DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

PRINCIPAL INVESTIGATORS
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WEBSITE
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PROJECT SUMMARY

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

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.

The Numbers

DOE PROGRAM OFFICE:
OE – Transformer Resilience and Advanced Components (TRAC)

FUNDING OPPORTUNITY:
AOP

LOCATION:
Golden, CO

PROJECT TERM:
10/01/2020 to 0/20/2022

PROJECT STATUS:
Incomplete

AWARD AMOUNT (DOE CONTRIBUTION):
$800,000

AWARDEE CONTRIBUTION (COST SHARE):
$000,000

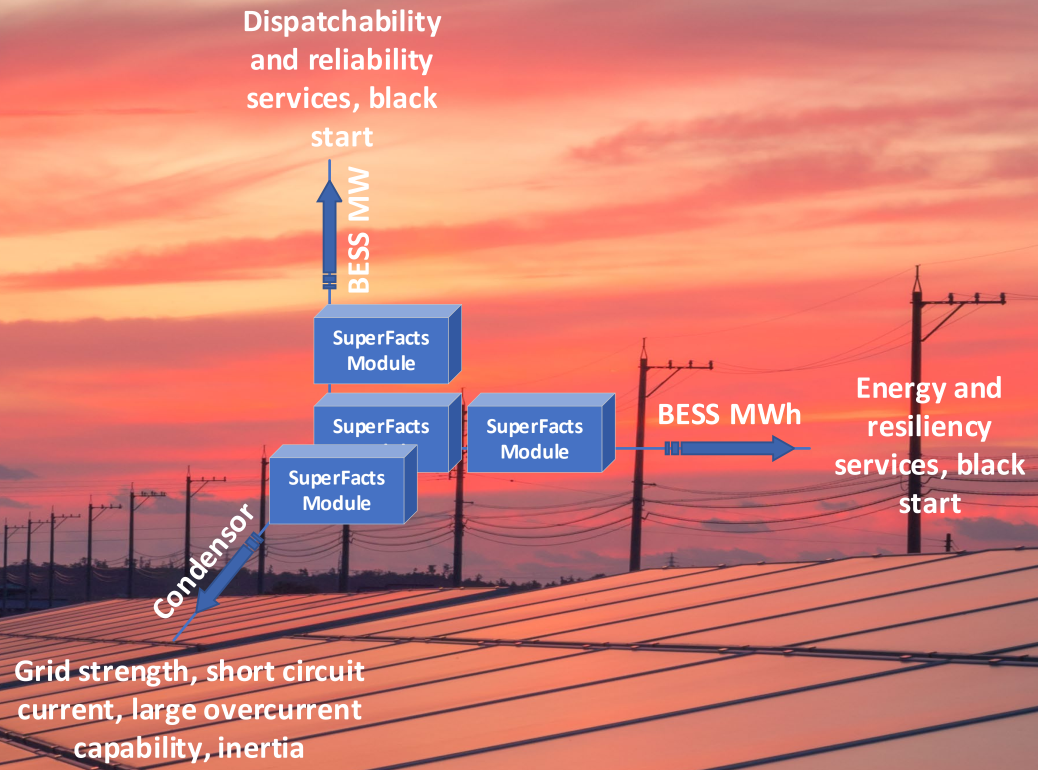
PARTNERS:
None

Innovations

- The proposed hybrid system consisting of synchronous condenser with grid-forming battery energy storage is innovative and has not been implemented anywhere.
- The proposed fully scalable solution combining SC and GFM BESS using integrated standardized control solution will allow provision of all possible reliability services to the power grid at transmission and sub-transmission levels including black start of sections of transmission systems, grid strength firming and large overcurrent capability - services that cannot be achieved by use of E-STATCOMS or other power electronics-based FACTS devices.

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)



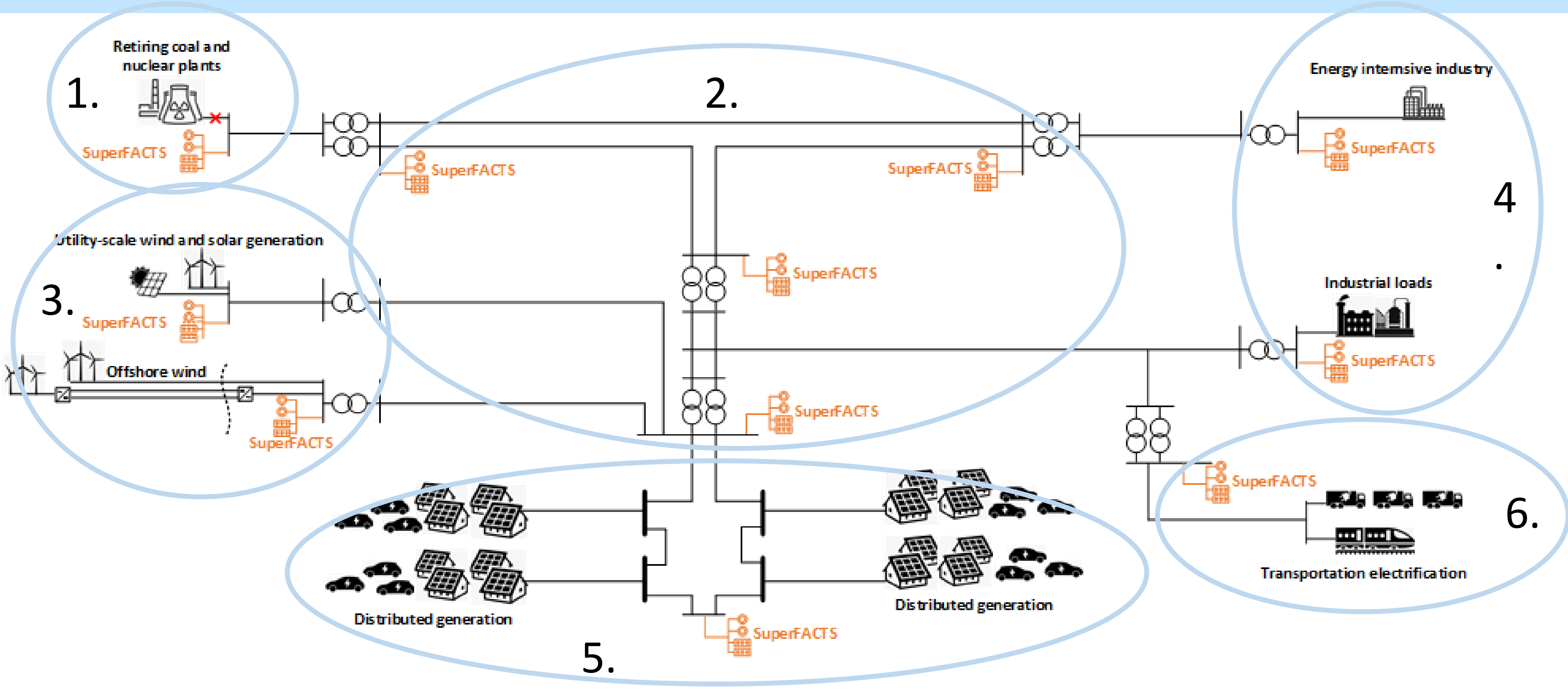
SuperFACTS scalability:

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

SuperFACTS use cases

Anticipated 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



Summary of major use cases:

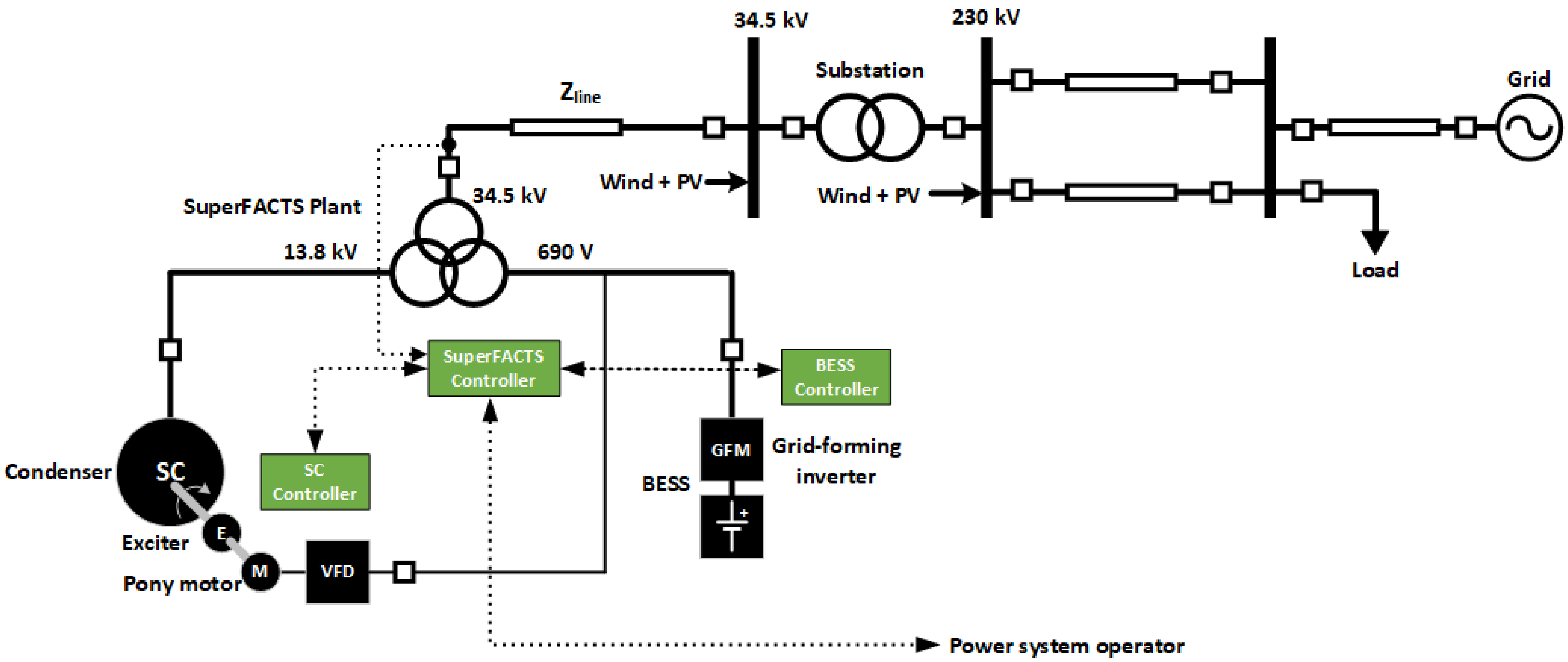
1. Replacing retiring conventional plants (taking advantage of existing infrastructure) for active and reactive power control services, maintaining grid strength and protection adequacy
2. Transmission services (power flow control, voltage support, black start etc.)
3. Integrating variable generation (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

Technical Approach

- 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.



