Dynamic Stability Considerations for High VG Penetrations:

Grid Forming and Synchronous Condensers

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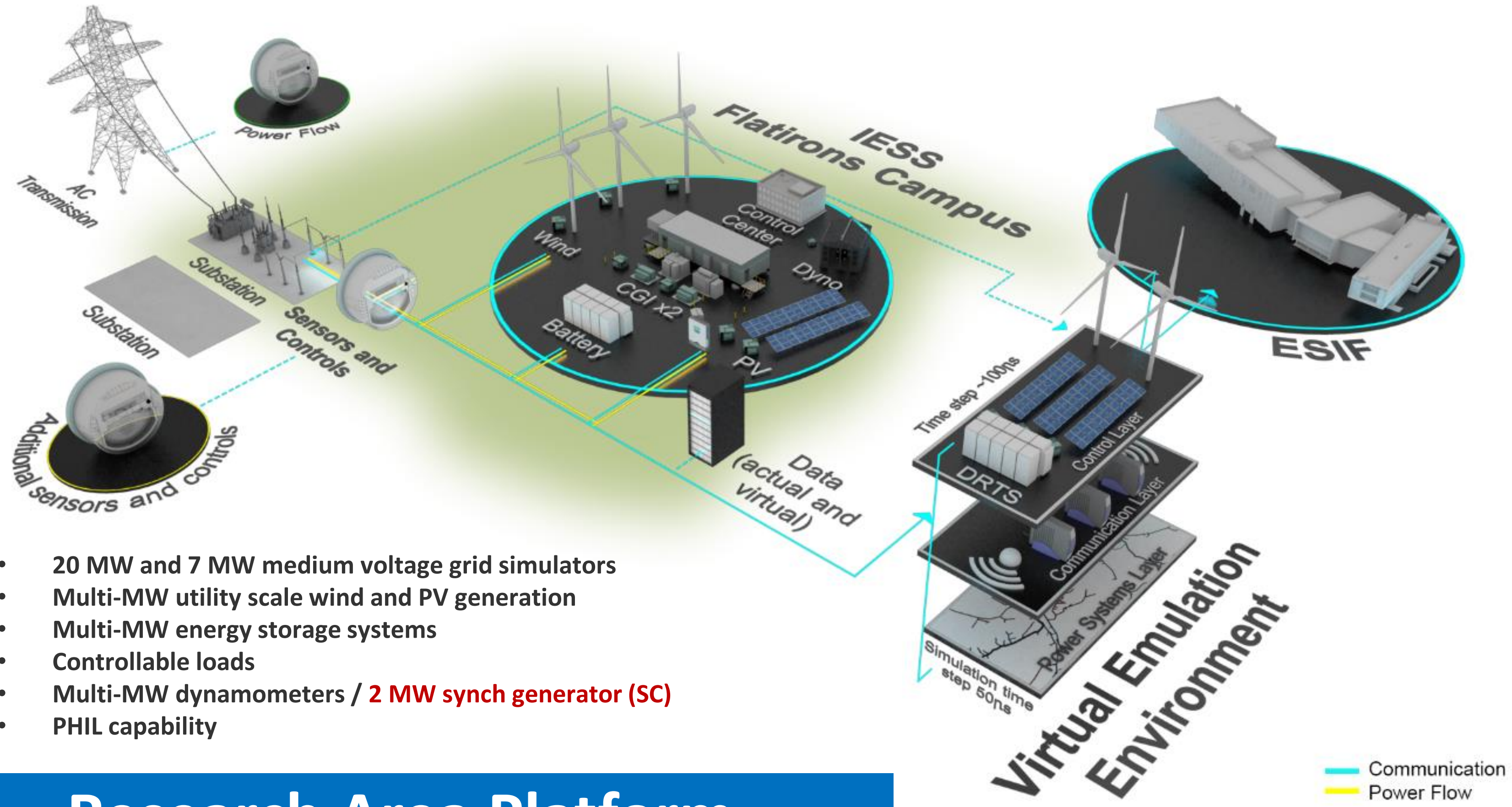
Main Engineering Challenges for High VRE Grids

- Lowering of system inertia, degrading frequency stability with increasing penetration
- Degrading voltage stability in weaker grids
- New protection methods at any level in the grid (lack of short-circuit current)
- Who and how will be providing grid forming? Why can't we operate all inverters as grid forming? Do we still need grid following? New black-start paradigm?
- New stability issues in inverter dominated grids – control interactions and resonances
- How we need to control new transmission technologies – FACTS, HVDC, multi-terminal HVDC? New roles for synchronous condensers?
- Role of frequency in future inverter–dominated grids and in 100% grids:
  - Option 1: everything is inverter coupled (even hydro and all loads), no synchronizing torque, frequency stability becomes totally irrelevant
  - Option 2: We still have some synch generation at 100% (hydro, CSP, etc.), so classic frequency stability still matters.
- Reliability and resiliency of decentralized and autonomous grids, MVDC/LVDC grids
- Issue of cyber security in inverter dominated grids



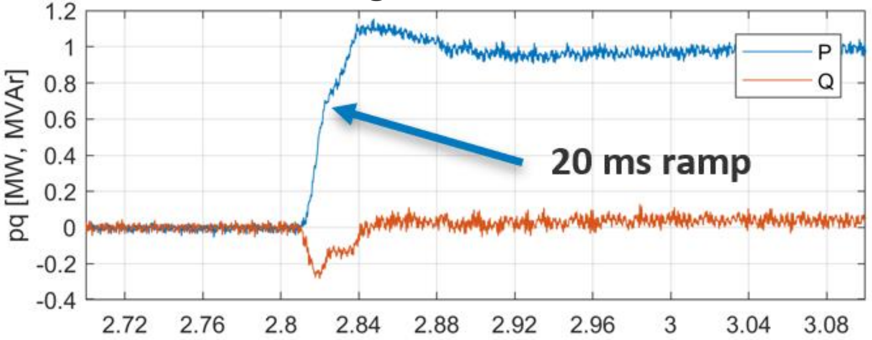
- 20 MW and 7 MW medium voltage grid simulators
- Multi-MW utility scale wind and PV generation
- Multi-MW energy storage systems
- Controllable loads
- Multi-MW dynamometers / 2 MW synch generator (SC)
- PHIL capability

