Modeling Challenges:

Dynamic Interactions Between Inverters, Grid Forming Inverters

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Challenges for Distribution Planning, Operational and Real-time Planning Analytics Workshop

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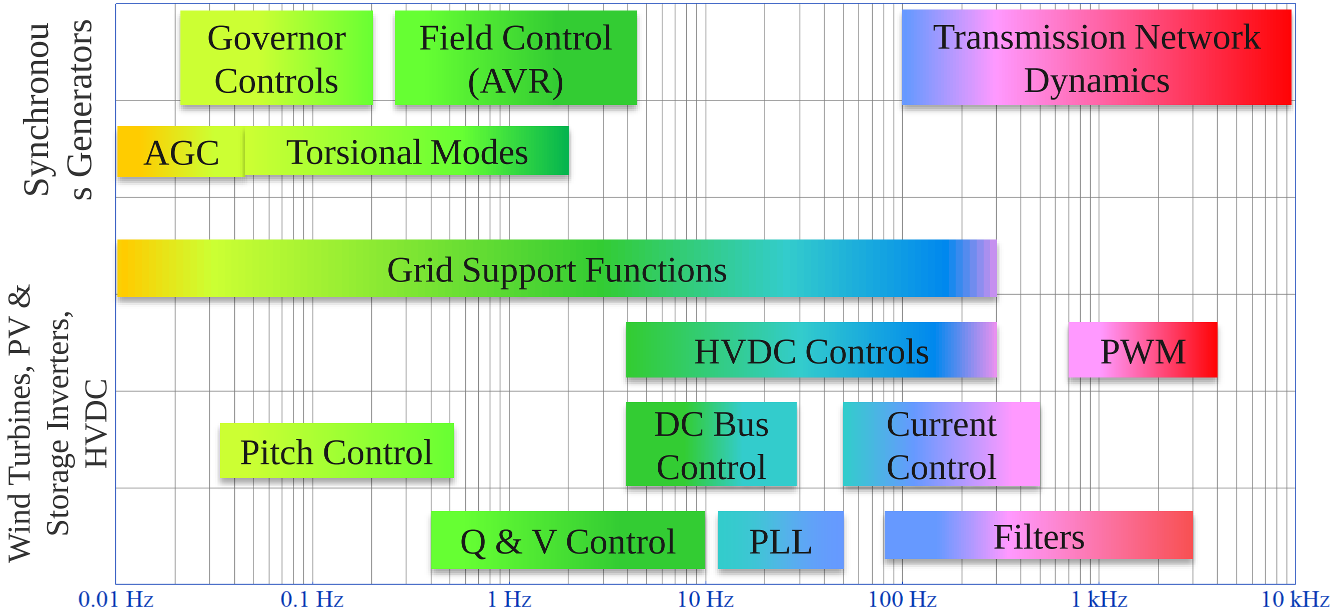
Services by Multi-Technology (Hybrid) Plants

- Dispatchable renewable plant operation
  - Long-term and short-term production forecasts
  - Capability to bid into day-ahead and real-time energy markets like conventional generation
- Ramp limiting, variability smoothing, cloud-impact mitigation
- Provision of spinning reserve
- AGC functionality
- Primary frequency response (programmable droop control)
- Fast frequency response (FFR)
- Inertial response:
  - programmable synthetic inertia for a wide range of H constants emulated by BESS
  - Selective inertial response strategies by wind turbines
- Reactive power/voltage control
- Advanced controls: power system oscillations damping, wide-area stability services
- Resiliency services: black-start, islanded operation
- Stacked services
- Plant electric loss reduction, AEP increase
- Selective plant configuration for BESS: ability to serve a whole wind power plant, or selected rows/turbines
- Battery SOC management
- Optimization model-predictive control strategies – work in progress
- Revenue optimization

NREL-First Solar Project

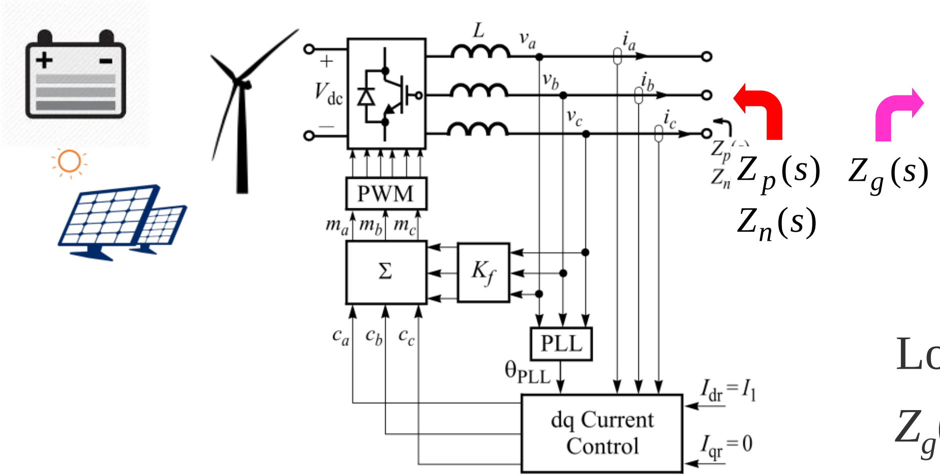
NREL-PG&E project

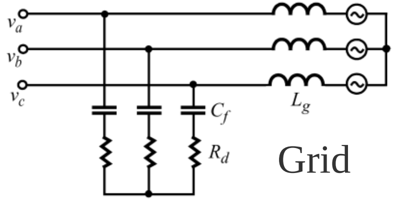
Control Interactions



- Power electronics-based generation and T&D systems have increased control interaction problems