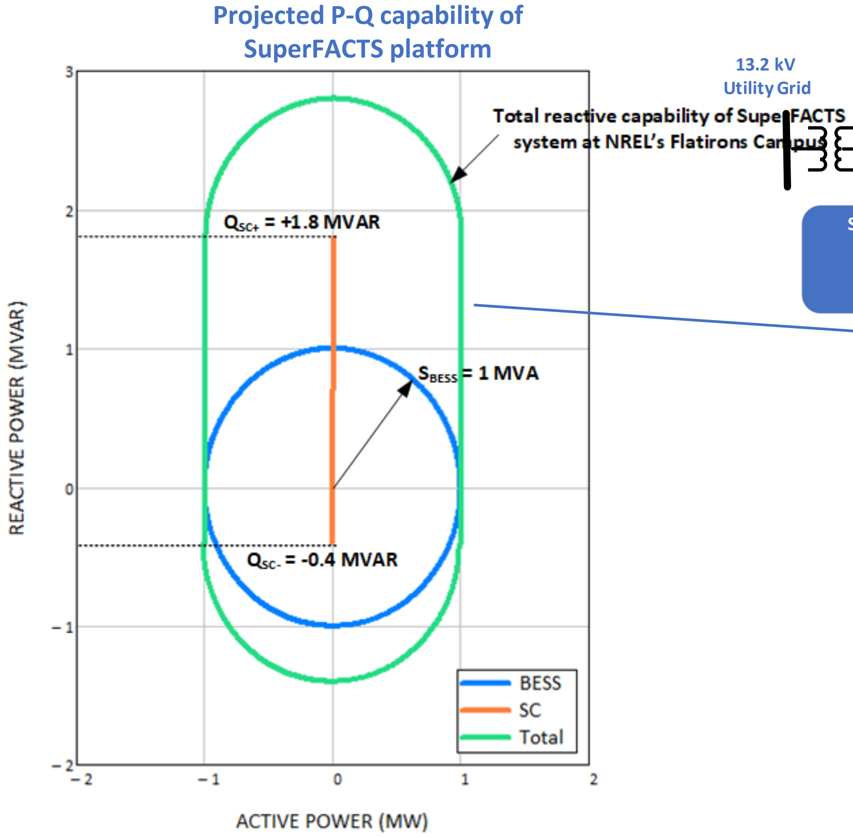
- The project tasks are intended to develop robust and validated controller capable of providing all control functions for SuperFACTS system.
- The project goals are achieved through demonstration testing of real SuperFACTS system at NREL's Flatirons Campus.
- This project is conducted in coordination with ORNL team that is conducting research in the area of Solid-State Power Substations.

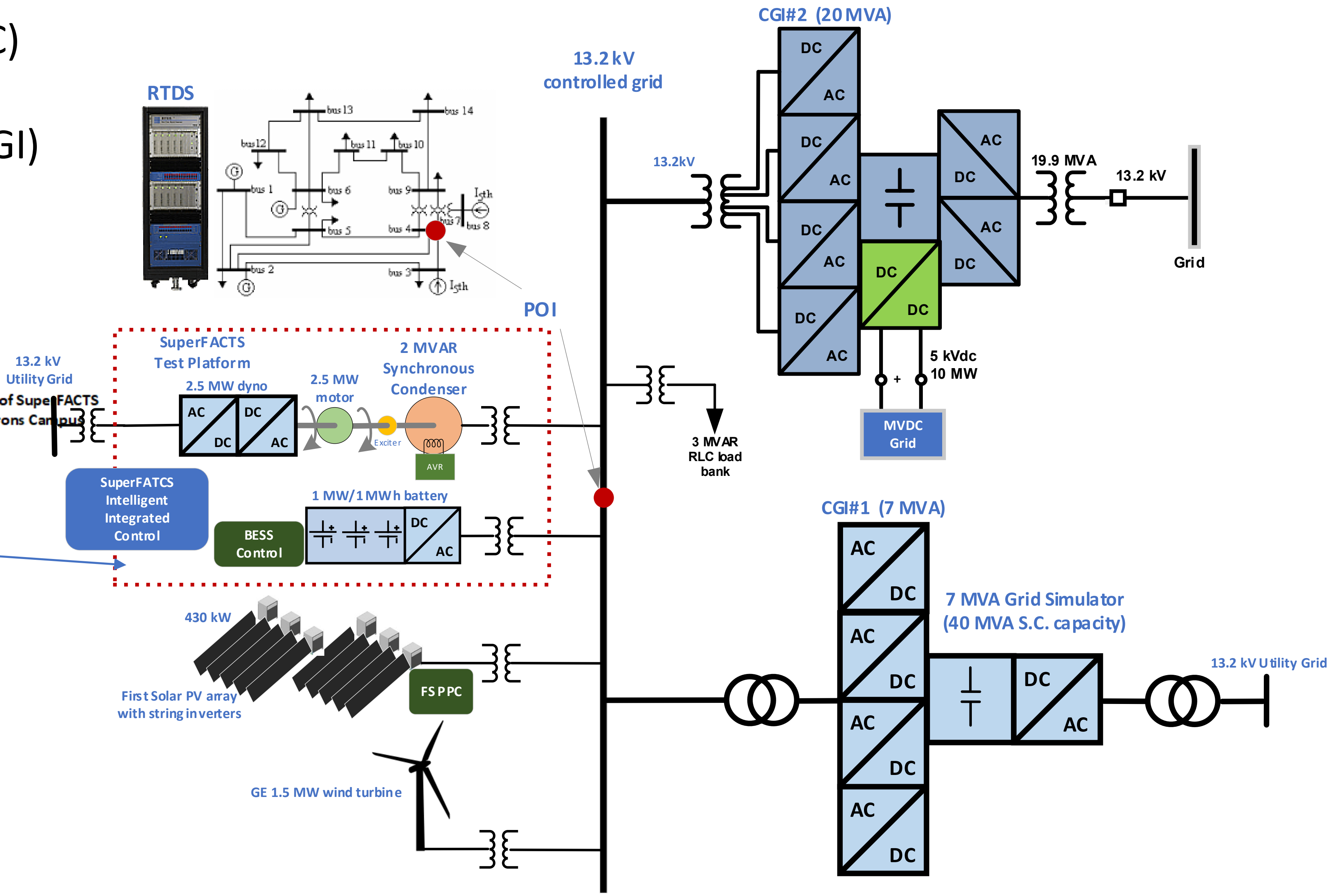
SuperFACTS Test Platform

Test platform was developed using:

- 2.2 MVA synchronous generator (operated as SC)
- 1 MW / 1 MWh GFM BESS
- PHIL-enabled 7 MVA / 13.2 kV grid simulator (CGI)
- Utility scale wind turbine generator and V plant

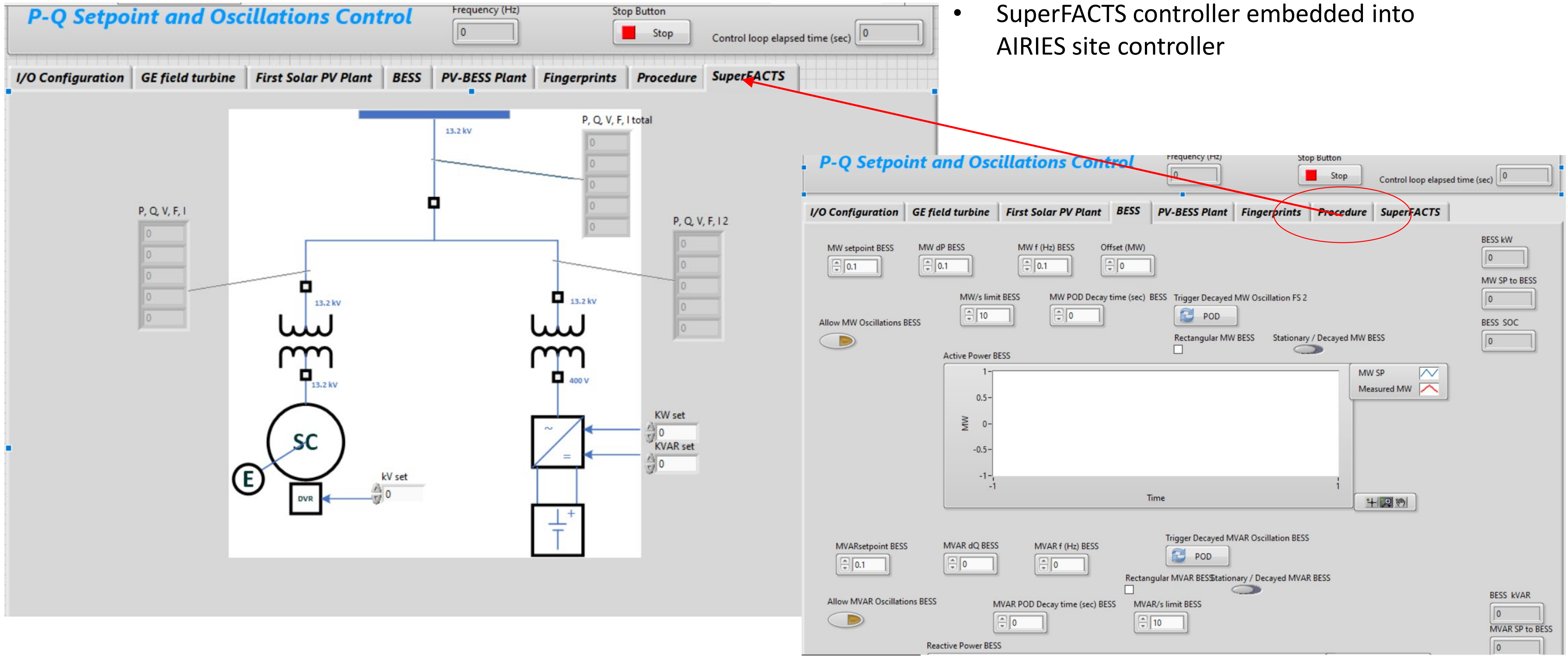
2.2 MVA synchronous machine installed on NREL 2.5 MW dynamometer





