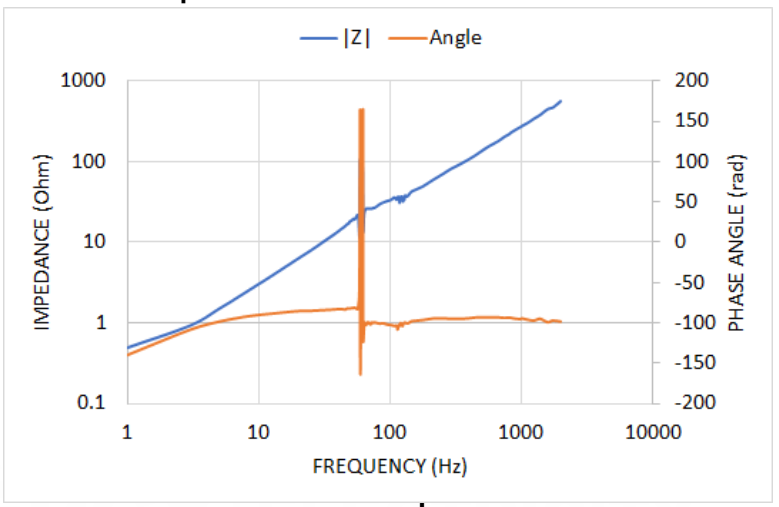




Measured impedance - 2.2 MVA BESS Inverter



Measured impedance - 2.5 MVA SC



GFM BESS demonstrates better damping characteristics compared to GFL

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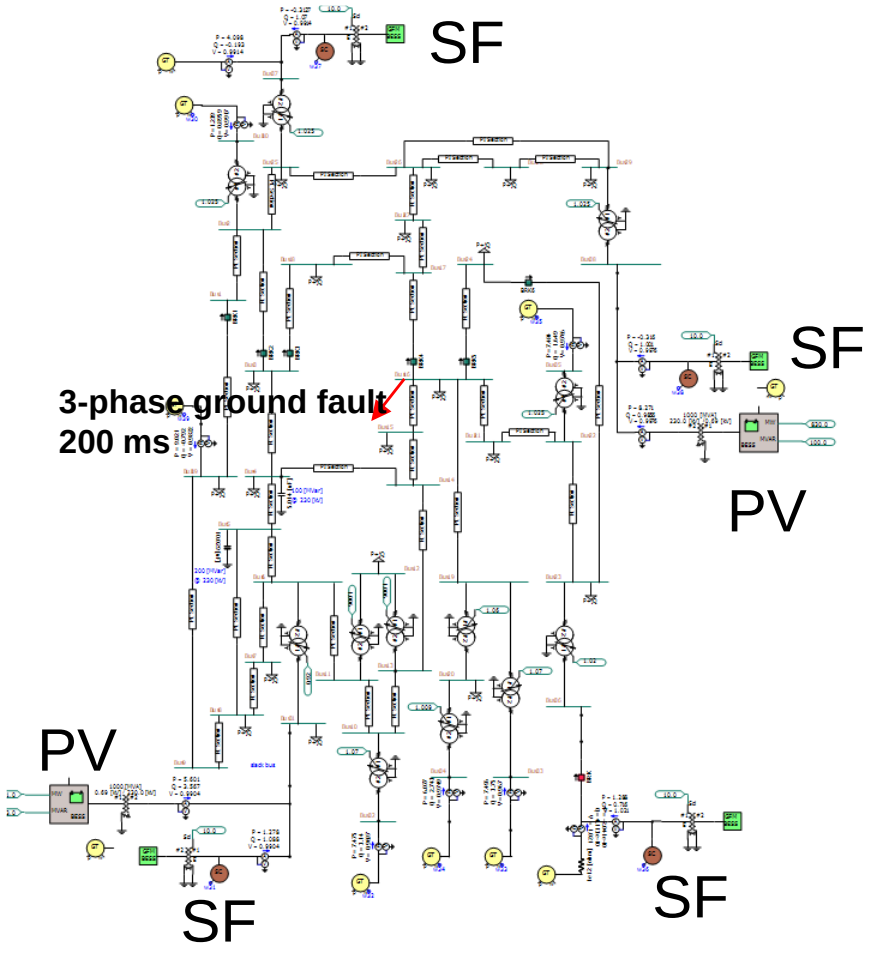
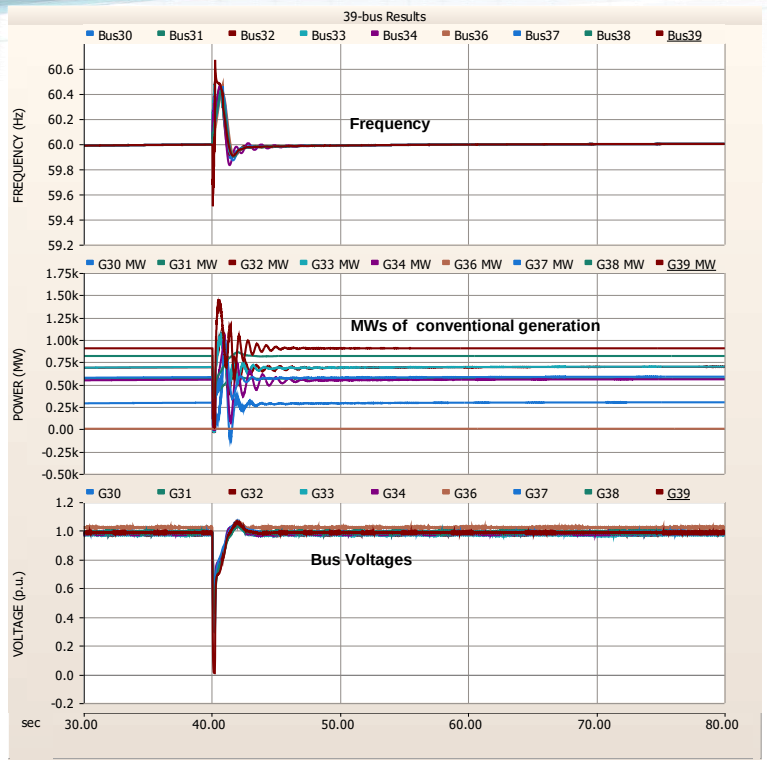
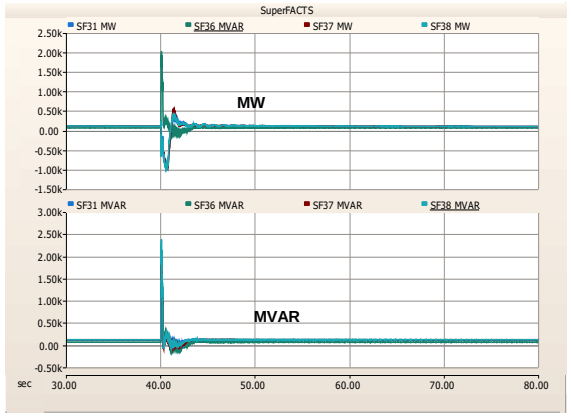
39-bus system – ground fault