Impedance-Based Analysis



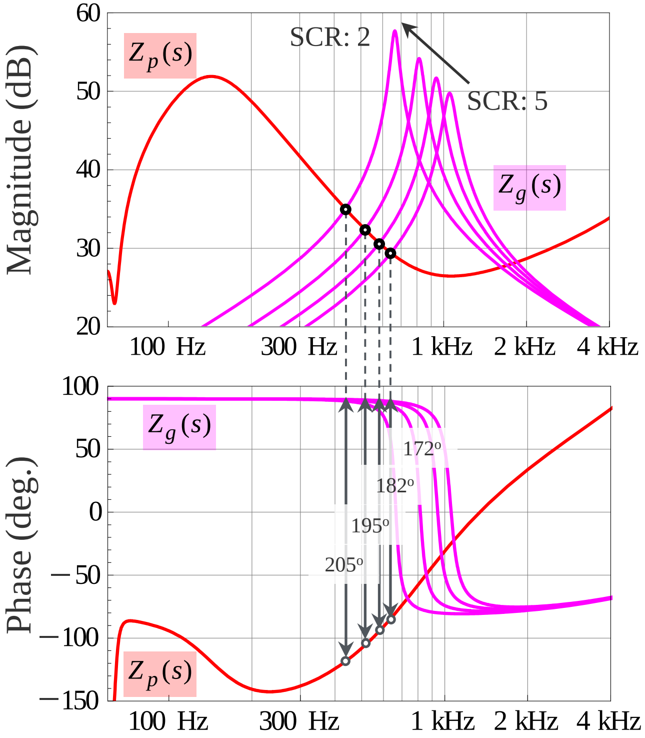


Loop gain:

$$Z_g(s)/Z_p(s), \quad Z_g(s)/Z_n(s)$$

- Impedance responses of inverter/plant and grid are compared
  - Impedance intersection points give frequencies of resonance modes
  - Phase difference at intersection points gives damping

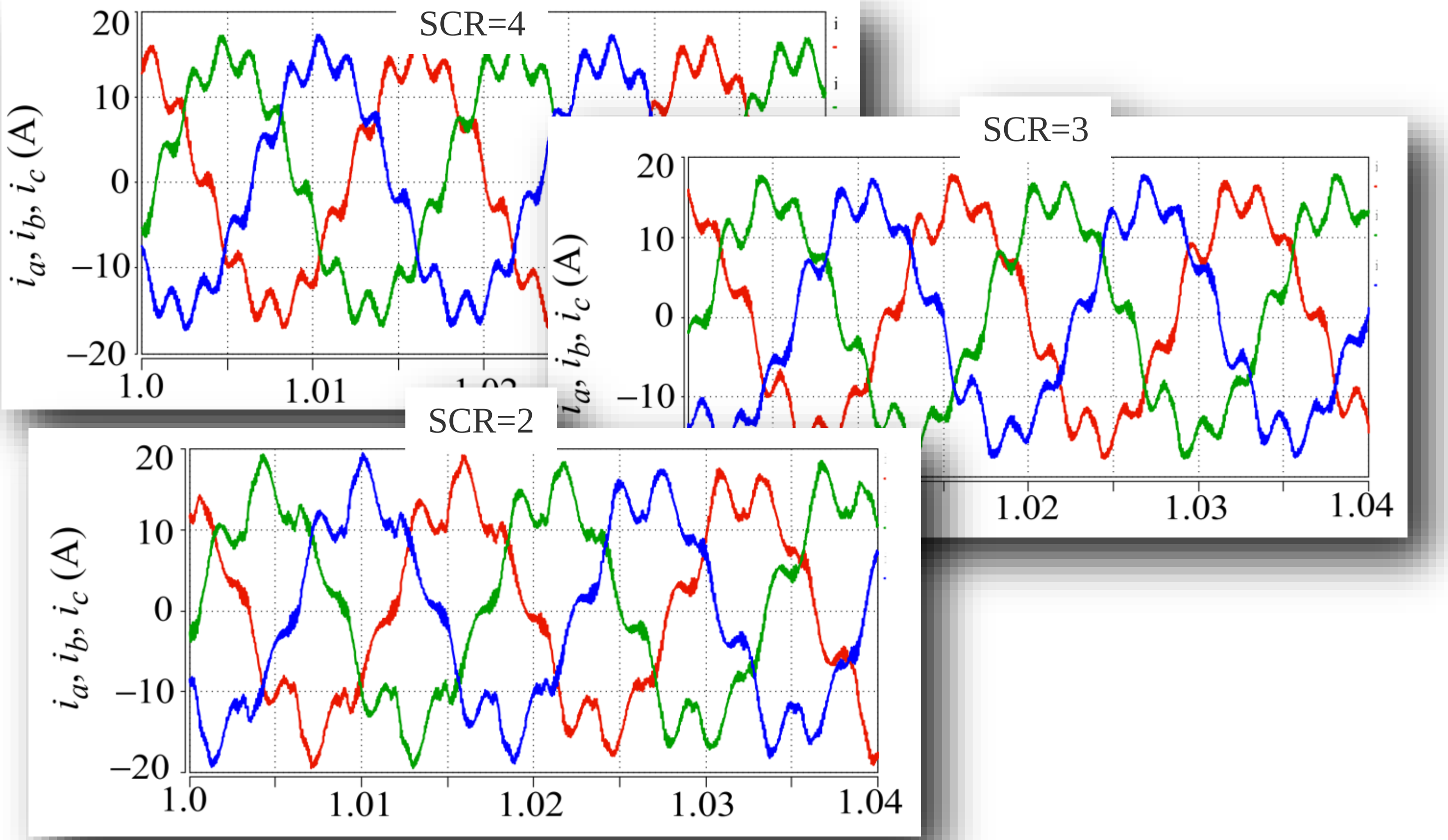
Resonance: Frequency and Damping



SCR	Grid Inductance, L_g	Resonance Frequency	Phase Margin
5	4.6 mH	641 Hz	+8°
4	5.7 mH	584 Hz	−2°
3	7.6 mH	512 Hz	−15°
2	11.5 mH	441 Hz	−25°