Source: NREL

Super FACTS Control Implementation

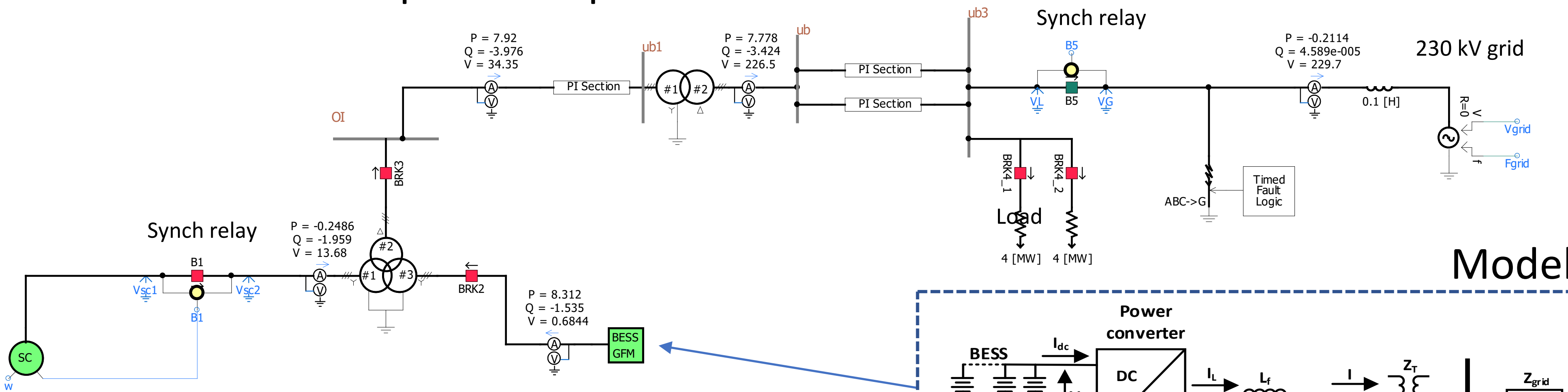


- SuperFACTS controller embedded into AIRIES site controller

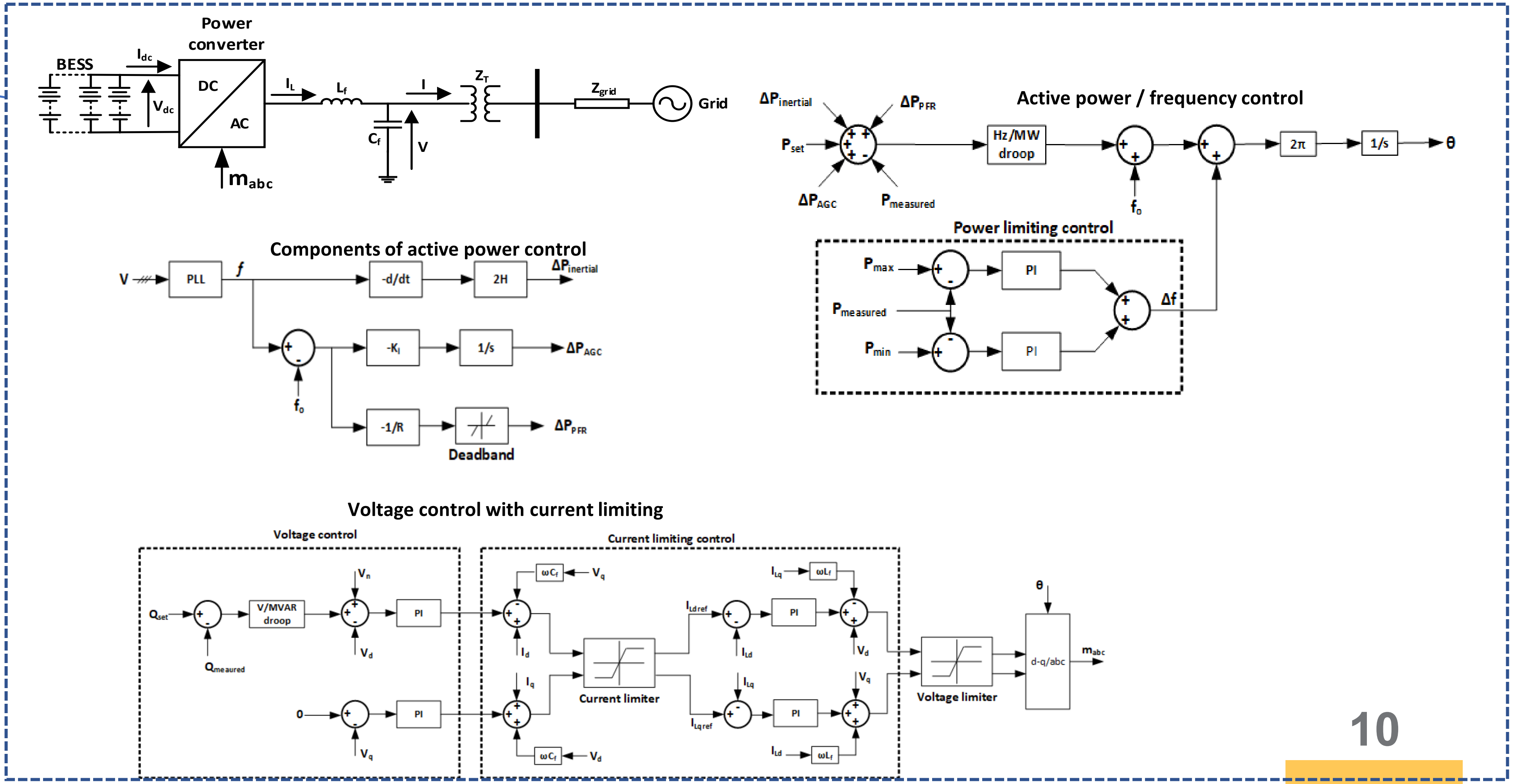
- Central SuperFACTS controller implemented in NI PXI RT hardware
- Can operate on operator setpoints, or setpoints coming from any interface or historic time series
- Modbus interface between PXI and BESS controllers
- Ethercat to analog interface between PXI and DVR

Modeling and Simulations

PSCAD model of SuperFACTS plant



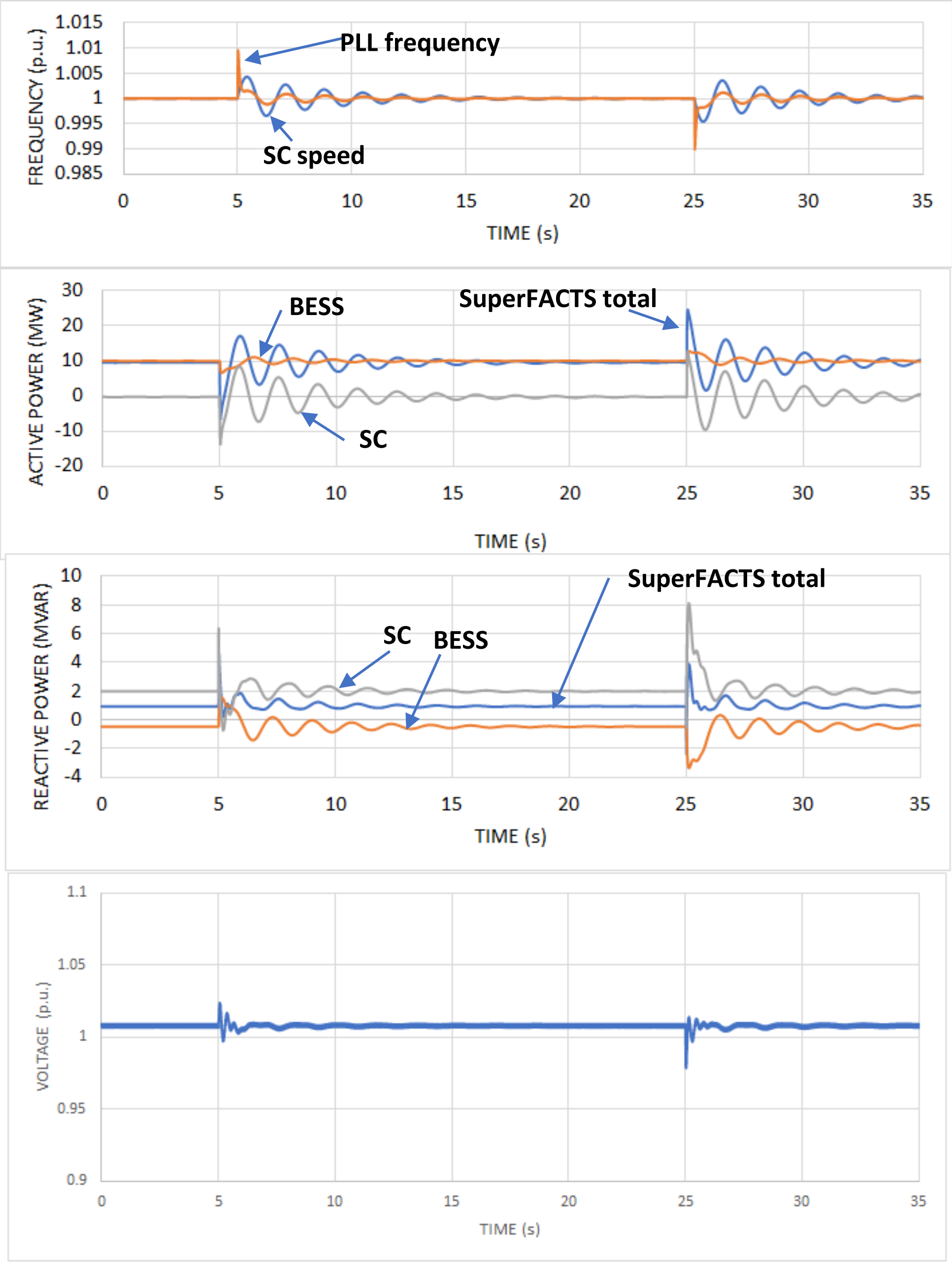
Model of GFM BESS with Current Limiting



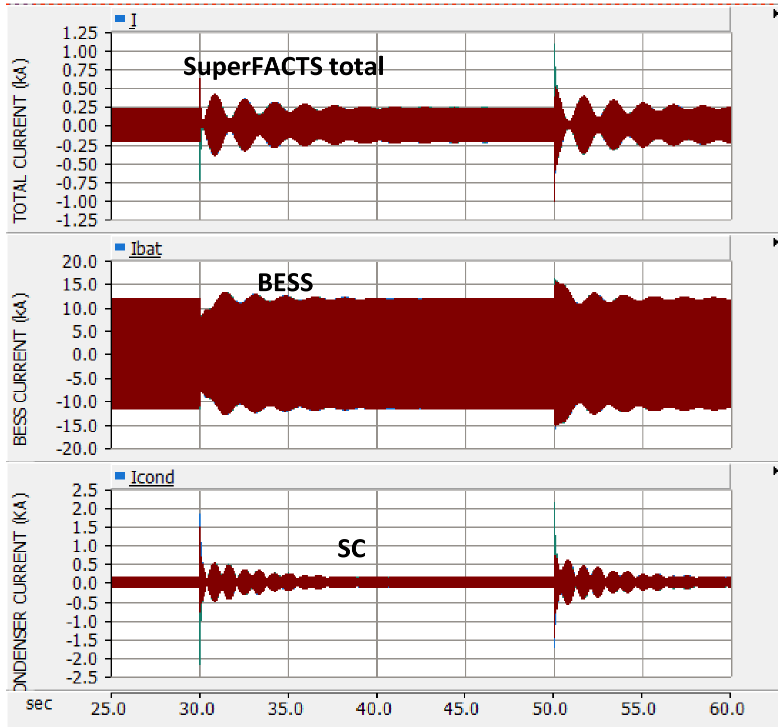
- Stable operation of SuperFACTS plant under different load, grid frequency and voltage conditions have been demonstrated
- Additional controls implemented in GFM BESS to compensate the inertial response of SC if needed for oscillations free power output
- Black-start services were simulated with different scenarios