Research Area Platform

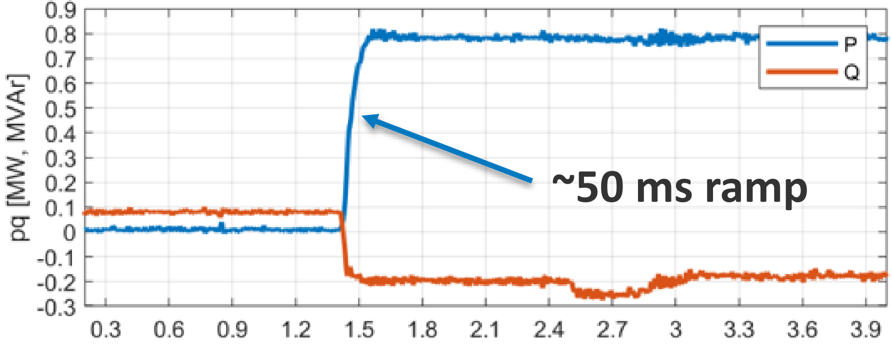
Image source: NREL

BESS Characterization

BESS Active and Reactive Power Response in Grid Following Mode



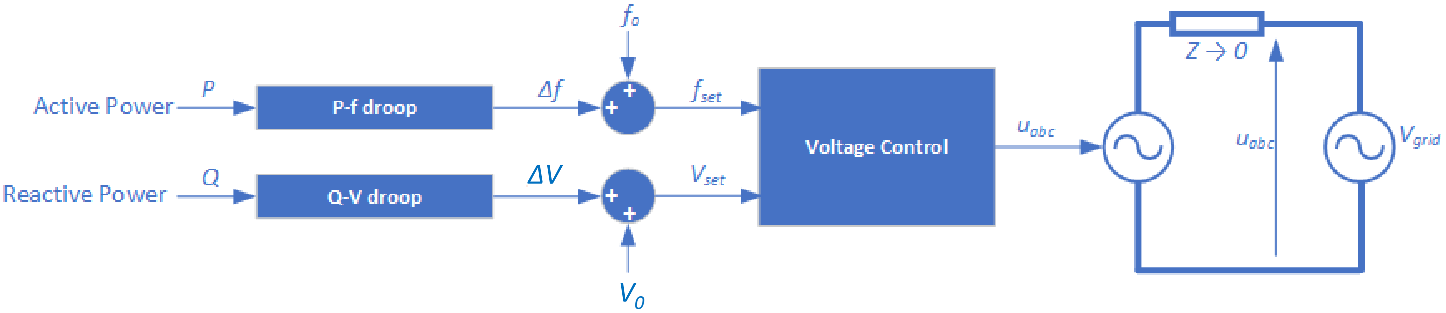
BESS Active and Reactive Power Response in Grid Forming Mode



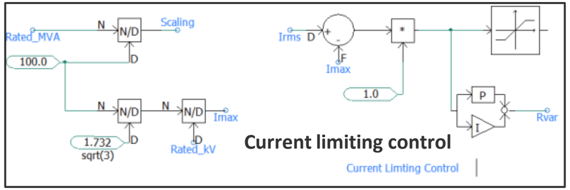
1MW / 1 MWh BESS at NREL test site

GFM BESS Model

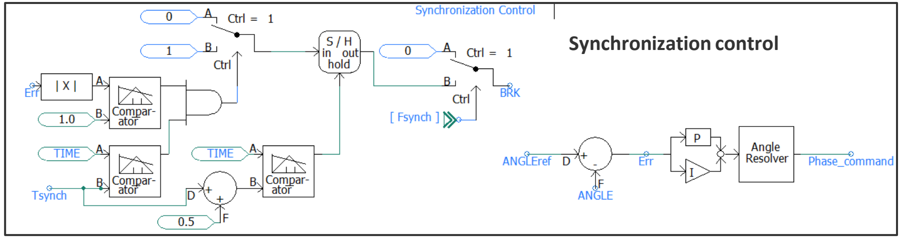
Grid Forming Control



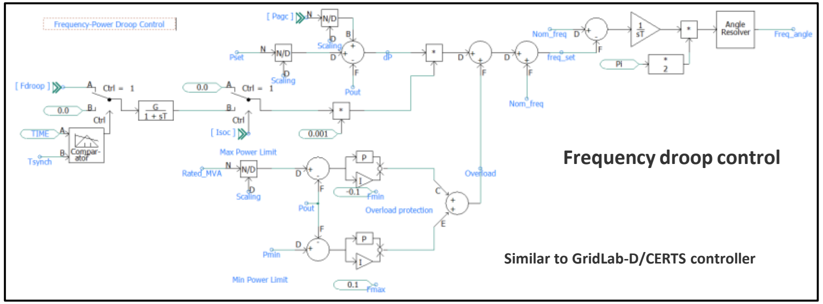
- **Autonomous load tracking**
- **No direct current control / overloading**



Current limiting control

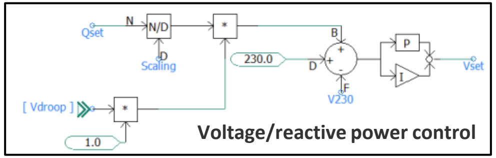


Synchronization control



Frequency droop control

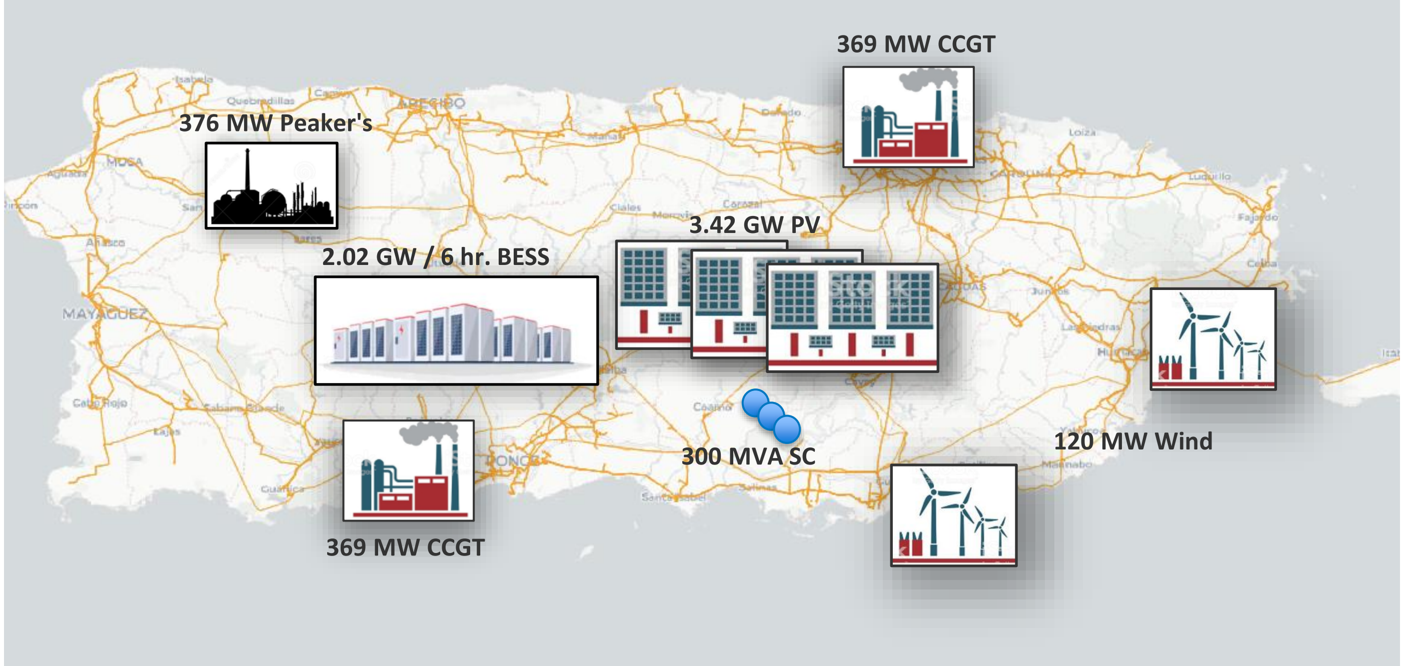
Similar to GridLab-D/CERTS controller



Voltage/reactive power control

PREPA IRP Study – High PV and BESS case

- High PV/ High storage scenario with 2.2 GW peak load – IRP PSS/E case translated to PSCAD
- All BESS modeled as Grid Forming, PV modeled as conventional Grid Following resource
- GFM BESS operates with f-P droop, voltage control and connected to AGC
- Dispatch case: 2.2 GW load, ~3GW of PV, BESS charging, only single CCGT is online, synch condensers on or off
- Some PV plants have 5% MW headroom for services