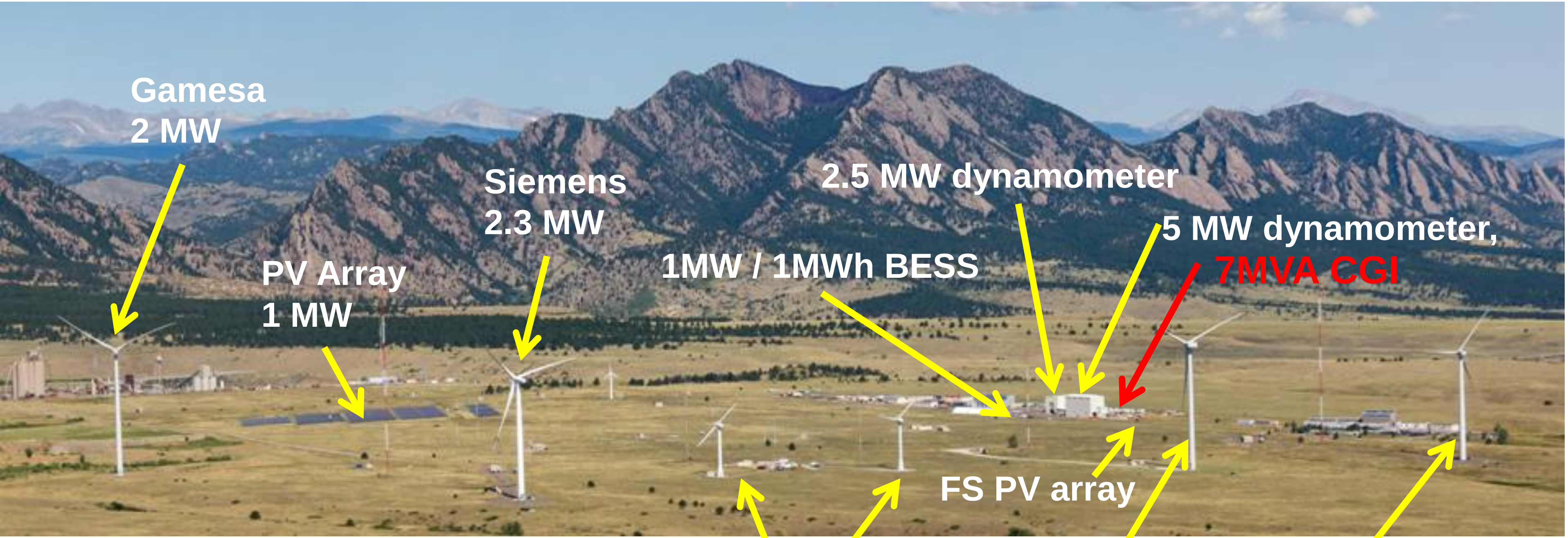
- Unstable Resonance for Weak Grids
  - Unstable for SCR<5.0
  - Resonance Frequency Decreases with SCR and its “Severity” Increases

Resonance-Generated Distortions



NREL Flatirons Campus

- *Total of 12+ MW variable renewable generation currently*
- *7 MVA Controllable Grid Interface (CGI)*
- *Multi-MW energy storage test facility*
- *2.5MW and 5 MW dynamometers (industrial motor drives)*
- *13.2 kV medium voltage grid*
- *1.5 MW total PV capacity*



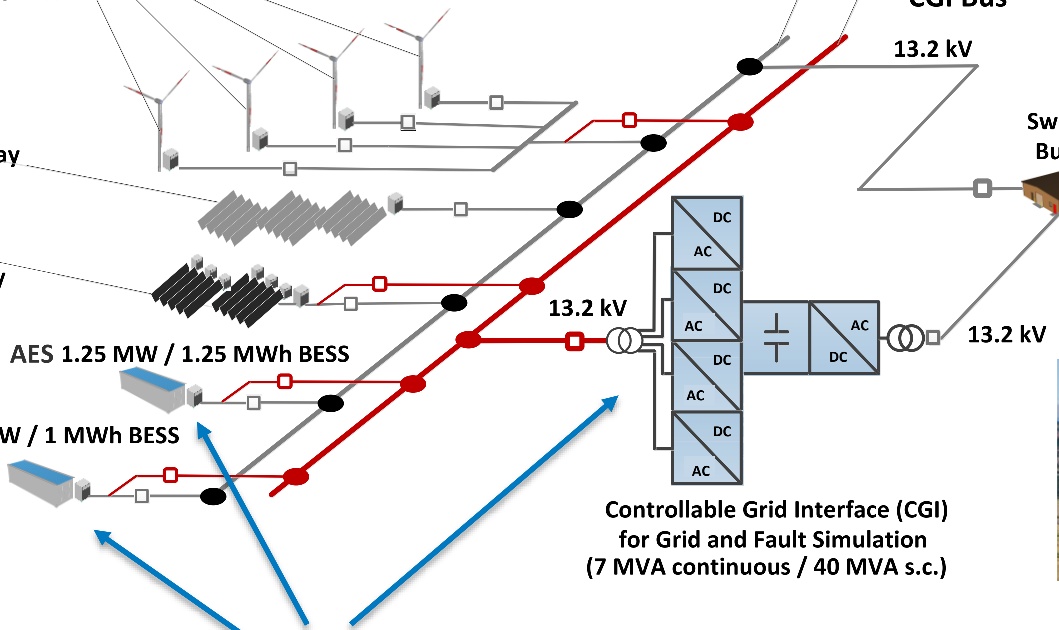
Research Turbines
2 x 600 kW

GE/Alstom
3 MW

GE 1.5 MW

NWTC Controllable Grid Platform

Flexible testbed for many black start schemes



NWTC Wind Turbines
Alstom 3 MW
GE 1.5 MW
Gamesa 2 MW
Siemens 2.3 MW

SunEdison
1 MW PV Array

First Solar
430 kW PV array

AES 1.25 MW / 1.25 MWh BESS

1 MW / 1 MWh BESS

Regular grid,
Xcel Bus

Controlled grid,
CGI Bus

13.2 kV

13.2 kV

13.2 kV

13.2 kV tie-line

Switchgear
Building

115 kV

Xcel
Substation

Controllable Grid Interface (CGI)
for Grid and Fault Simulation
(7 MVA continuous / 40 MVA s.c.)