Simulated Cases – grid frequency and phase angle variations

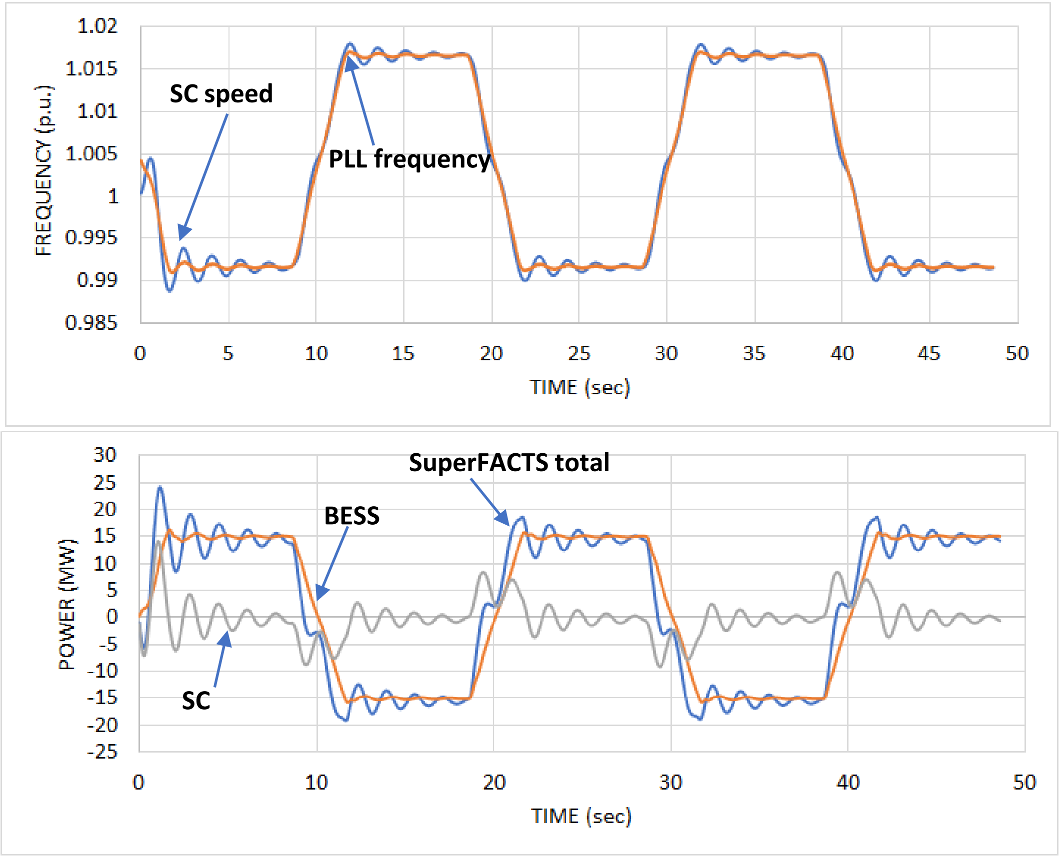
Response to grid voltage phase jumps (30^{O})



Inst. current during phase jump (30^{O})

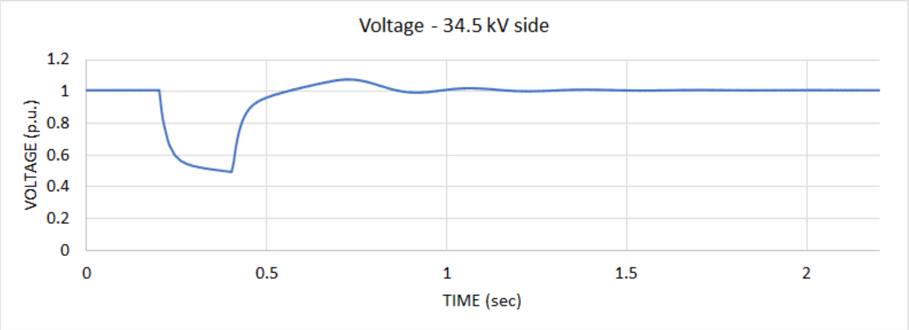


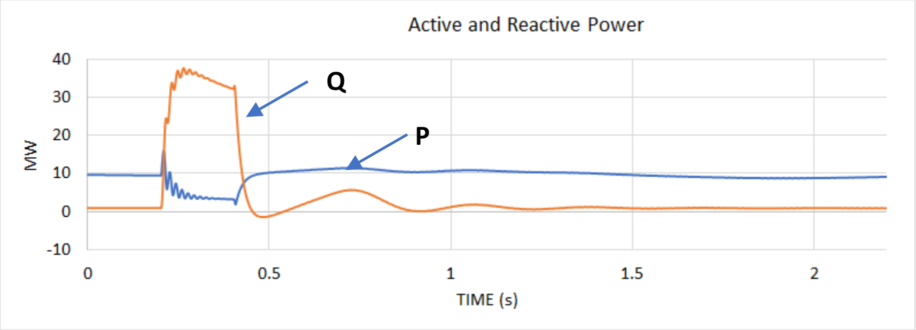
Response to grid frequency variations

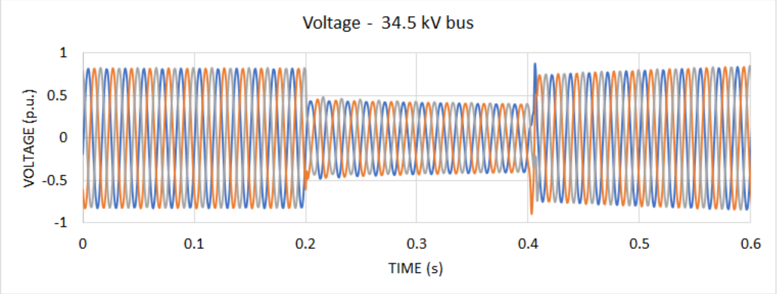


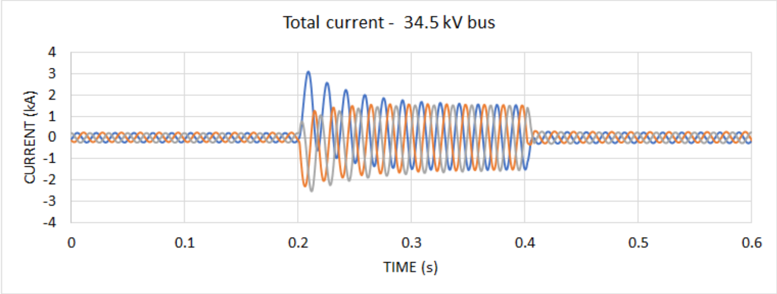
Simulated cases – voltage fault ride-through

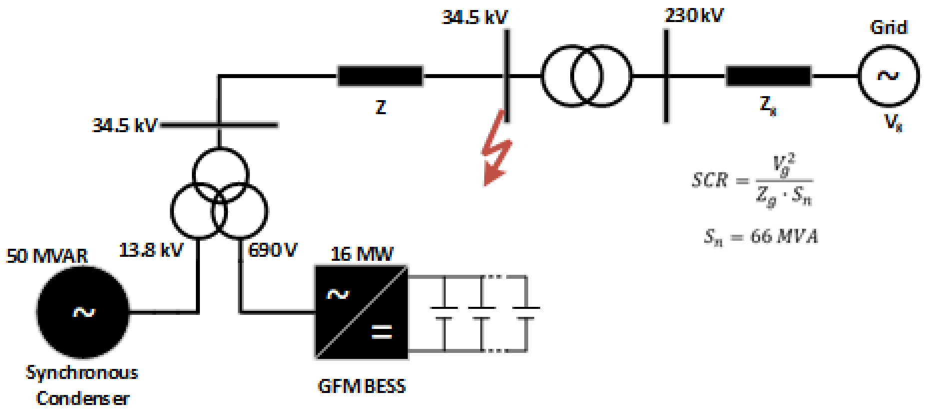
- All fault current is provided by SC
- GFM BESS operates in current limiting mode during faults