Synchronous Condensers and FACTS

Hybrid Synchronous Condensers

- Enhanced system inertia
- Increased SCR / system strength
- Dynamic voltage regulation
- Reactive power injection / absorption for improved transient performance
- PSS like oscillations damping support
- Improved power quality
- Black start capability / provision of reactive inrush currents

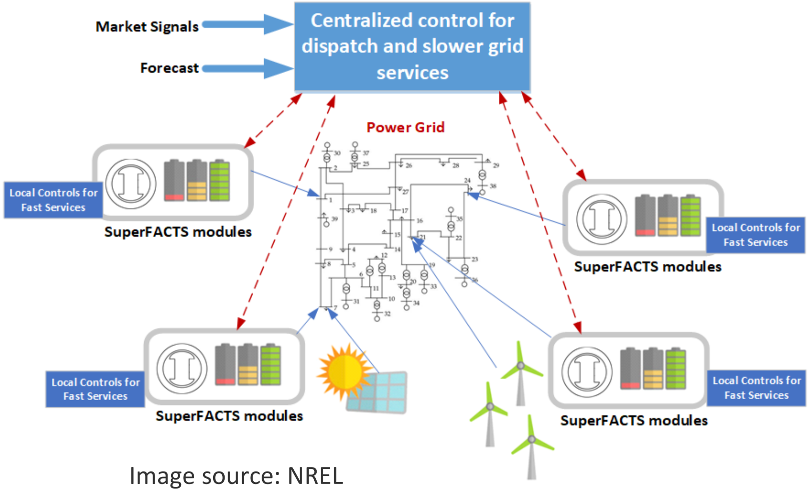


Image source: NREL

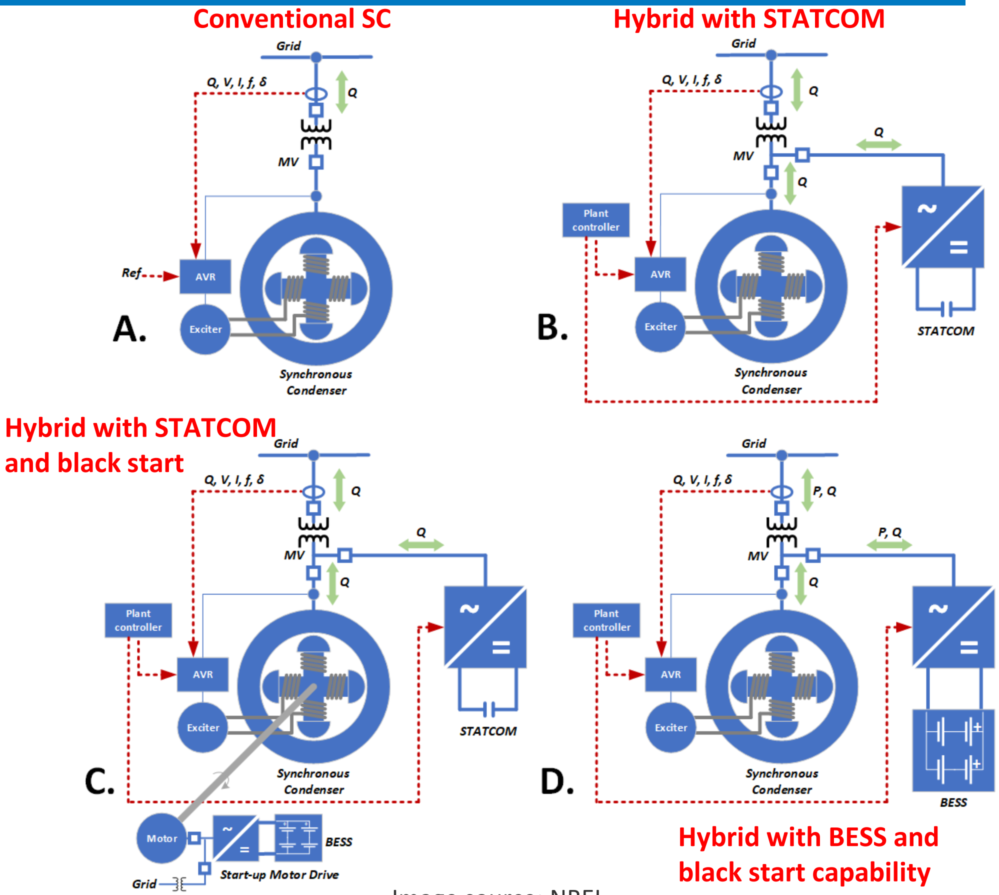


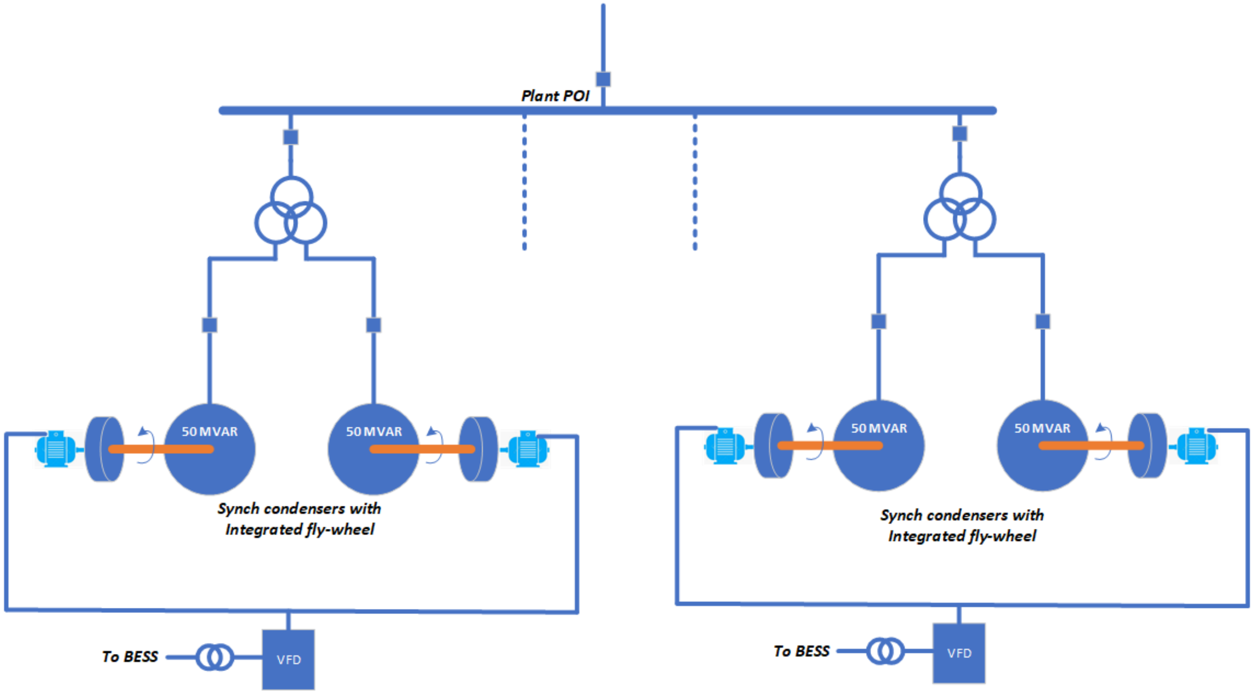
Image source: NREL