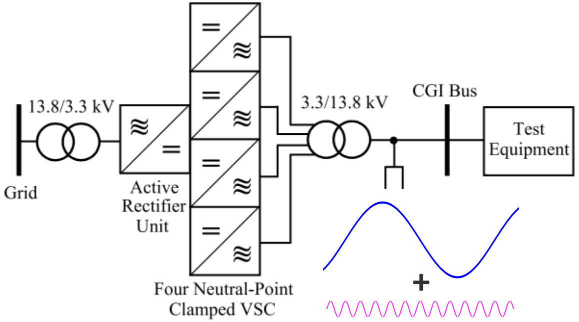
Grid forming

Aerial view of the site

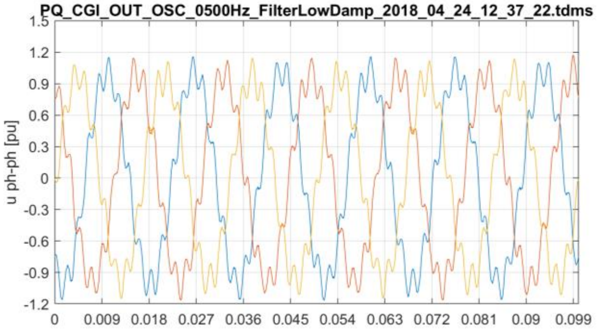
Image source: NREL

Impedance Measurement Using CGI

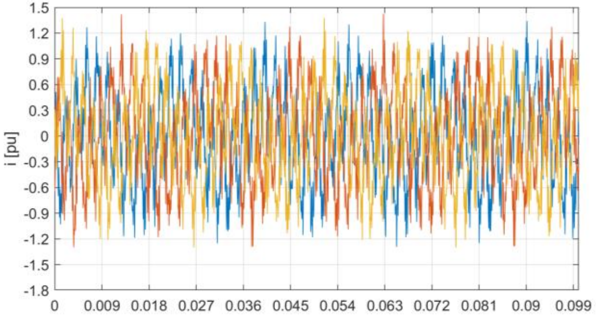
- 7-MVA, 13.2-kV grid simulator (CGI)



- Perturbed voltages



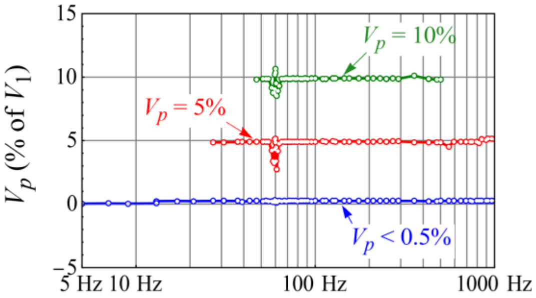
- Response currents



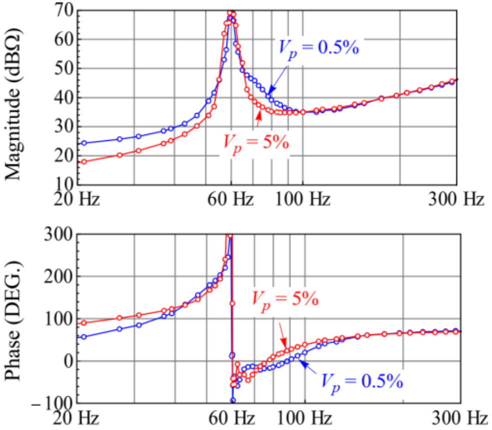
Impedance of 1-MW/13.2-kV BESS System

- Inverter-interfacing 1-MW/ 1-MWh battery energy storage system

  - Voltage perturbation magnitude



- Impedance response

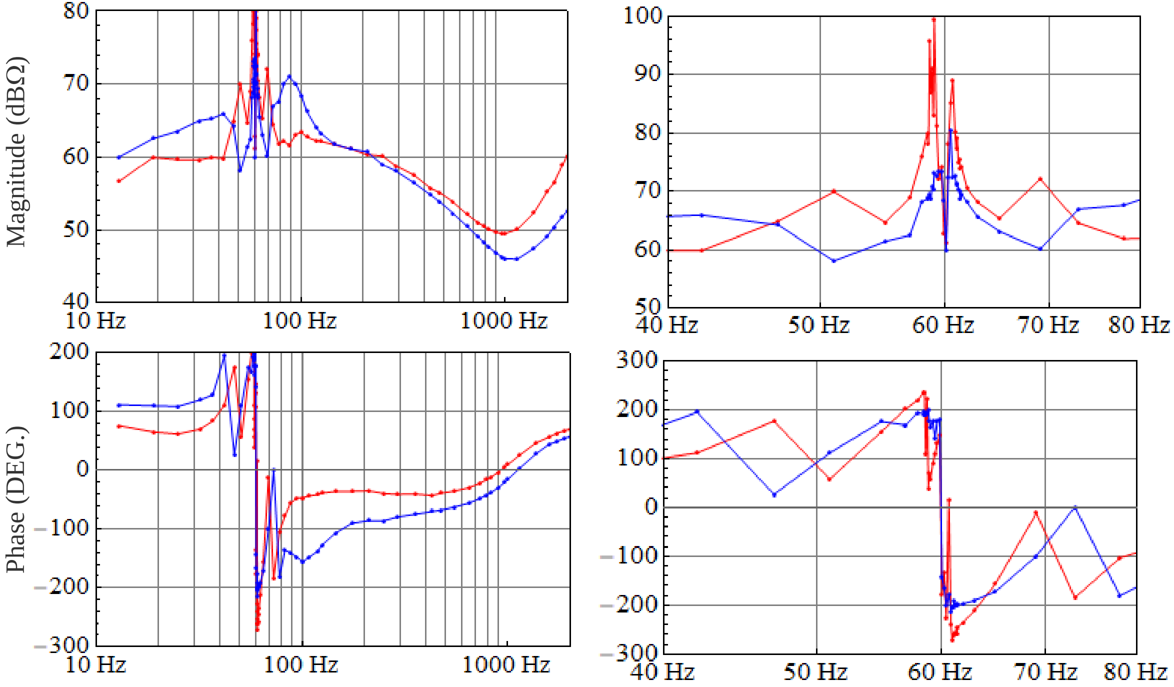


- Different control elements dominate at different frequencies.