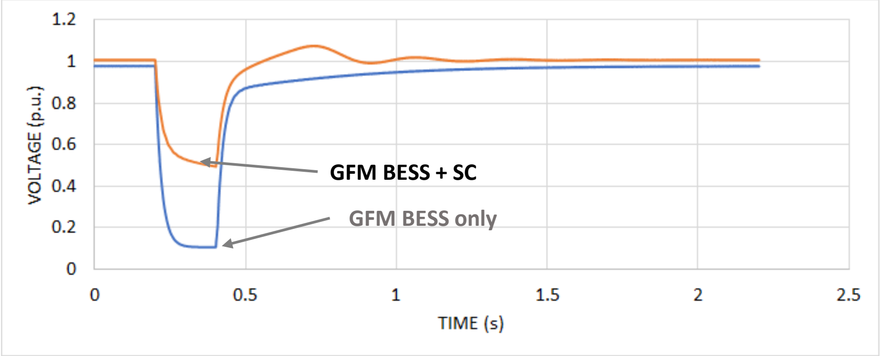


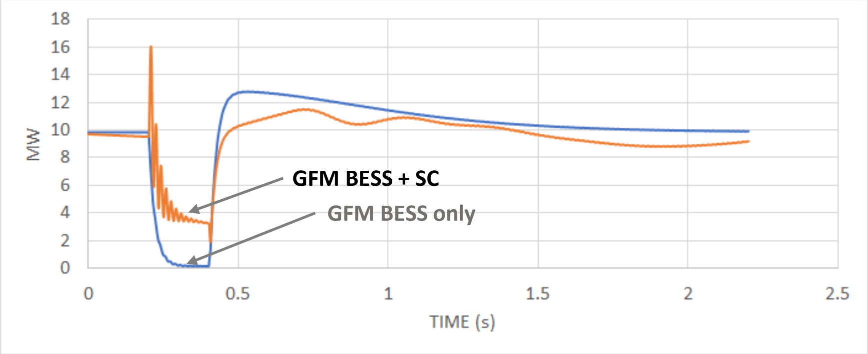


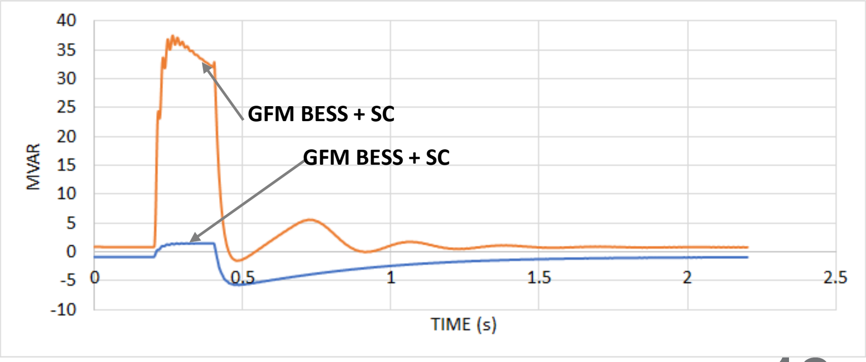


Weak grid case: SCR=1.5

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

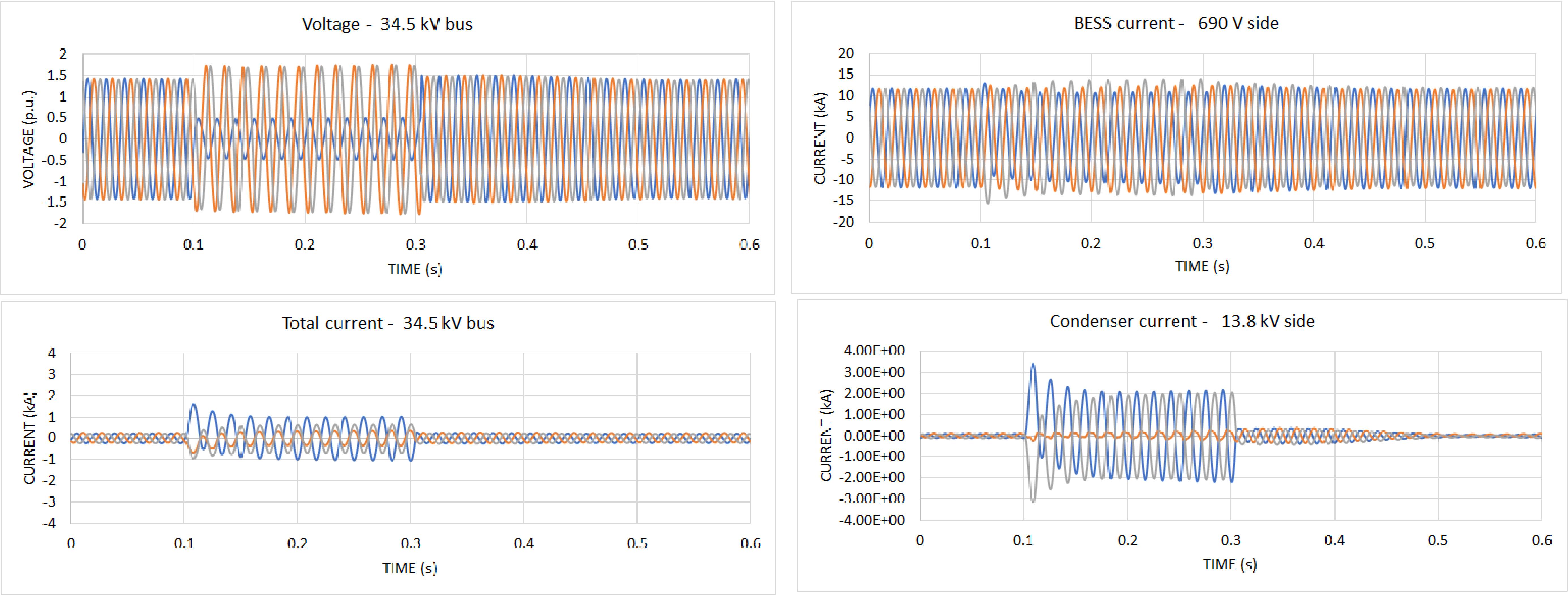






Simulated cases – unbalanced voltage fault

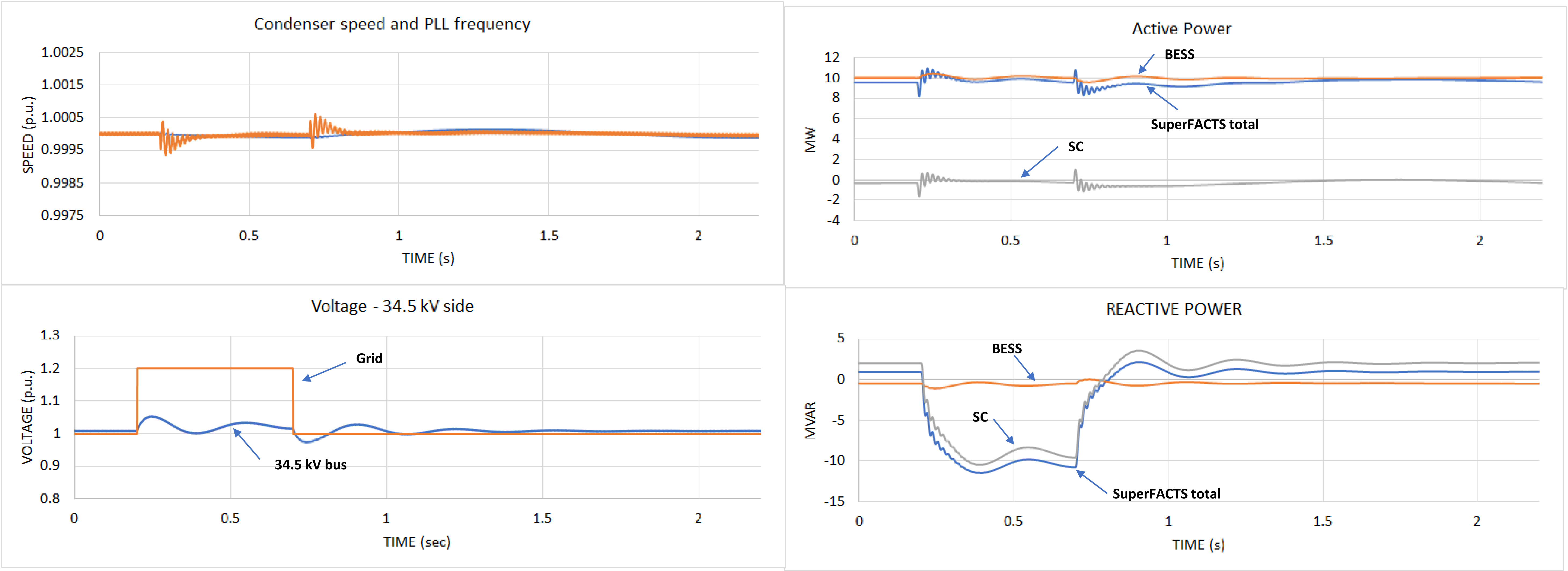
Weak grid case: SCR=2



- Robust ride-through under unbalanced fault conditions
- All fault current is provided by SC during fault

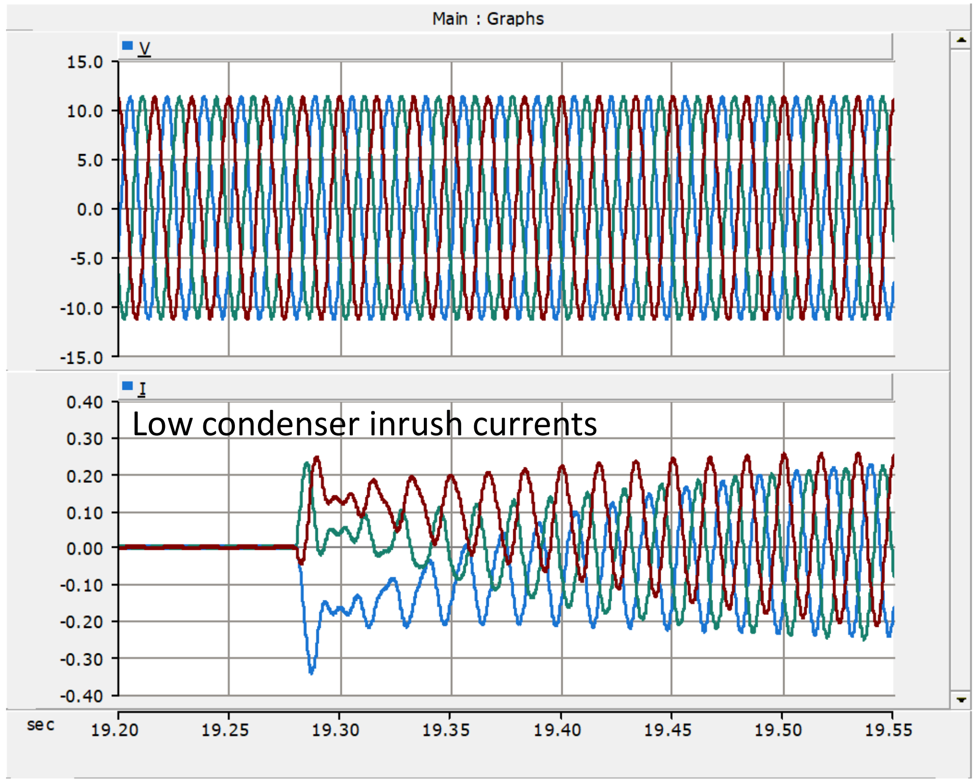
Simulated cases – high voltage fault ride-through