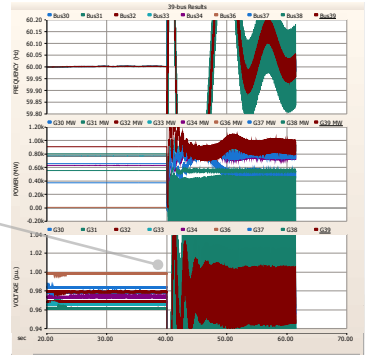




SuperFACTS Responses



No SuperFACTS



Fault

- Improved ride-through performance
- Enhanced grid strength

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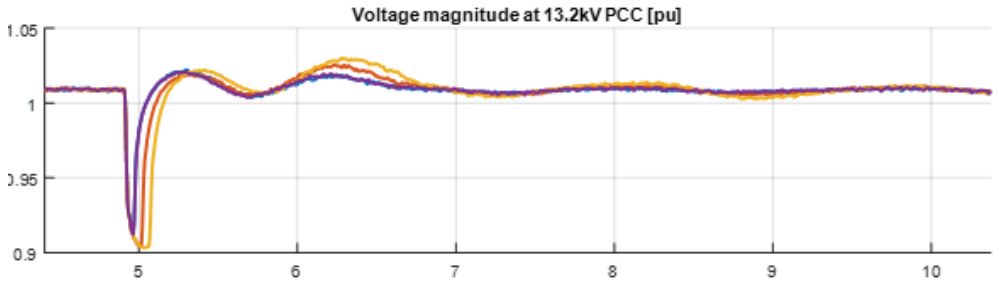
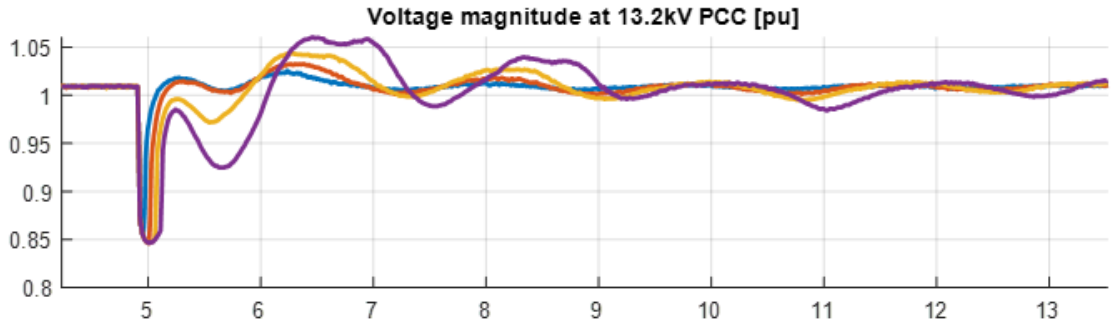
Measured transient performance