Impedance of First Solar PV Plant

Vendor 1, 4x40 kW Inverters: 160 kW, 0 VAR

Vendor 2, 2x125kW Inverters: 250 kW, 0VAR

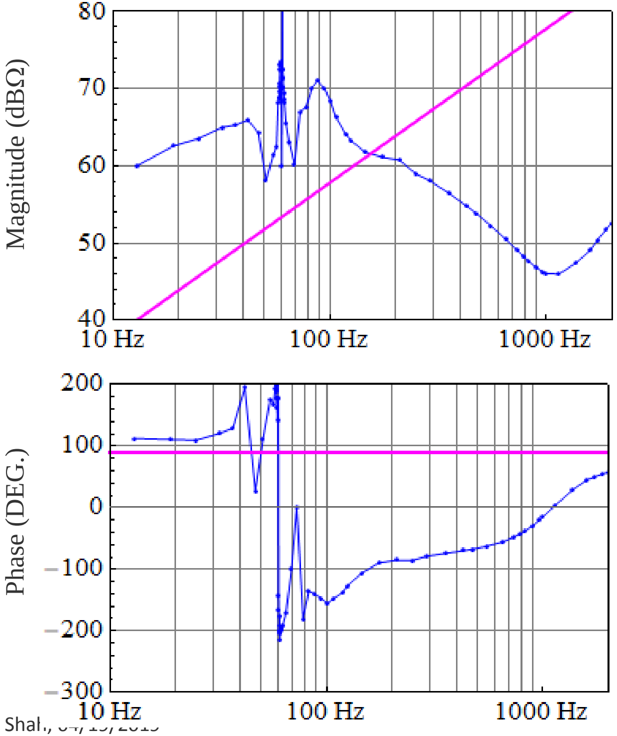


- Phase response goes below -90 degrees between 60 Hz and 200 Hz: Can potentially interact with grid and create undamped resonance

Resonance of Sungrow Inverters for Weak Grid

2 x125kW Inverters: 250 kW, 0VAR

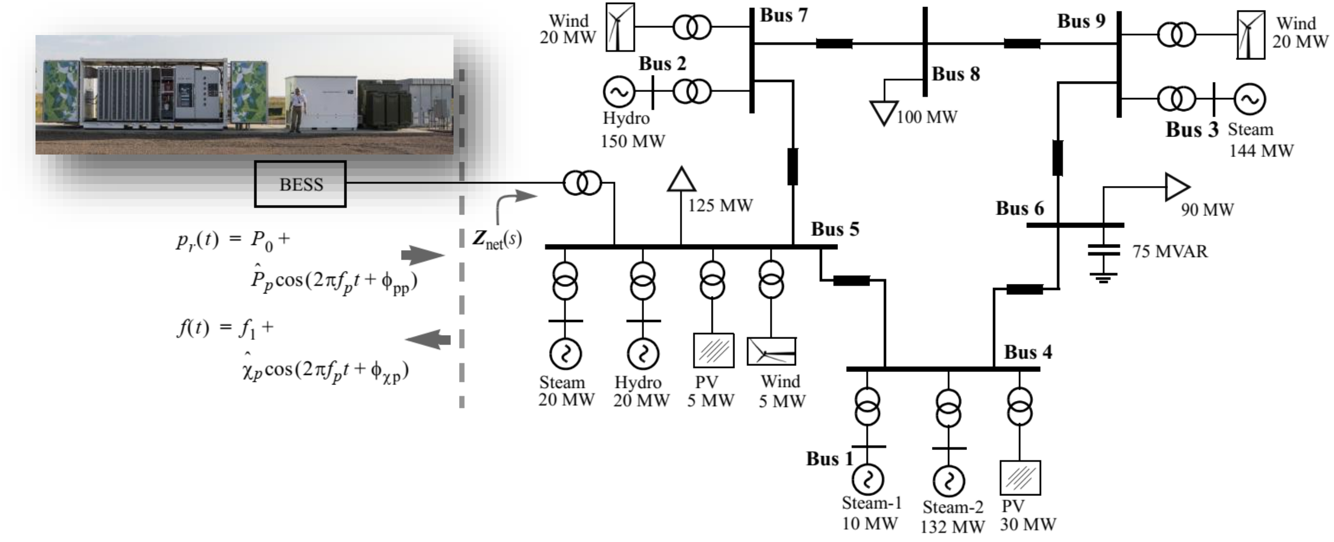
Grid Impedance: Lg = 1.2 H (SCR: 1.5)



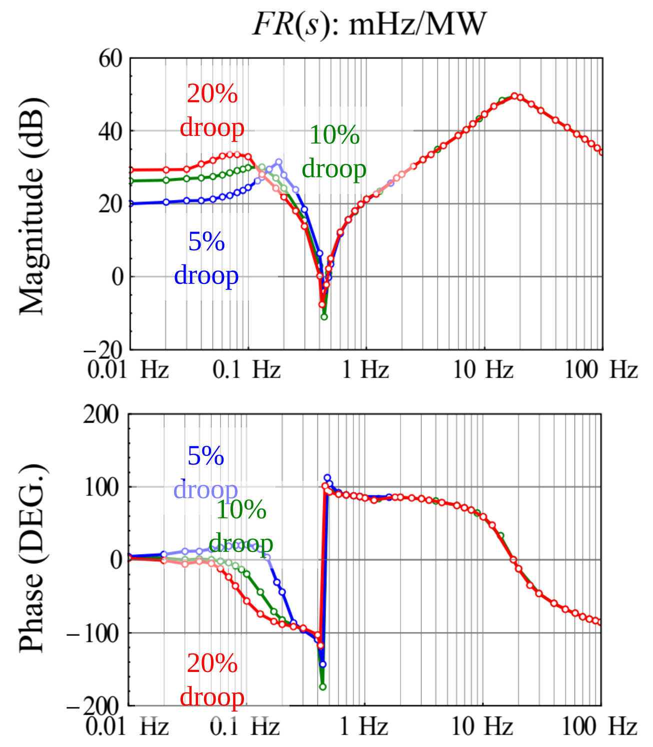
- 125 kW inverters will form undamped resonance between 100 and 200 Hz if the grid is inductive with SCR less than 1.5 on base of 250 KW, 13.2 kV
  - Corresponding grid inductance is 1.2 H

Power-Domain Impedance

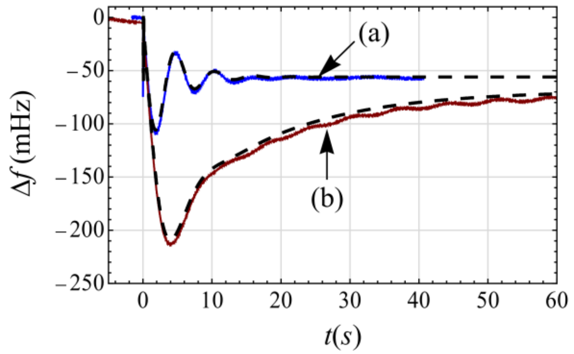
- Transfer function from Active Power to Frequency at Point of Interconnection