Weak grid case: SCR=2



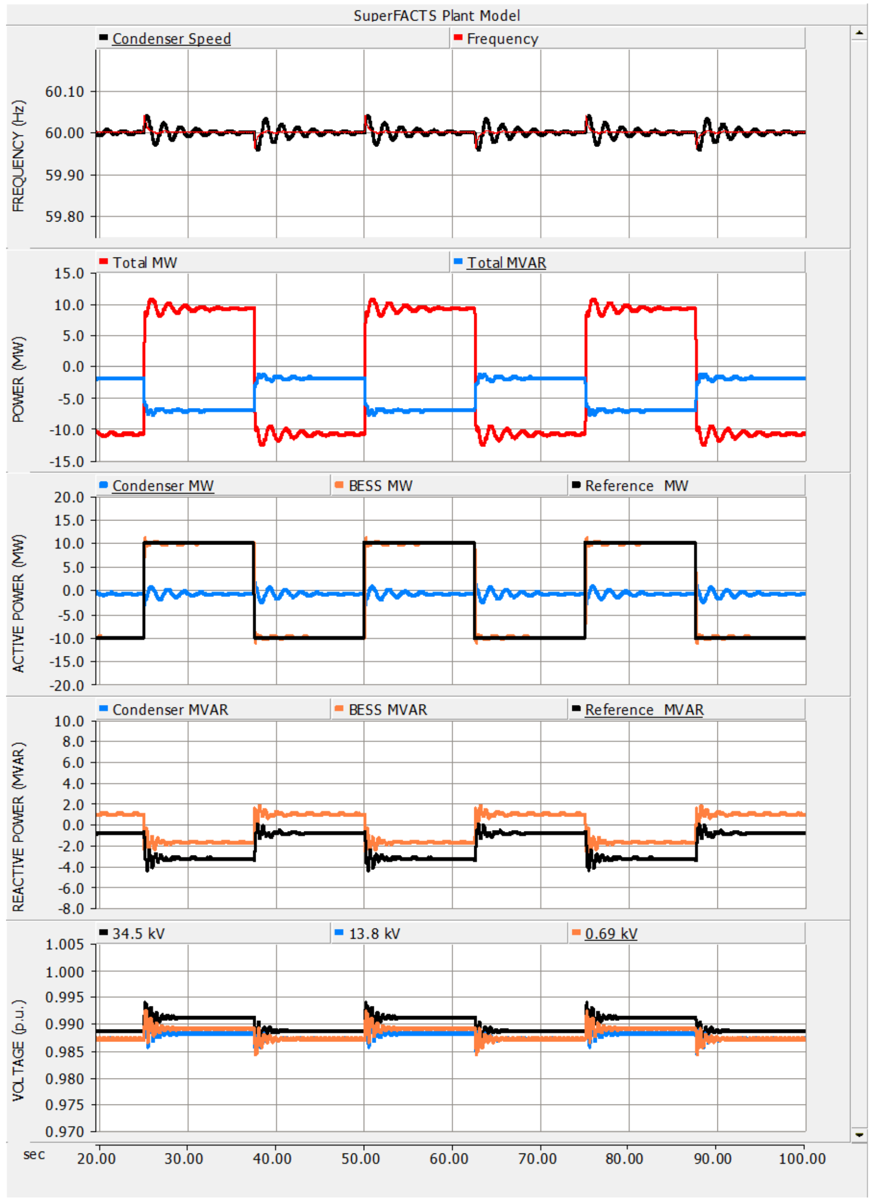
Simulated cases – BESS soft start and SC synchronization

- Synchronization relay between BESS and SC is implemented

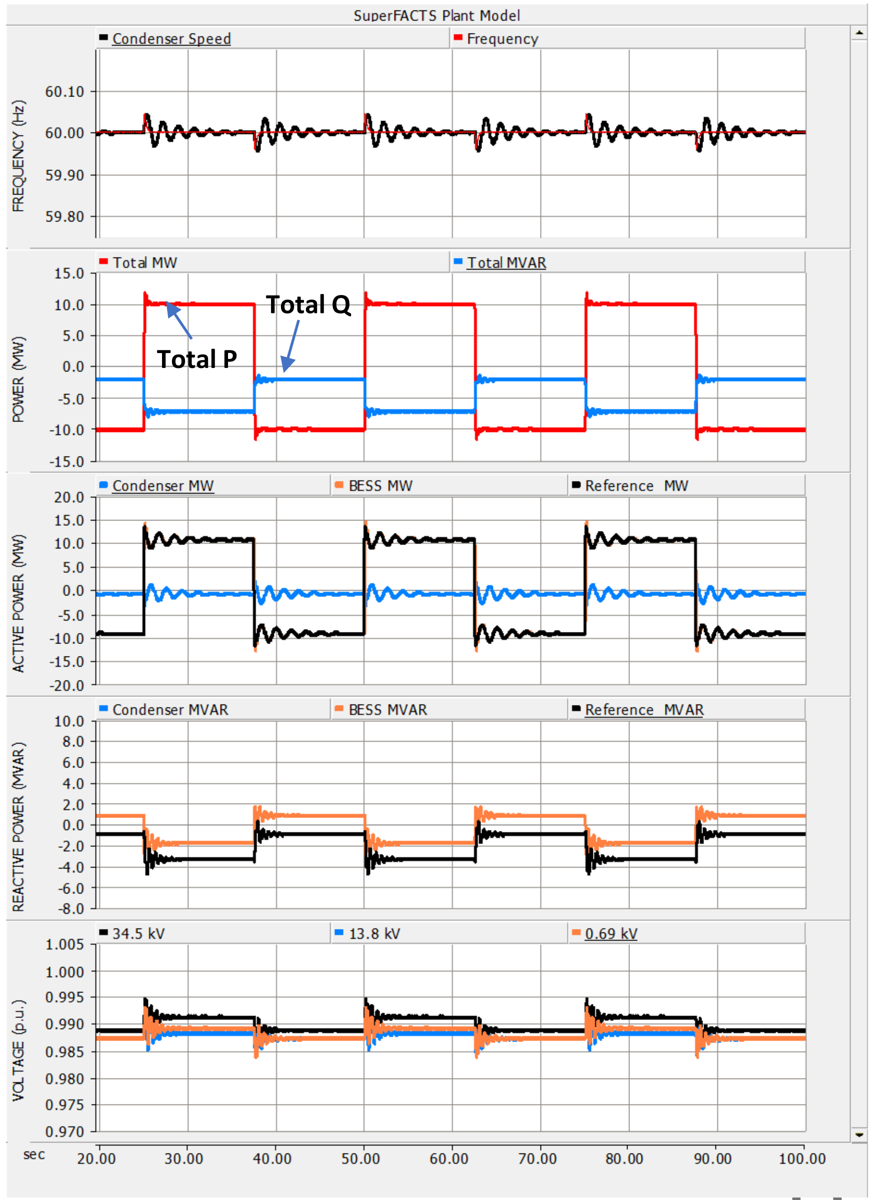


Two control strategies implemented

BESS does not compensate for SC inertia

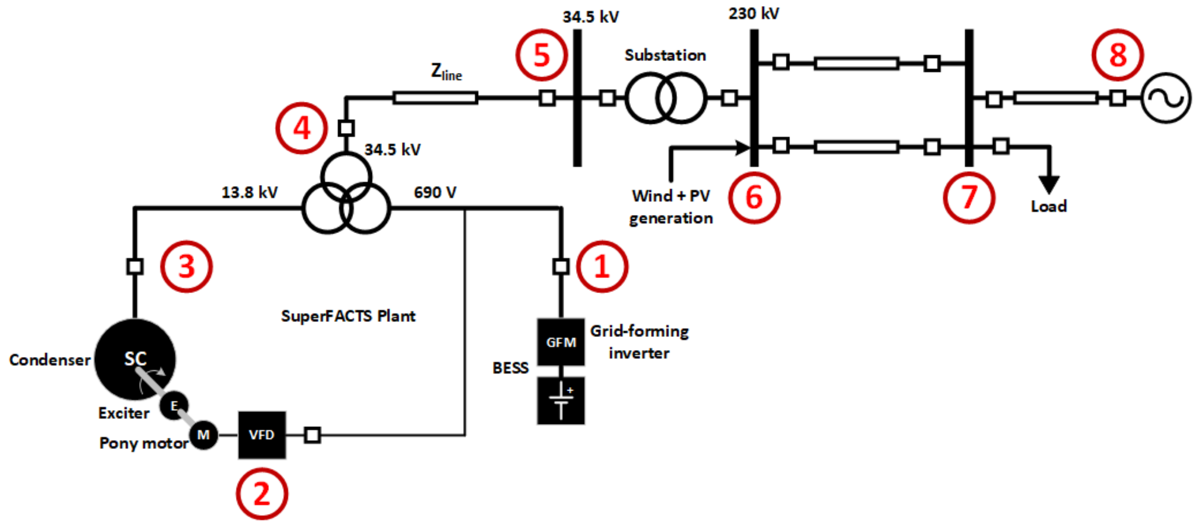


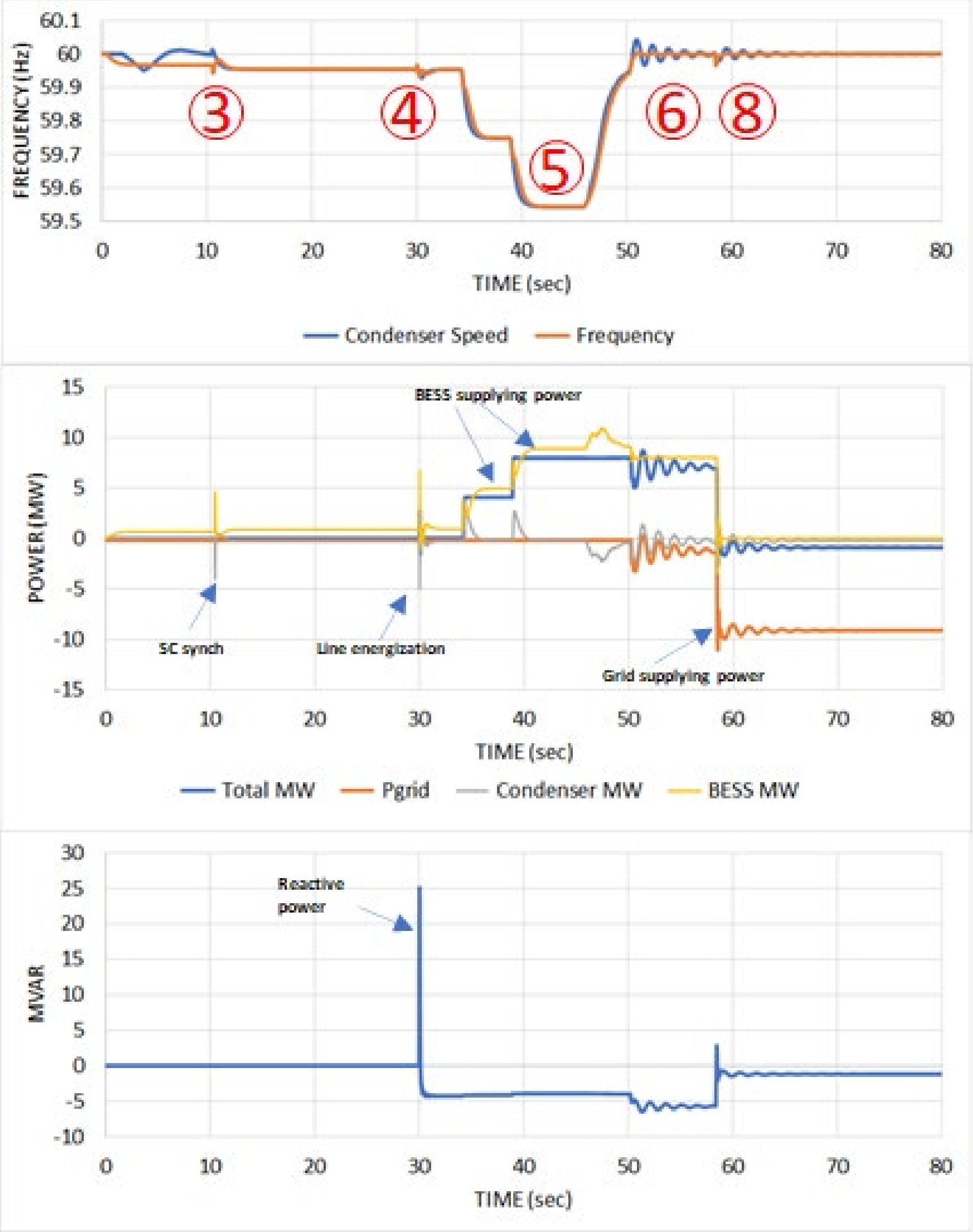
BESS compensates for SC inertial response