Modular Synch Condenser Model

- Modular synch condenser plant with integrated high inertia flywheels
- Similar to ABB's commercial solution
- Size, components and control parameters can be set to meet several criteria:
  - Inertia (MW·s)
  - Desired SCR levels
  - Voltage stability considerations

Image source: ABB

Single line diagram of PSCAD model



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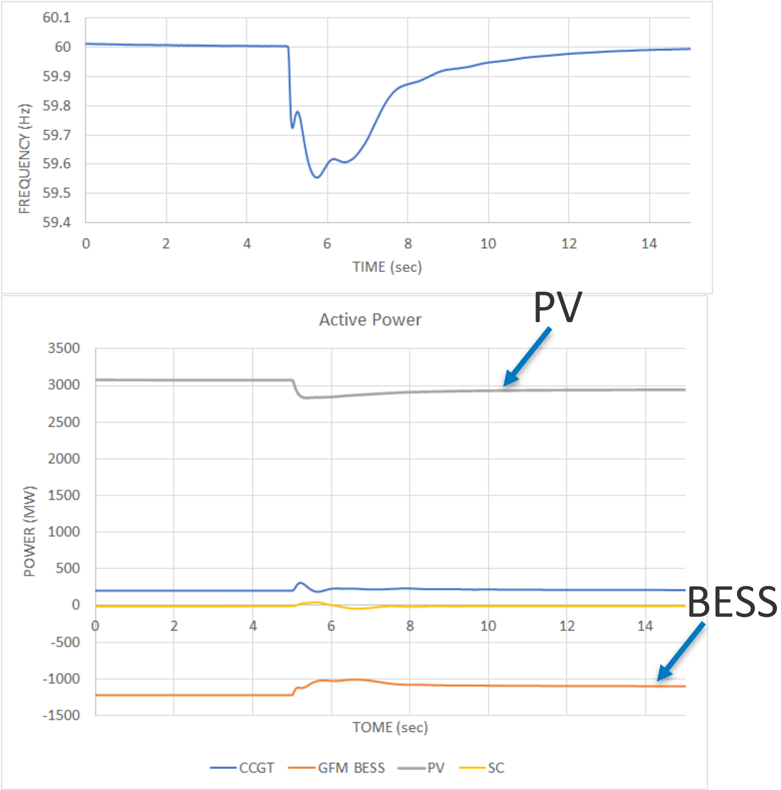
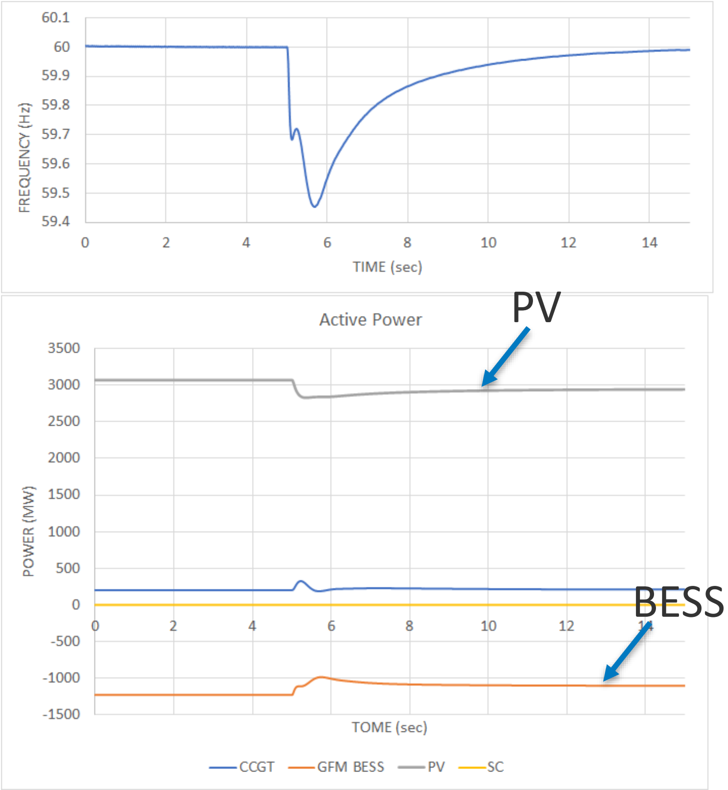
Loss of 250 MW PV