Frequency Response Characterization



Loss of generation



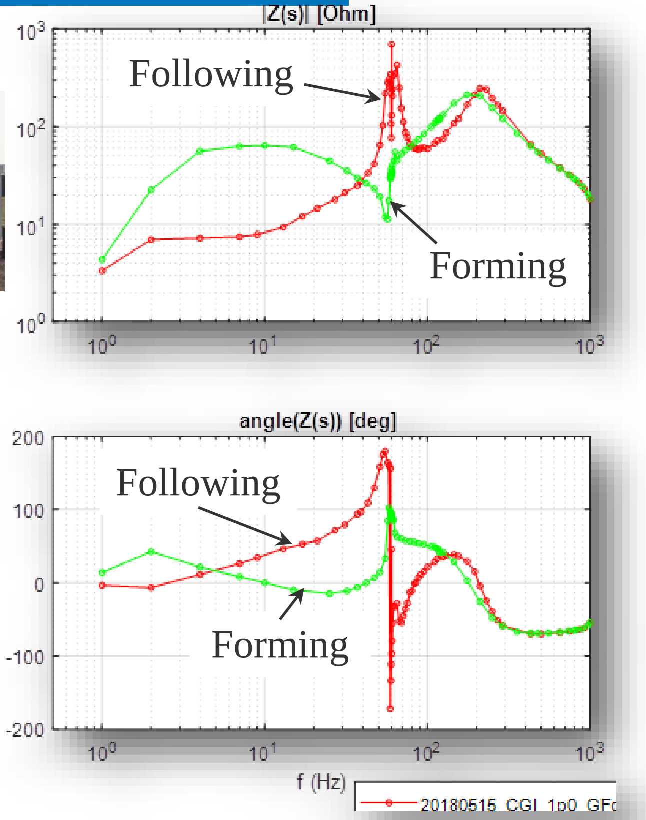
Applications:

- Real-time Estimation of Inertia, Primary Frequency Response (PFR), Nadir, etc.
- Frequency Support Design by Renewable Generation

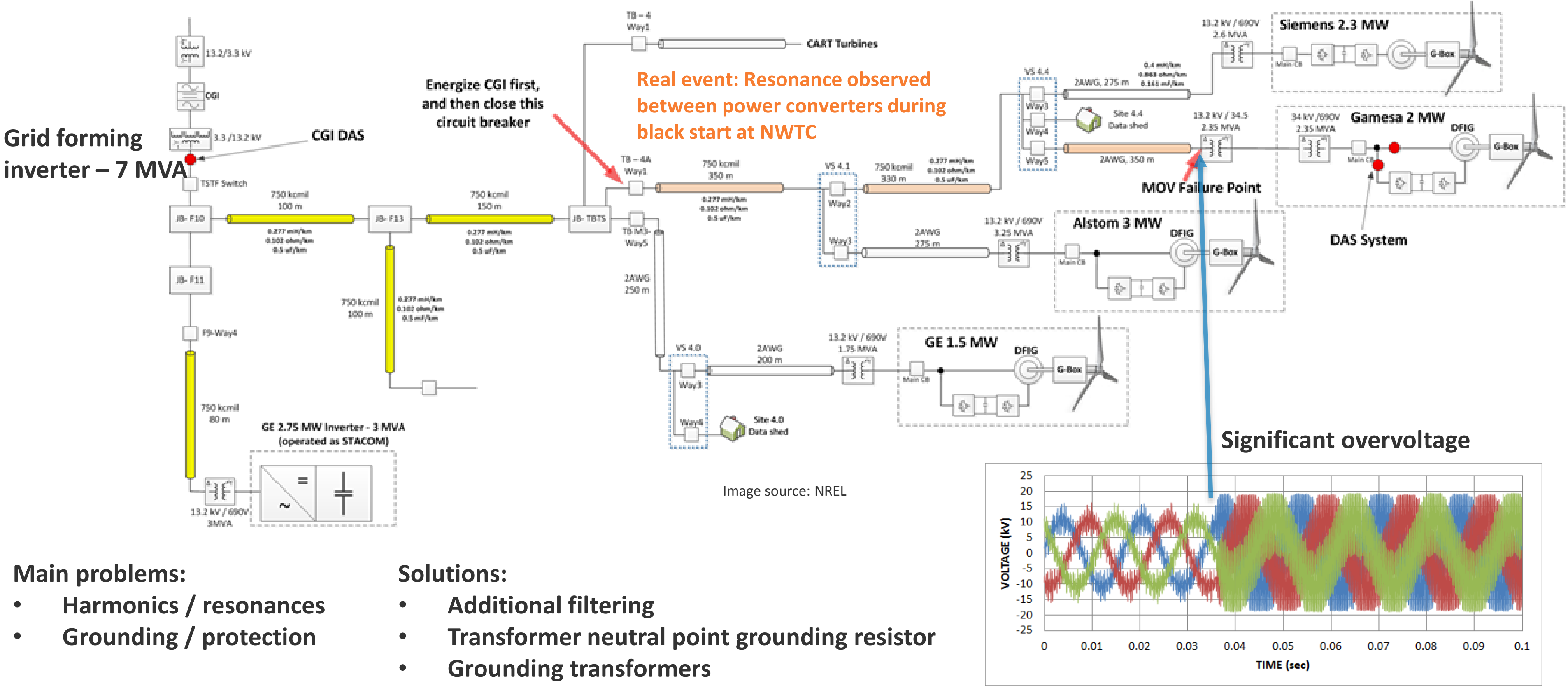
Grid-Forming Inverter from *Outside*

- BESS Inverter

- Impedance measurements can **quantify** different aspects of grid-forming ability



Black-start of Wind Power Plant (13.2 kV system)



Grid forming inverter – 7 MVA

CGI DAS

Energize CGI first, and then close this circuit breaker

Real event: Resonance observed between power converters during black start at NWTC

Significant overvoltage

Image source: NREL

Main problems:

- Harmonics / resonances
- Grounding / protection
- Inrush currents

Solutions:

- Additional filtering
- Transformer neutral point grounding resistor
- Grounding transformers
- Oversized inverter (40 MVA SC capability)

Challenges and Future Research

- Adoption of impedance characterization by industry
  - Root-cause finding, grid codes, control design, impedance specs
- Impedance measurement using grid simulators
  - High-fidelity model validation
  - Control design; Testing for grid codes
- New impedance-based tools
  - Design of grid-support functions
  - Testing of grid-forming ability of inverters