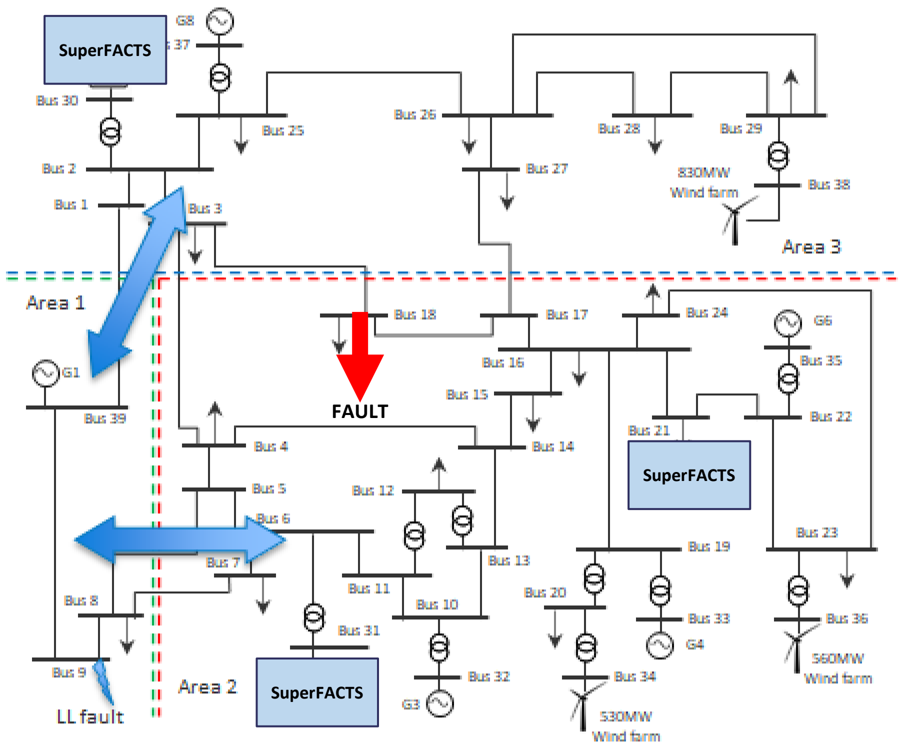
Simulation of black start

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

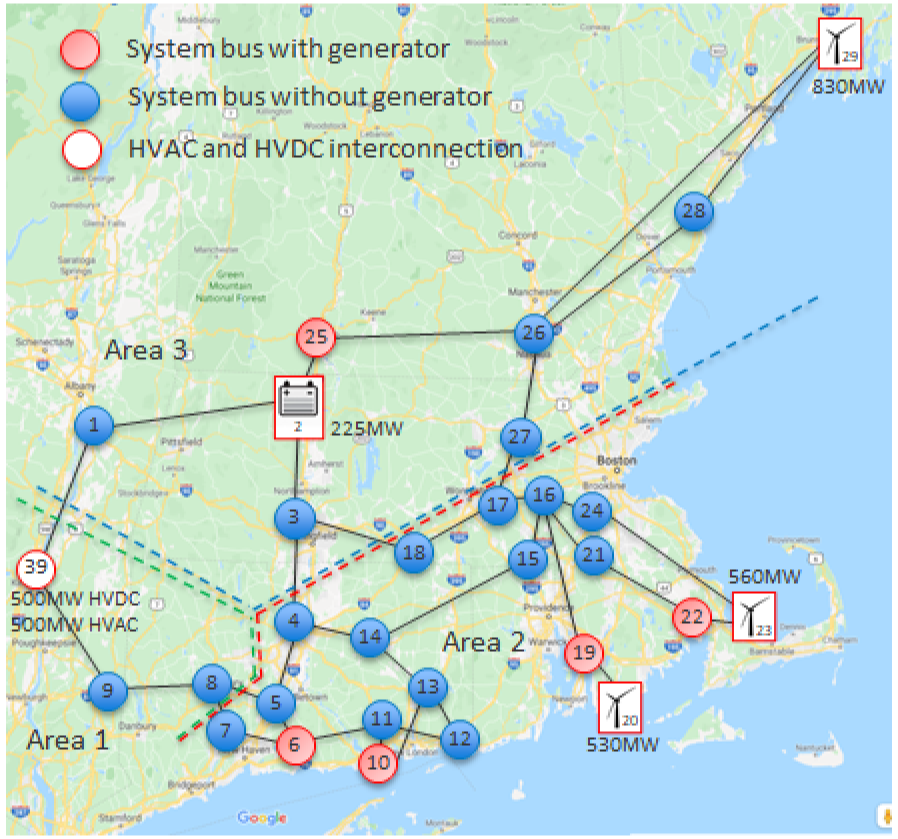




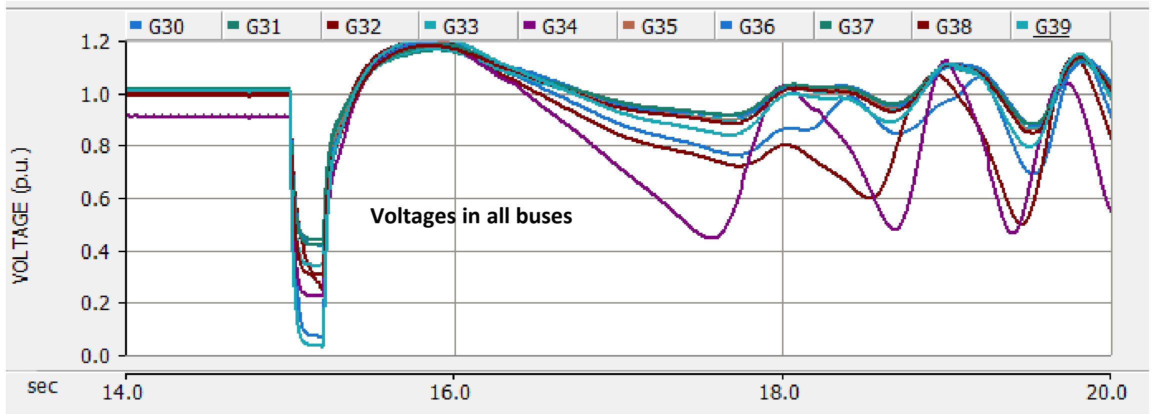
Simulation cases – SuperFACTS in 39-bus test system



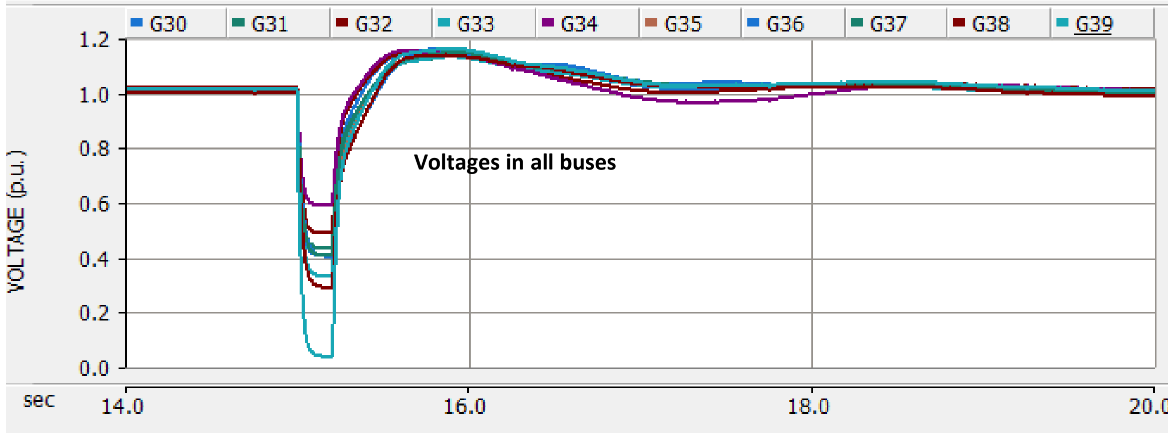
- Oscillation modes can be found between area 1 and area 3 and between area 2 and area 3.

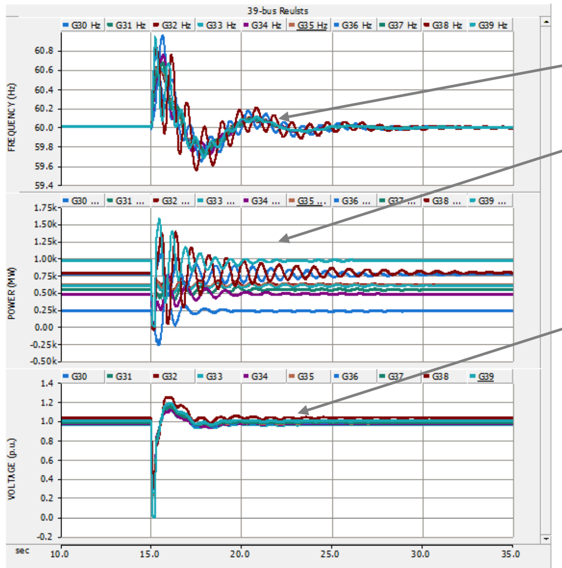


- 40% IBRs
- Grid strength is compromised
- Voltage fault takes the system out of synchronism



- 40% IBRs supplemented with SuperFACTS
- Grid strength is restored
- Robust fault ride-through