CCGT dispatched at 240MW

1a. 300 MVA condensers online

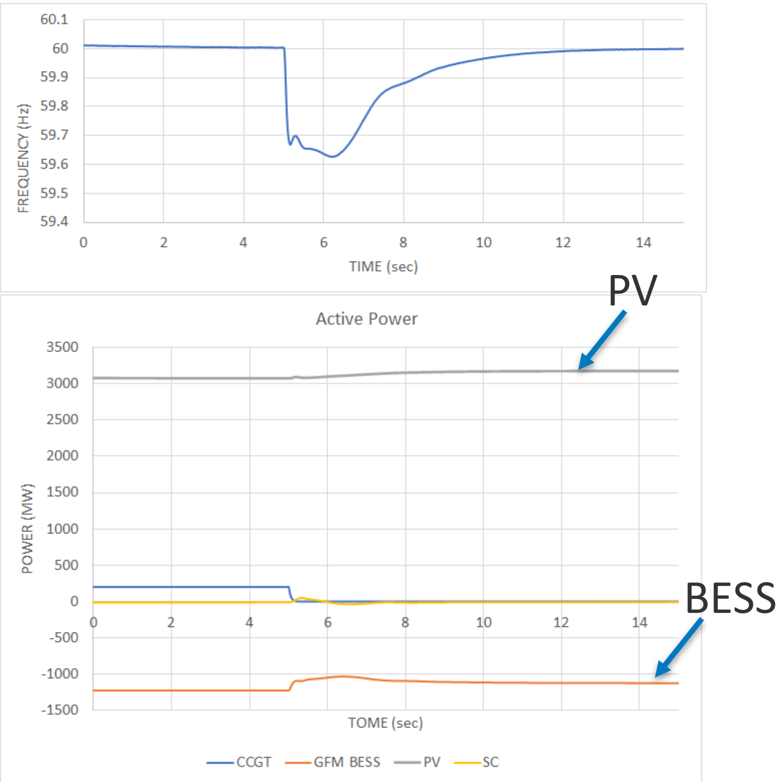


1b. No condensers

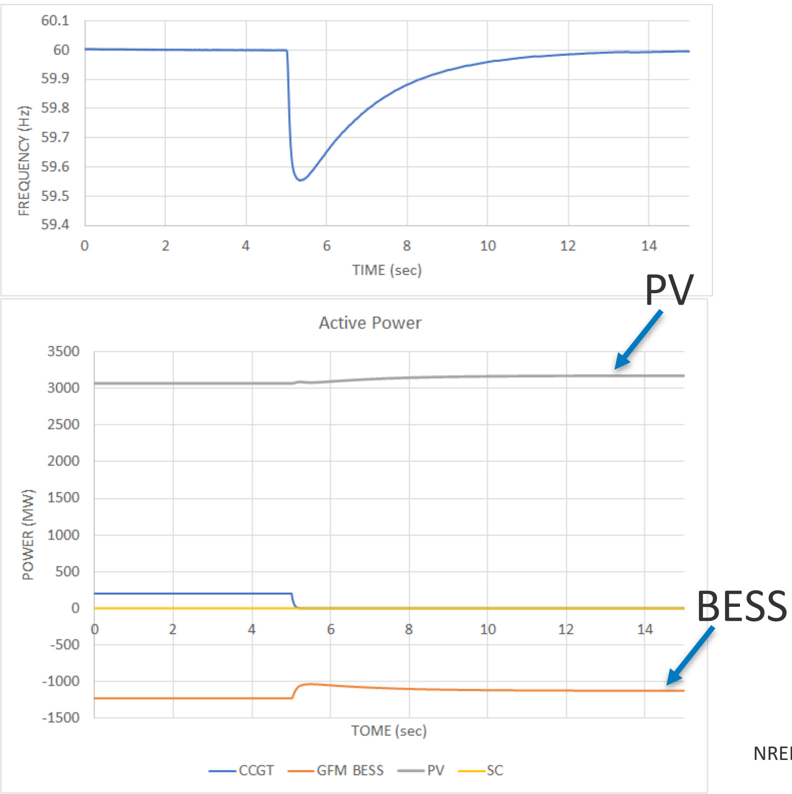


CCGT loss

2a. 300 MVA condensers online

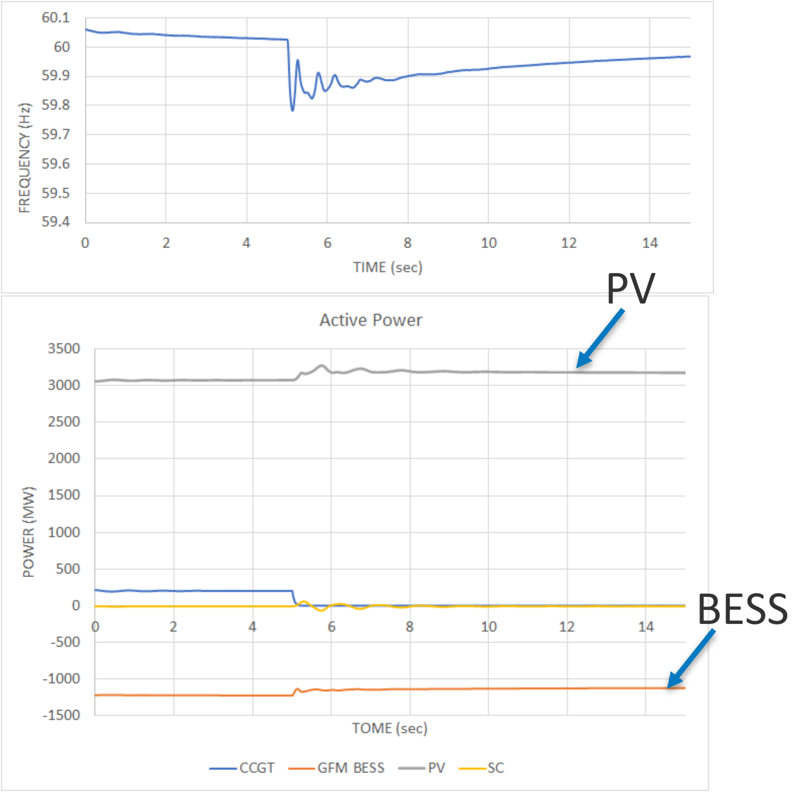


2b. No condensers

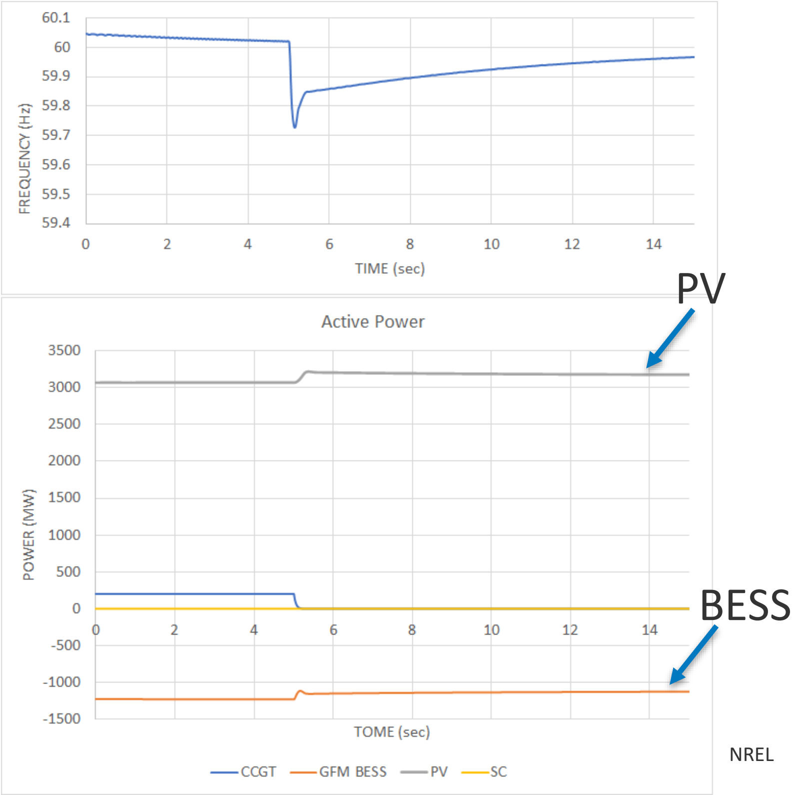


CCGT loss, PV provides inertia + droop

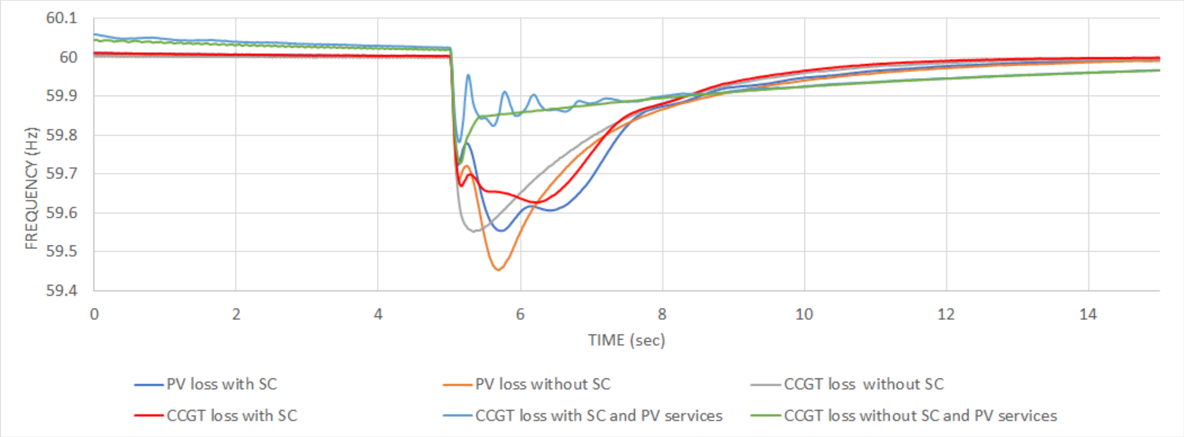
3a. 300 MVA condensers online

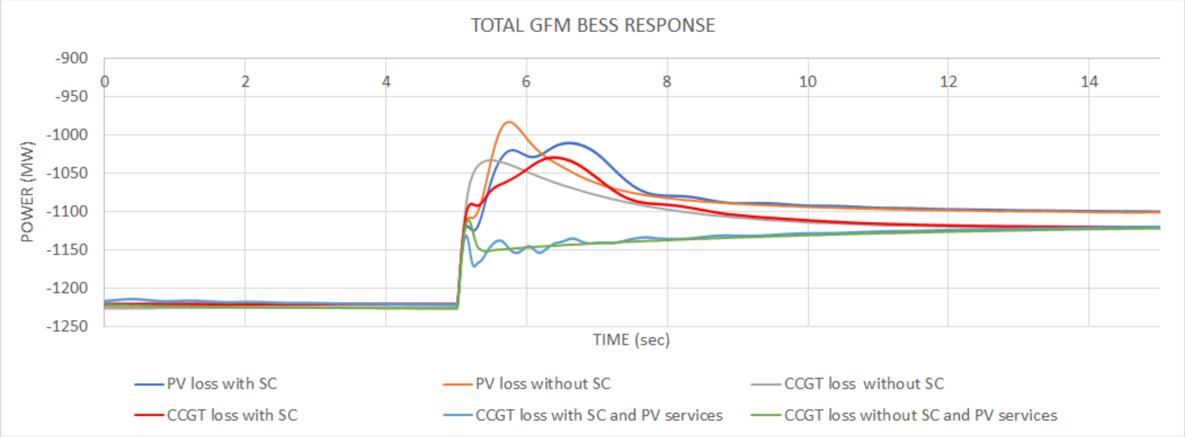


3c. No condensers