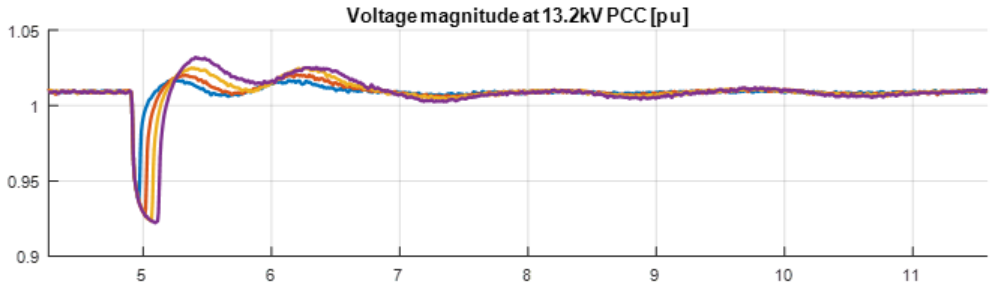
1ph L-L fault



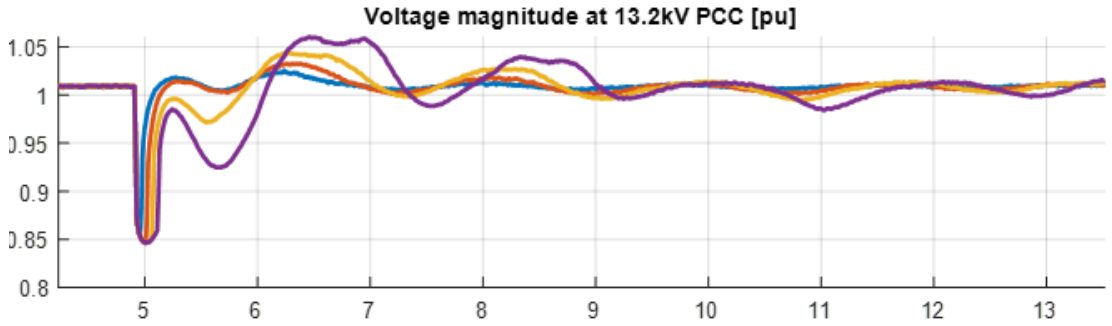
3ph L-L fault



1ph L-gnd fault

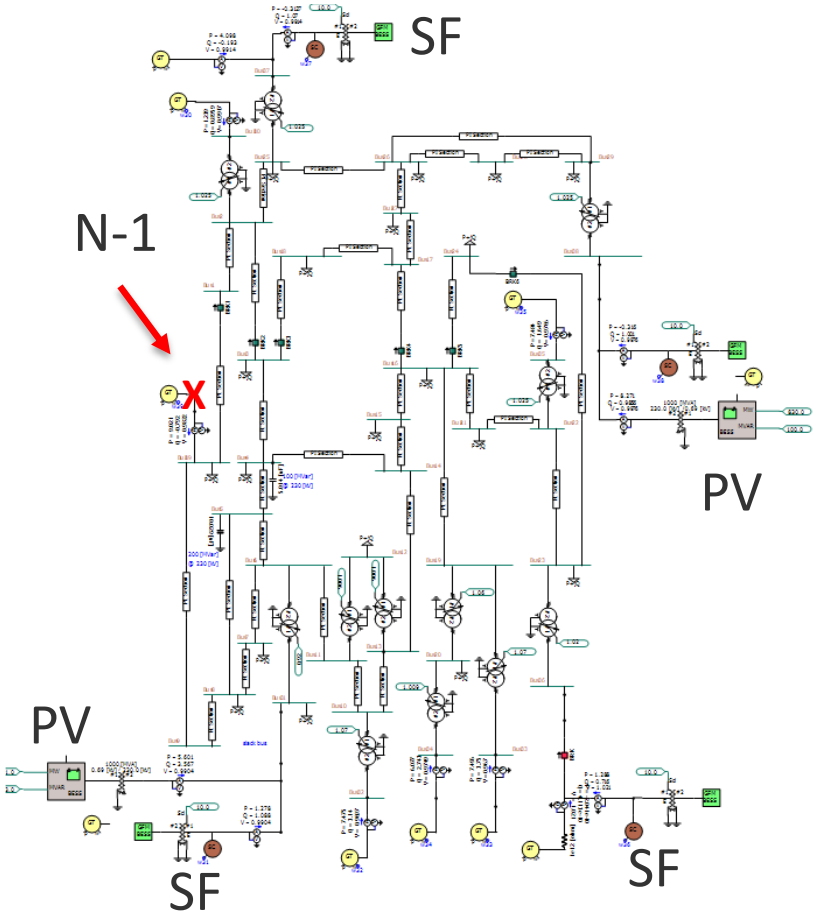


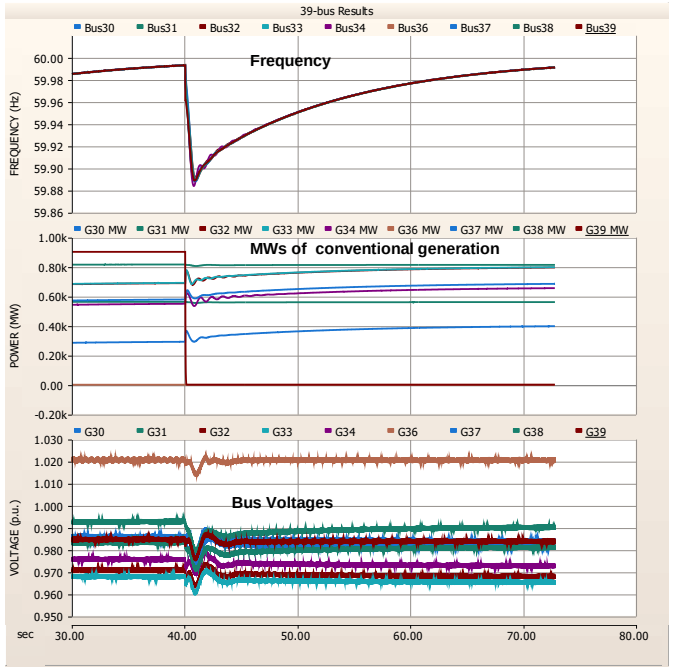
3ph L-gnd fault