Distribution System Testbed for Islanded Testing

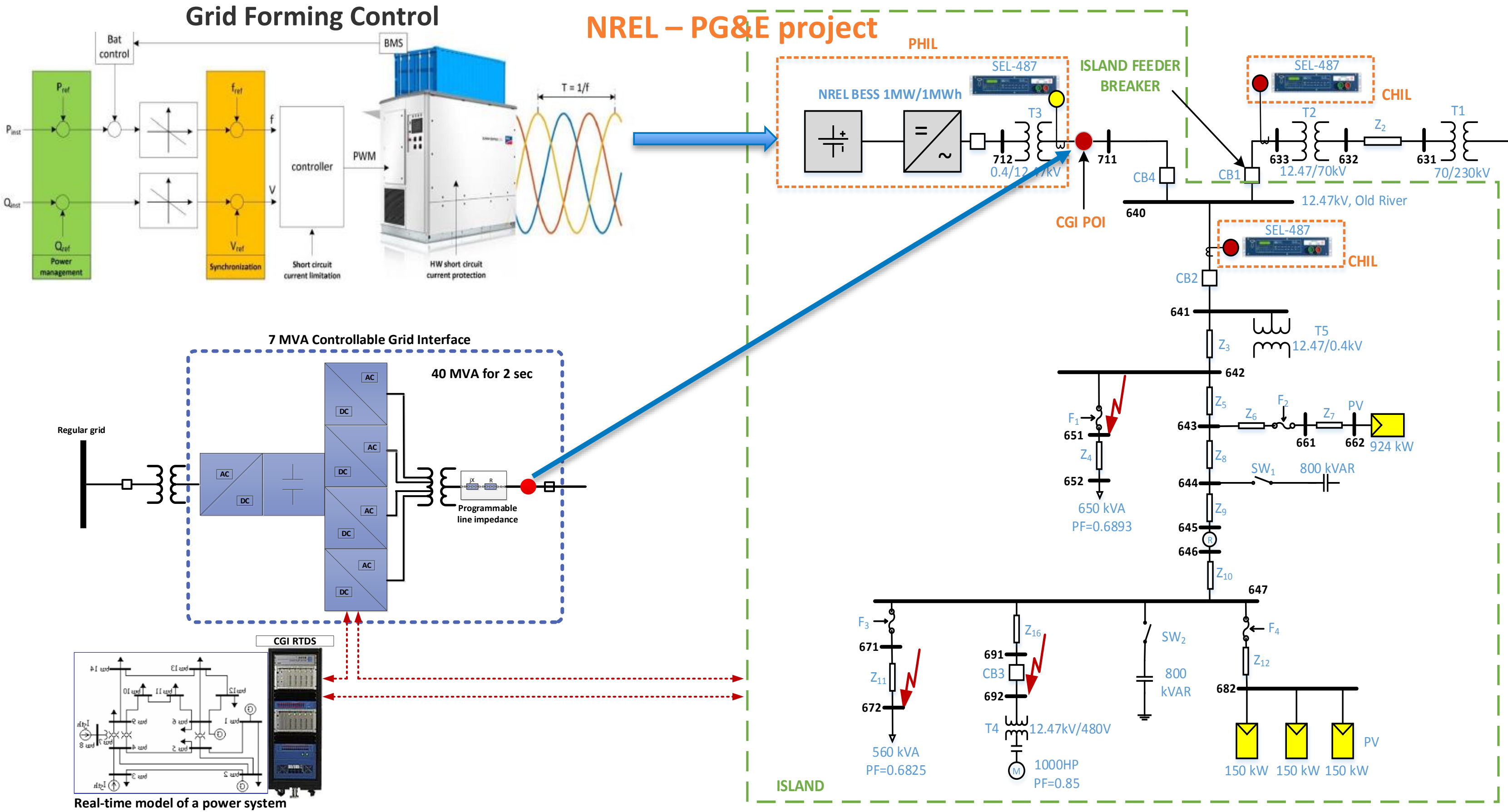
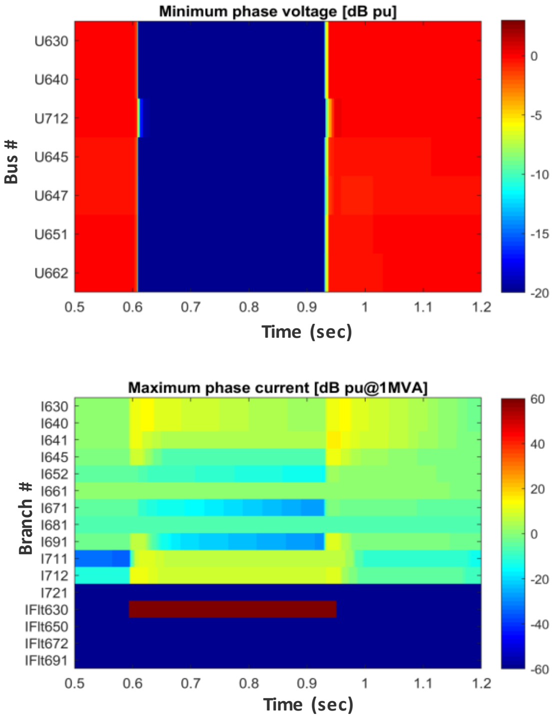