Comparison of Frequency Response Cases

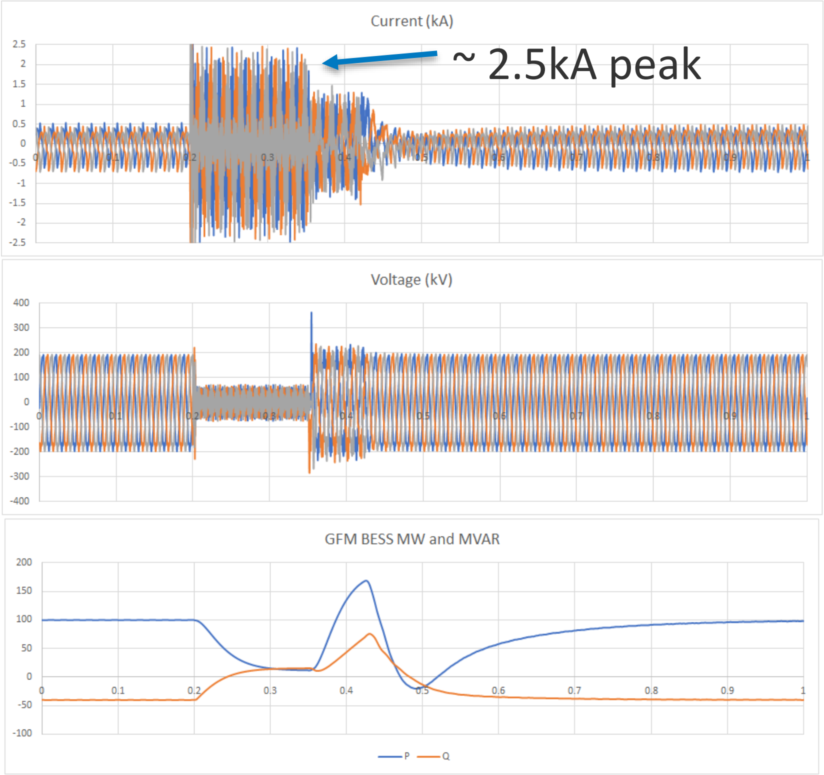




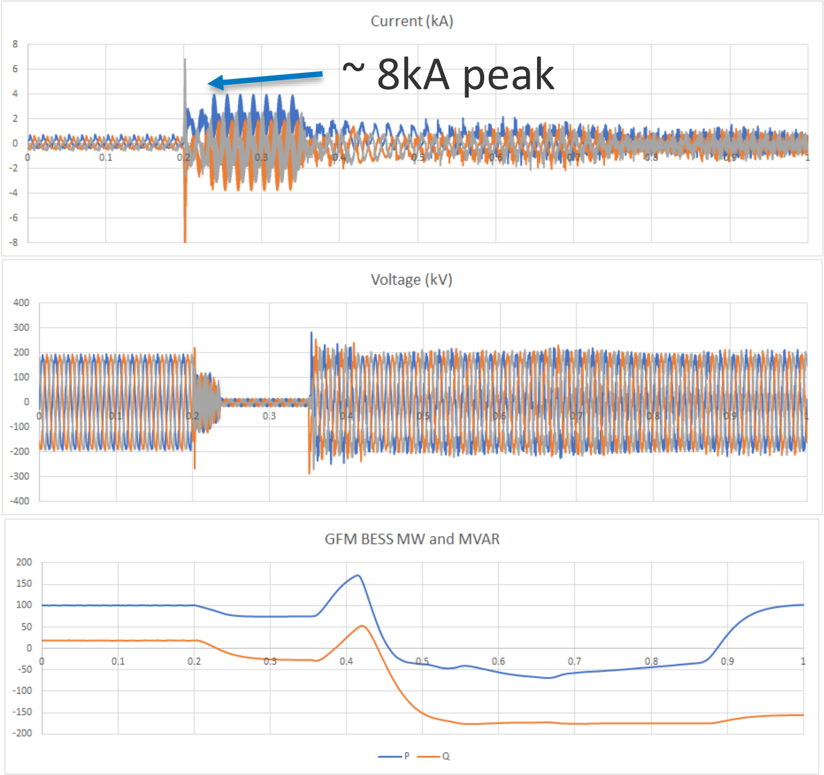
- Inertia of synch condensers helps GFM BESS to improve frequency response but not by much in very high this penetration case
- GFM BESS with simple droop control seems to provide adequate frequency response at 100% (and close to 100%) cases
- The value of condensers in this case will be more for SCC contribution, SCR boosting and voltage stability