PHIL experiment

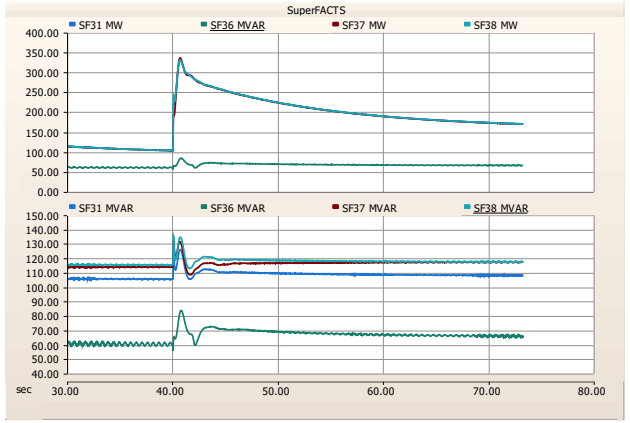
39-bus system: Largest N-1 Response



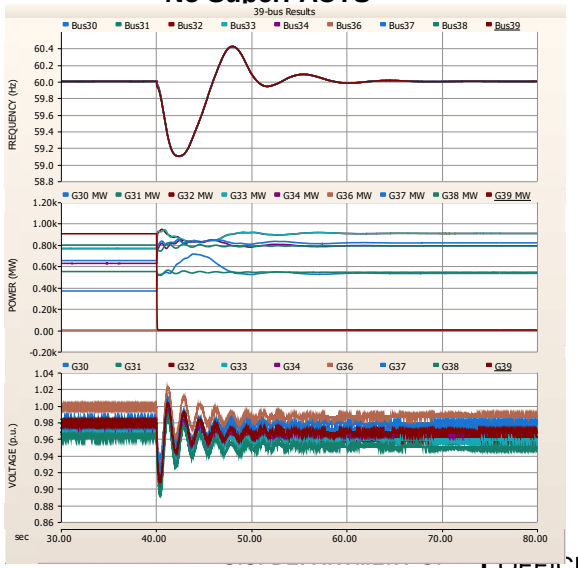


- Better frequency response
- Lower frequency nadir
- Better voltage stability

SuperFACTS Responses