Generator speeds

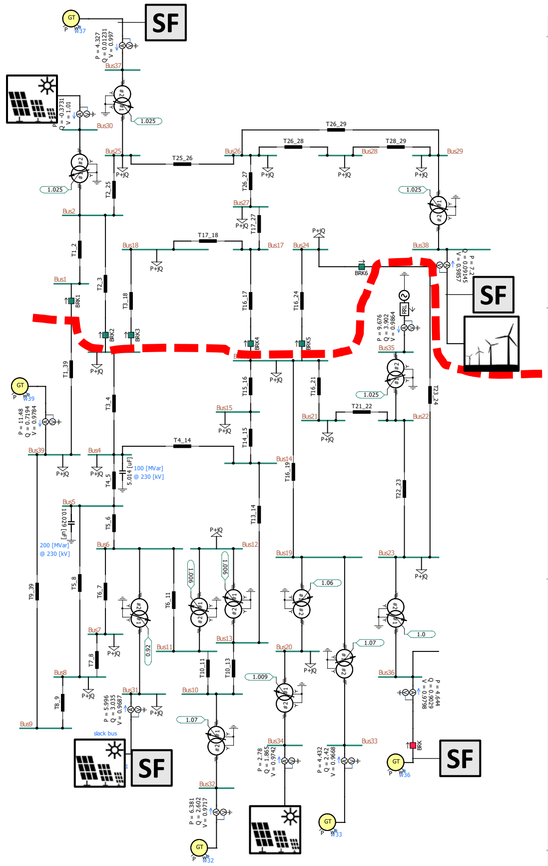
Generator power outputs

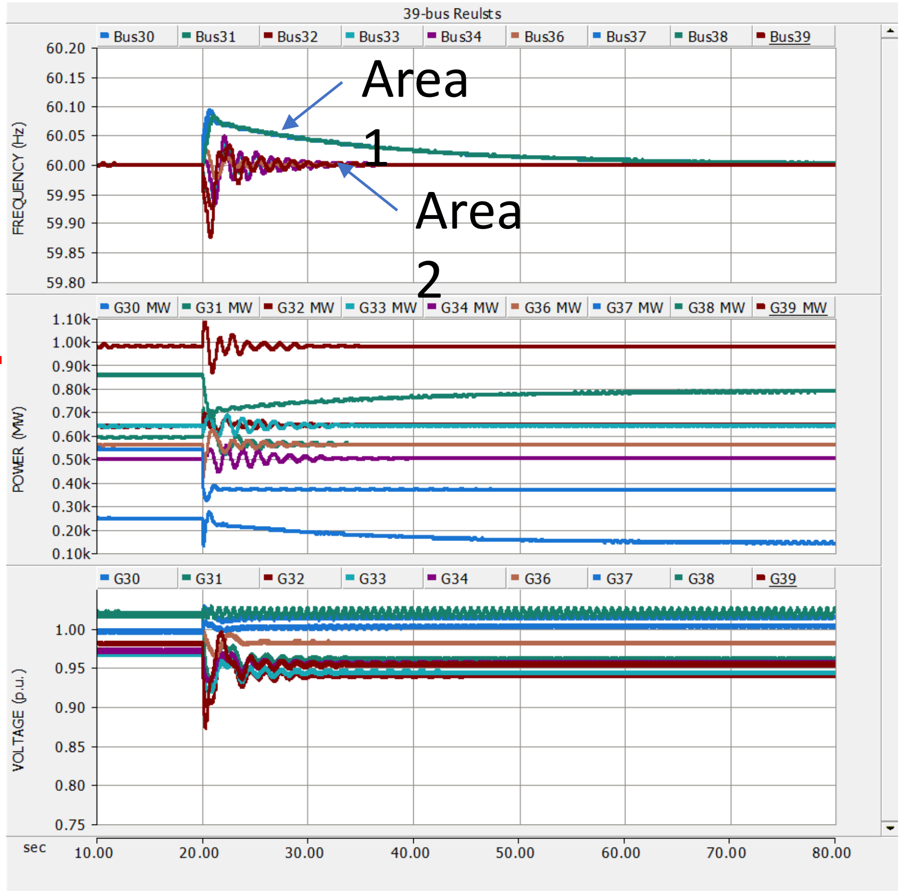
Voltages in all buses

- 100% synchronous case
- Response to voltage fault

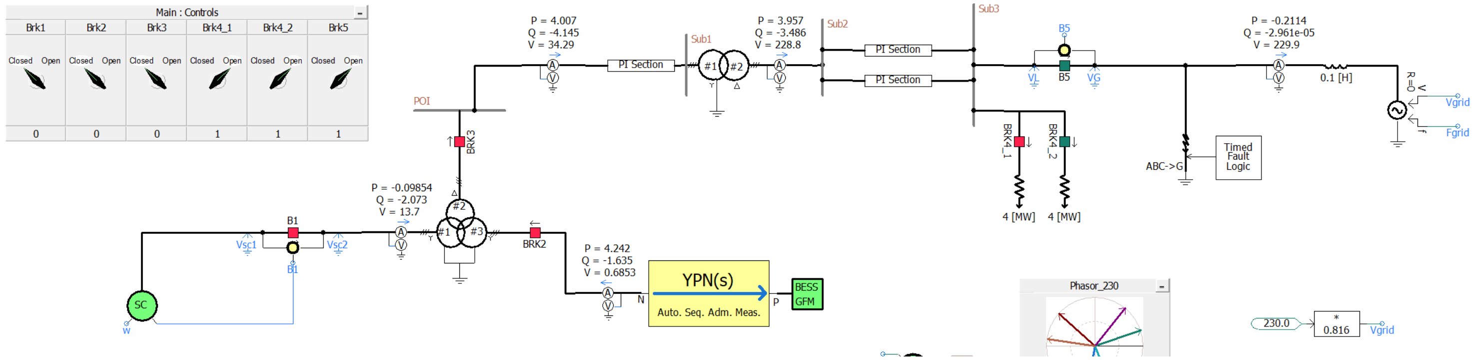
Other completed tasks

- System separation case
- SuperFACTS system provide seamless transition to islands in case of contingencies or cyber-attacks



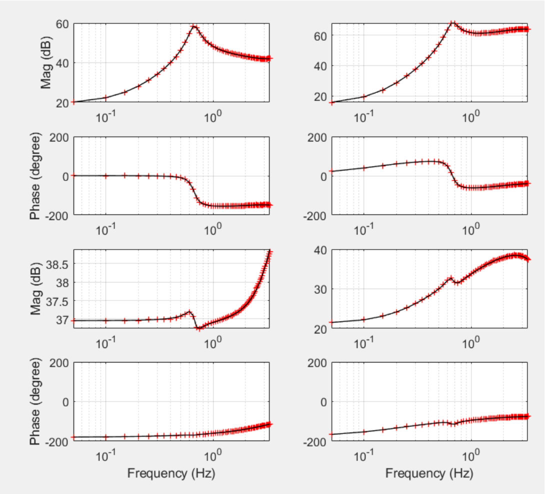


NREL-developed Impedance Scan Toolbox

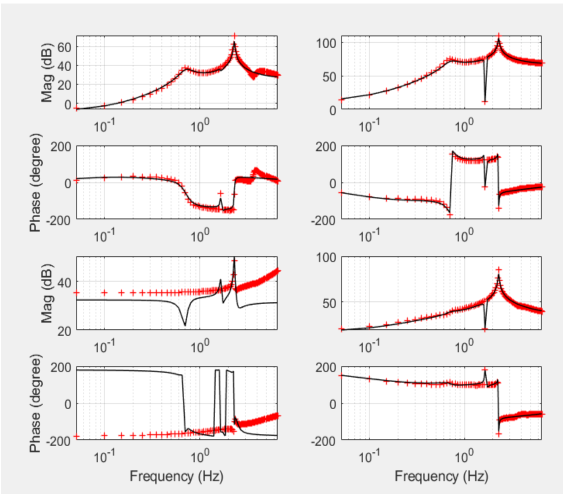


- **Impedance scans are performed for different droop settings to understand interactions between BESS and sync. condenser**
- **Will be extended to 39-bus system for evaluating stability in presence of multiple SuperFACTS devices**

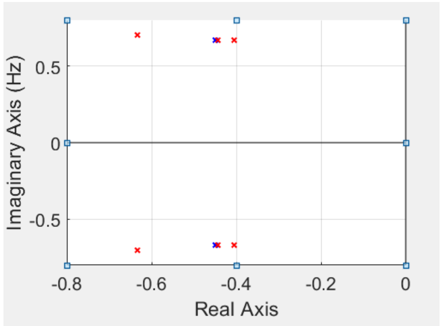
BESS DQ Admittance (50 mHz/MW)



BESS DQ Admittance (5 mHz/MW)



System Dominant Poles



Impact/Commercialization and Risks/Mitigation Strategy

- The project is still in proof-of-concept testing and validation stage

IP STATUS

No IP related activities yet

Main Risks

- Slower than usual lab activities due to COVID-10 situation
- Delayed delivery schedules for hardware

Mitigation

- Experiments conducted using PHIL model of synch condensers until full system is operational

Project Milestones

3.1: Task 1: Identify all use cases for SuperFACTS concept, develop a test plan — **100%**
Start date: 10/1/2020 — End date: 12/31/2020

3.2: Task 2: Develop control theory for SuperFACTS concept — **100%**
Start date: 1/1/2021 — End date: 3/31/2021

3.3: Task 3: Develop SuperFACTS Controller
Start date: 4/1/2021 — End date: 6/30/2021 — **100%**

Task 4: Deploy controller and conduct initial testing — **100% in PHIL mode, Synch condenser delivery – September 2021, installed in Oct-Nov 2021**
Start date: 7/1/2021 — End date: 9/30/2021

Task 5: Demonstrate ability to provide reliability services on transmission level
Start date: 10/1/2021 — End date: 12/31/2021 — **100%** — **Paper presented at 11th Solar Integration Workshop in Berlin, Germany**
Presentation at ESIG fall workshop

Task 6: Demonstrate ability to provide blacks start services
Start date: 1/1/2022 — End date: 3/31/2022

Task 7: Demonstrate benefits of SuperFACTS operation in a large power system
Start date: 4/1/2022 — End date: 6/30/2022

Task 8: Demonstrate benefits of SuperFACTS in islanded grids
Start date: 7/1/2022 — End date: 9/30/2022

Entity	Funding Planned by Fiscal Year		Total
	Year 1 (FY21)	Year 2 (FY22)	
NREL	$400,000	$400,000	**$800,000**

Synergies

- Supplemental to other DOE-funded
  - SETO/WETO /WPTO 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.)

Future work

- Complete validation and demonstration testing for all use cases in Fiscal Year 2022 at NREL:
  - Testing under grid fault conditions
  - PHIL testing emulating larger power systems
  - Final report
  - Journal publication
  - Dissemination (ESIG and NERC workshops, conference presentations)

NREL test site. *Photo by NREL*

Opportunities for future research:

- SuperFACTS allocation optimization problem
- Levelized cost of energy and production cost analysis.

Acronyms

SC – synchronous condenser

BESS – battery energy storage system

GFM – grid forming

SCR – short circuit ratio

CGI – controllable grid interface

THANK YOU

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