Fault Performance of GFM BESS + Condenser Plant

200 MW GFM BESS

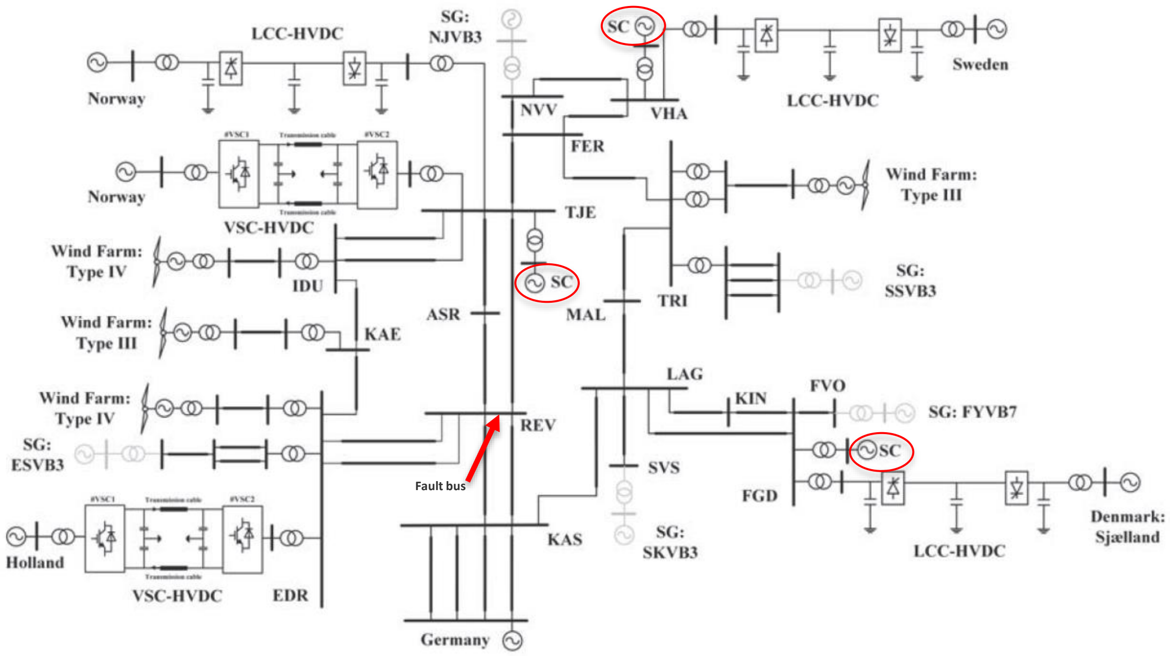


200 MW GFM BESS + 100 MVA Condensers



SCR Boosting by Synchronous Condensers

[Synchronous condenser allocation for improving system short circuit ratio](#)
J. Jia, G. Yang, AH Nielsen, V. Gevorgian, E Muljadi - 2018 5th International Conference on Electric Power and Energy Conversion Systems (EPECS)



Simplified model of future Western Denmark power system (400 kV)

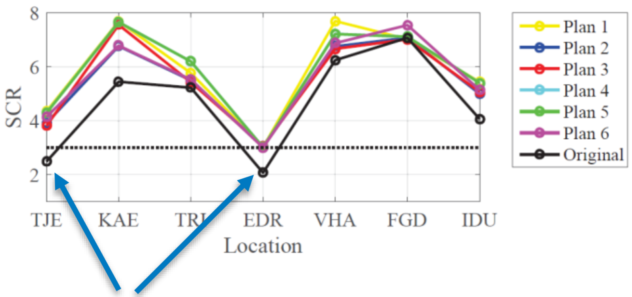
- Three SCs already exist in the system
- Existing LCC HVDC – do not contribute into SCR
- New VSC-HVDC
- Several synchronous plants will retire
- Type 3 and Type 4 wind power plants

Synch Condensers Allocation Plan

SYNCHRONOUS CONDENSER ALLOCATION PLAN

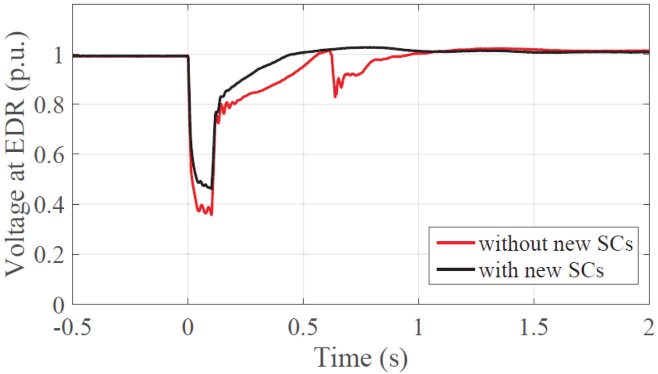
Set	Plan	Location and Rating [Mvar]	Cost [M$]
1	1	TJE(250), KAE(250), EDR(250), VHA(125)	30.25
	2	TJE(250), KAE(250), EDR(250), TRI(125)	30.25
	3	TJE(250), KAE(250), EDR(250), FGD(125)	30.25
2	4	REV(250), EDR(250), KAE(250)	25.50
	5	REV(250), EDR(250), ASR(250)	25.50
	6	REV(250), EDR(250), TJE(250)	25.50

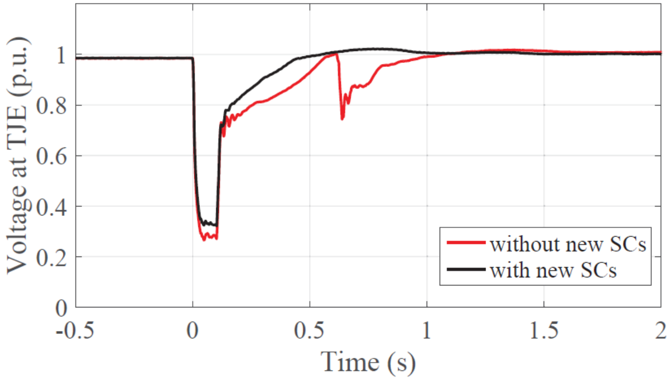
Optimization problem:
Find lowest cost solution to ensure SCR>3 for each 400 kV bus