No SuperFACTS



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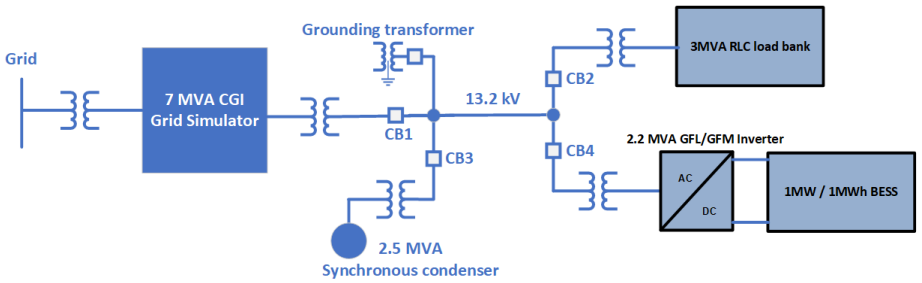
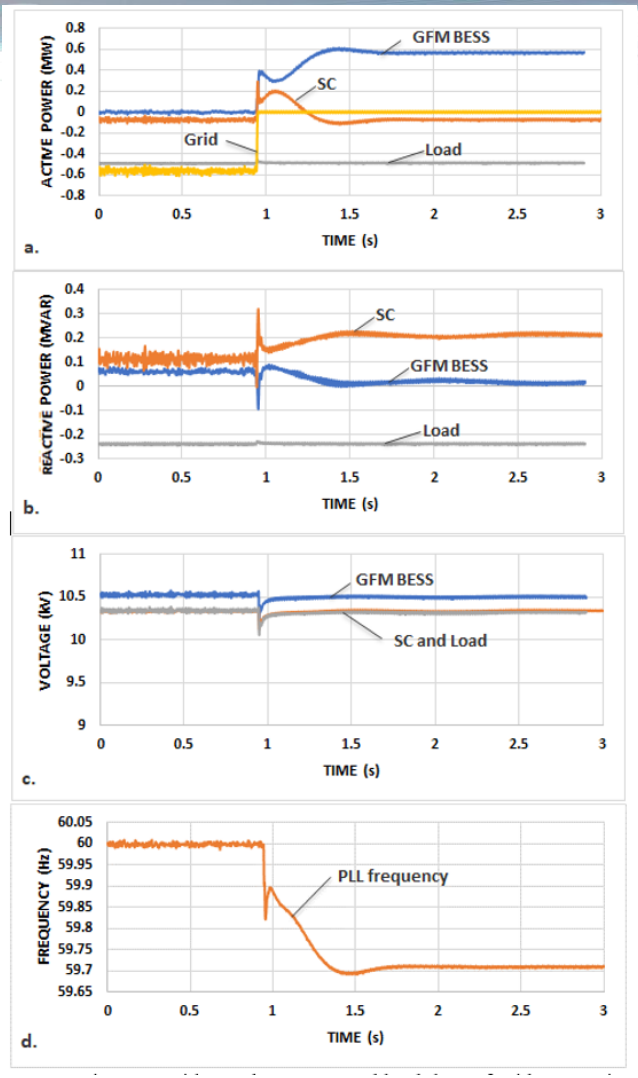
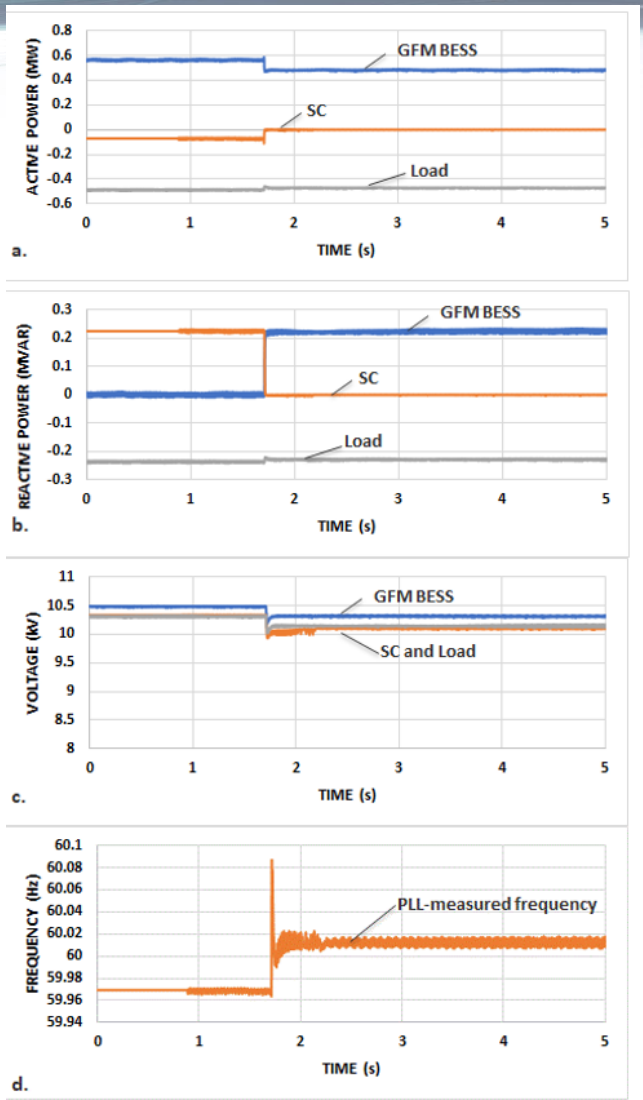
SuperFACTS Islanded Operation Test





Transition to island



Loss of synch condenser

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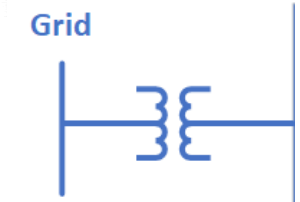
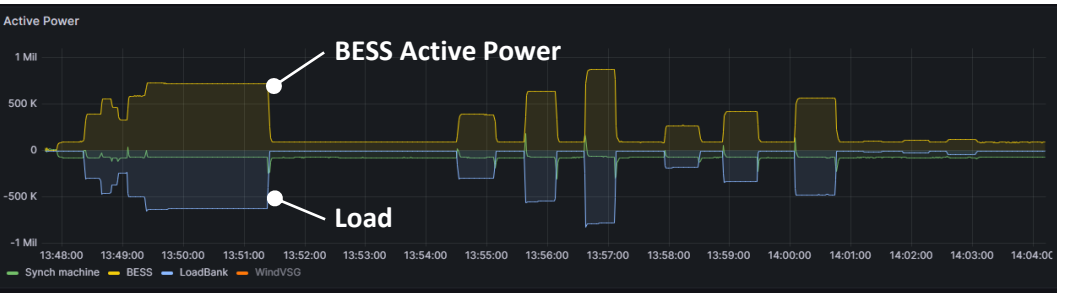
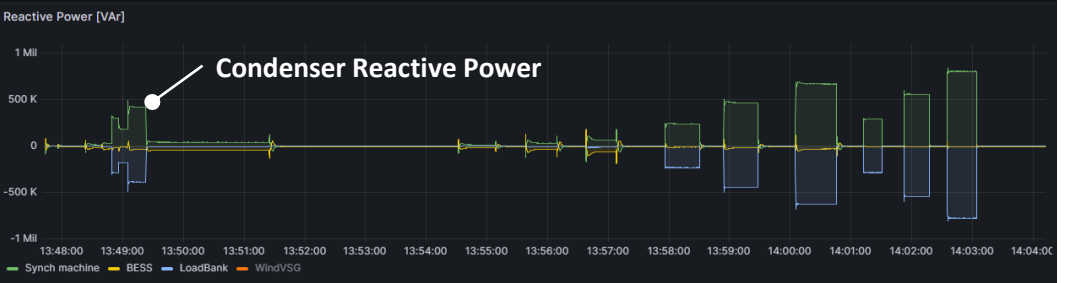
Black-start and operation in GFL mode