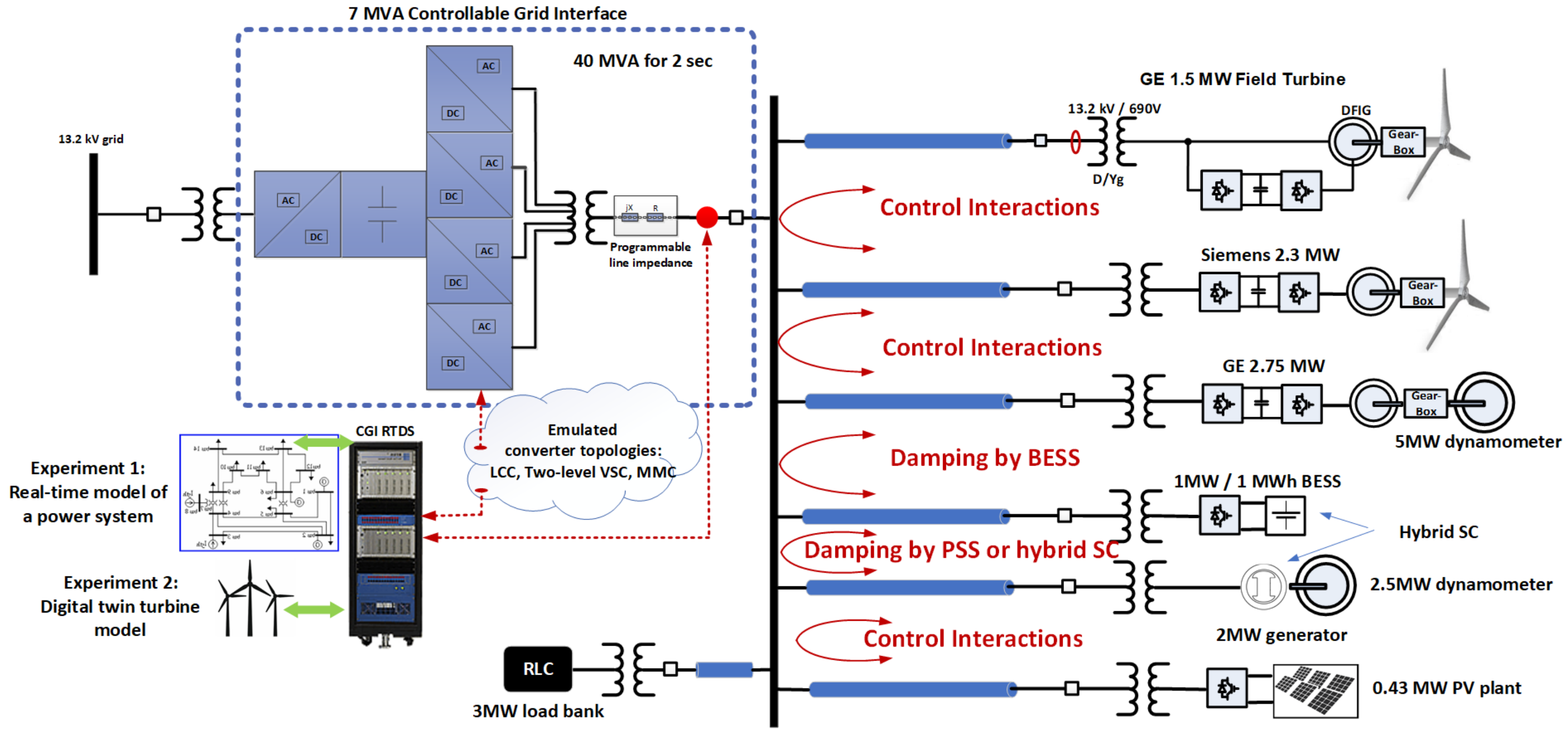
Weakest buses in the system

Comparison of fault performance





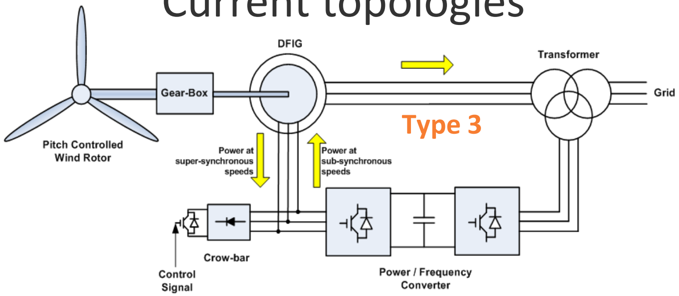
Stability Controls Demonstration Platform at NREL's Flatirons Campus

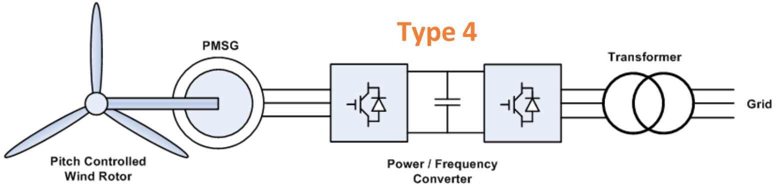


- Unique platform to validate all types of stability controls and protection for IBRs and hybrid systems
- Testing of hybrid synchronous condenser configurations
- Validation of black-start strategies and controls

Turbine Topologies

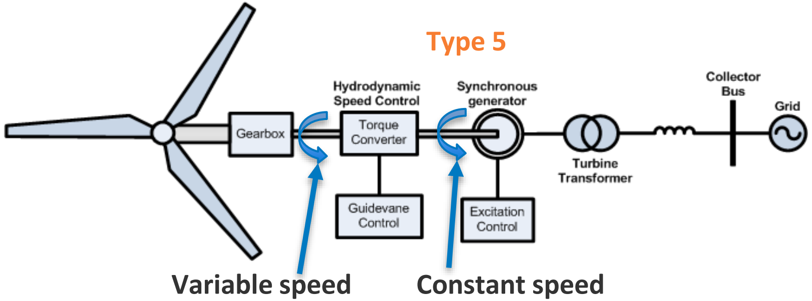
Current topologies





- Inverter-coupled solutions
- Can be operated as grid forming
- All limitations related to power electronics-coupled generation are applied
- Applicable to 100% grid but significant research is still needed in controls, power electronics and integration issues

One possible future solution from the past



- Type 5 wind turbine topology, some operational systems were built in the past (like pst DeWind's D8.2 2 MW WTG)
- Synchronous generator with fluid torque converter
- No power electronics
- Easy fault ride-through
- No power quality issues
- Generator operates at 13.8 kV
- Synchronizing torque
- Perhaps more research in **hydraulic coupling reliability** is needed (has been solved in automotive industry)
- Operates exactly as conventional a synch generator plant
- Provides inertia, short circuit current and grid forming naturally, no additional controls or equipment is needed
- Fully capable to operate as a **synchronous condenser** during no-wind periods

Summary

- Grid forming capability by IBRs is important for system stability in low/no inertia grids
- Determining optimal ratios between GFL and GFM resources in interconnected power systems is still a research question
- Research is needed to quantify benefits of hybrid synchronous condensers and their controls for system stability. What are the value of synchronous condensers in extremely low/zero inertia grids?
- Testing at scale is important to better understand stability issues and interactions between multiple technologies, validate controls and dynamic/transient models for future grid studies

Thank you

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