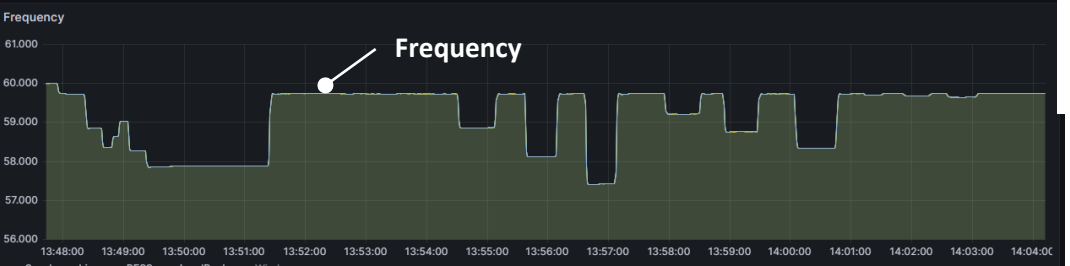
- SC and GFL BESS
- GFL BESS operates on 5% frequency and voltage droops

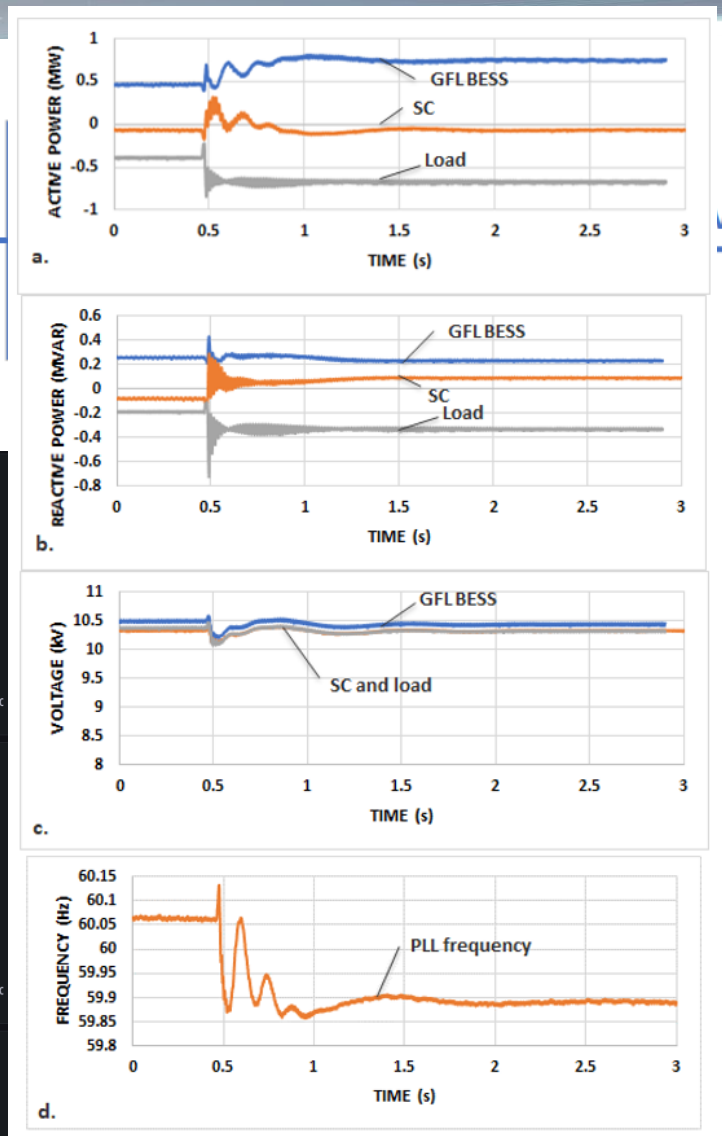


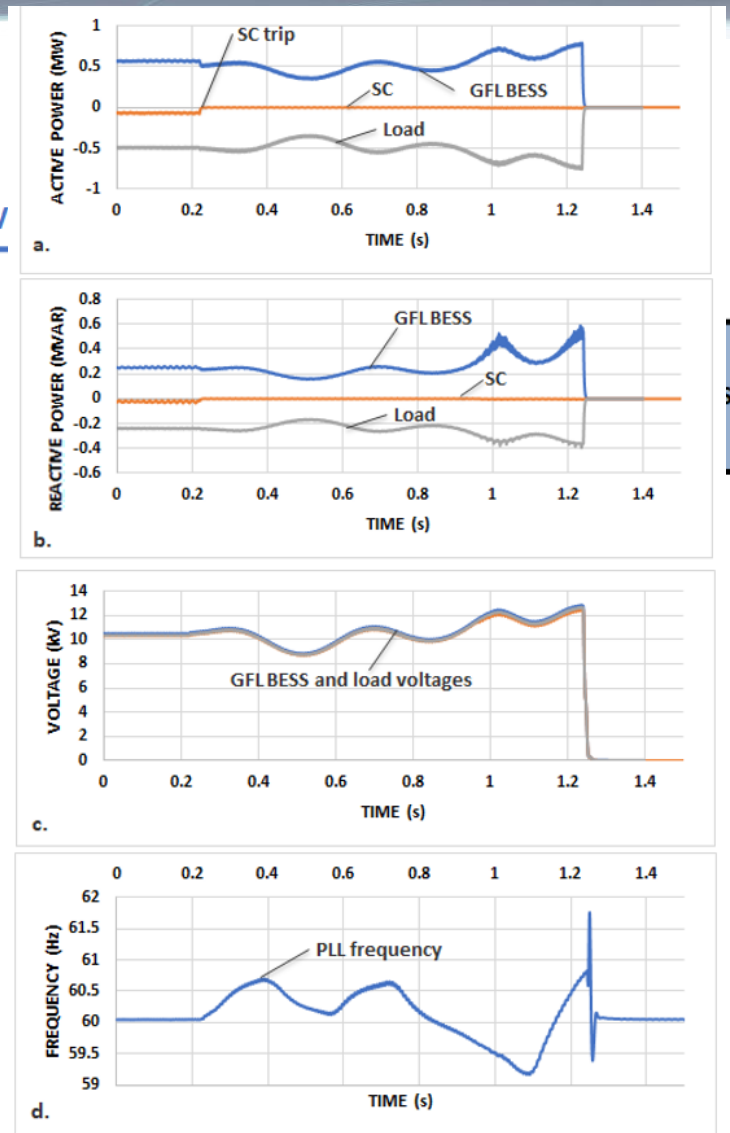
Black and start and operation









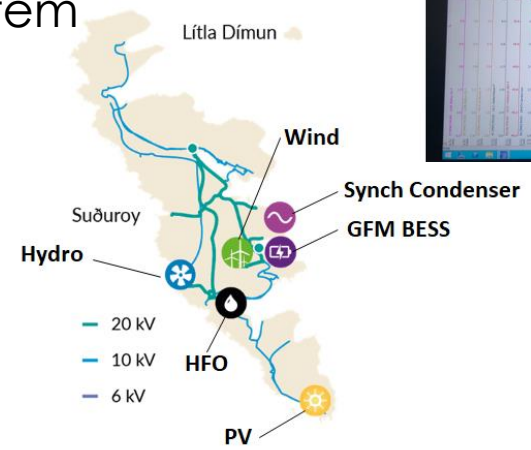


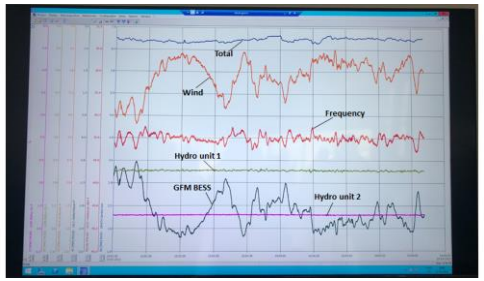
Synch condenser trip

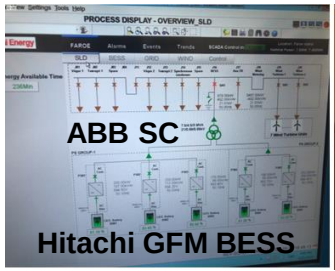
Impact/Commercialization

- Supplemental to other DOE-funded
  - SETO / WETO / WPTO / HFTO funded projects on hybrid systems including storage
- Facilitates the shift towards development of new research platforms under NREL's Advanced Research on Integrated Energy Systems (ARIES)
- Innovative use of prior and new multi-million DOE investments (CGI#1 and CGI#2, BESS, PHIL)
- New platform for industry and academia to conduct at scale research synchronous condenser-based systems
- Supplemental to all DOE island power system studies (Puerto-Rico, Hawaii, USVI, etc.)

Industrial implementation:
Faeroe Islands, Denmark
ABB, Hitachi system







6 MW/7.5 MWh grid-forming BESS combined with 8 MVA synch condenser

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Potential Future Work

Opportunities for future research:

- SuperFACTS allocation optimization problem
- Levelized cost of energy
- Impacts on power system production cost
- Impacts on reliability and resiliency metrics

THANK YOU

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Acronyms

SC – synchronous condenser

BESS – battery energy storage system

GFM – grid forming

GFL – grid following

SCR – short circuit ratio

CGI – controllable grid interface