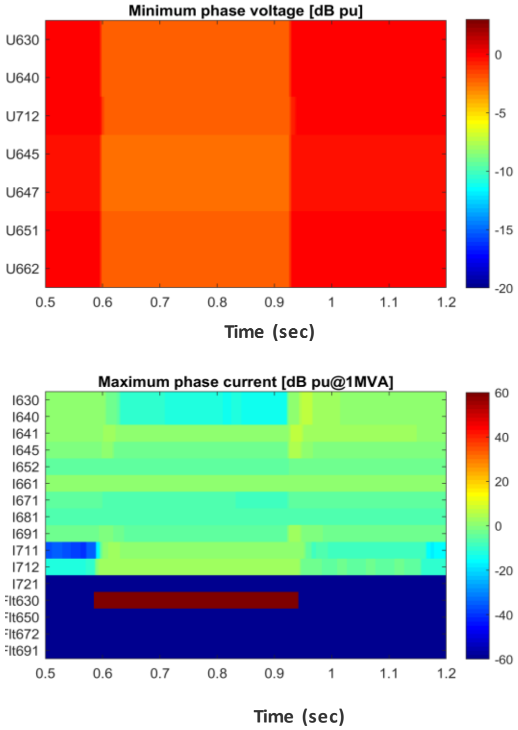
Image source: NREL

Example: Bus 630 L-to-L Fault

Low Z fault



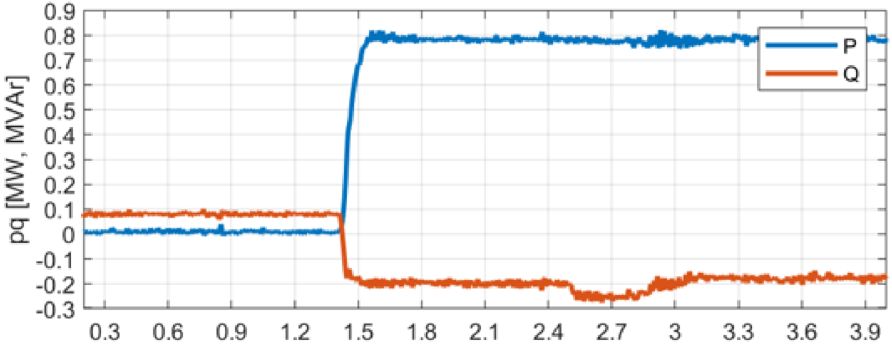
Hi Z fault



Islanded Distribution Circuit Restoration with BESS

PHIL testing results using 1 MW/1MWh BESS

BESS Active and Reactive Power
in Grid Forming Mode



Motor start event

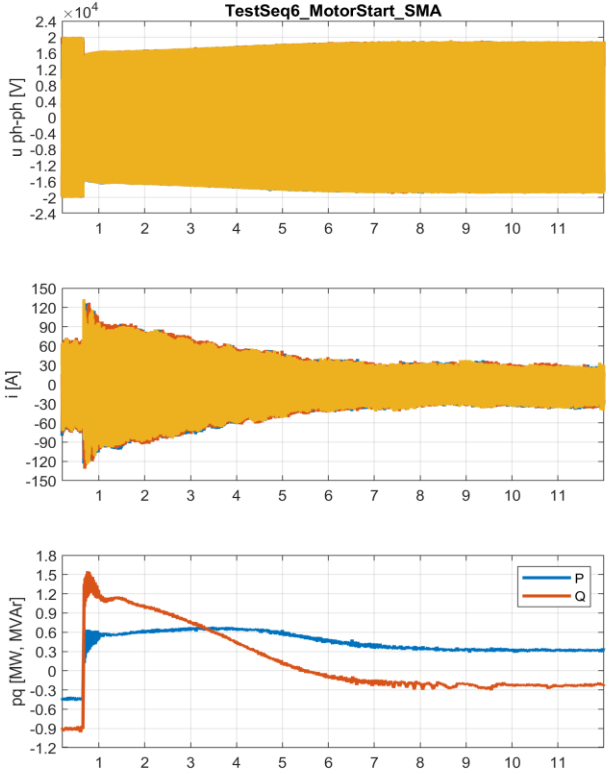
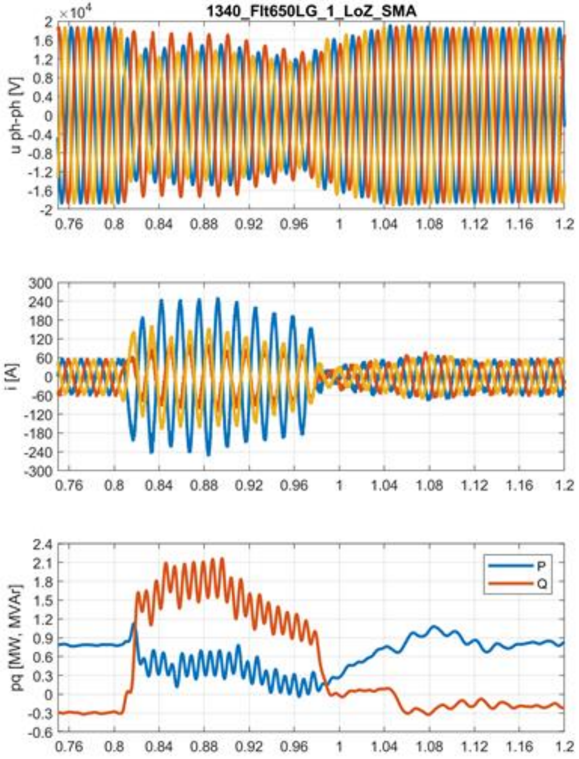


Image source: NREL

BESS Inverter Fault-ride Through in Grid Forming Mode While Operating an Islanded System

PHIL testing results using 1 MW/1MWh BESS



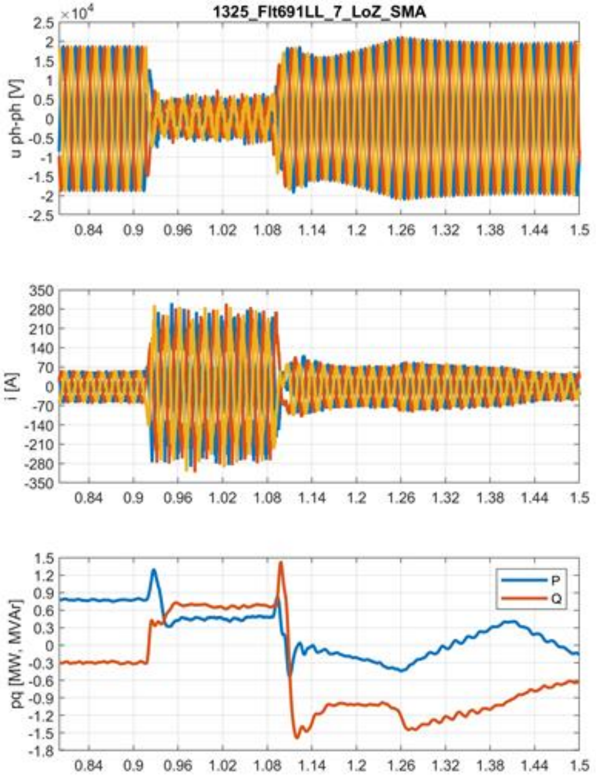


Image source: NREL

Definition of Black Start

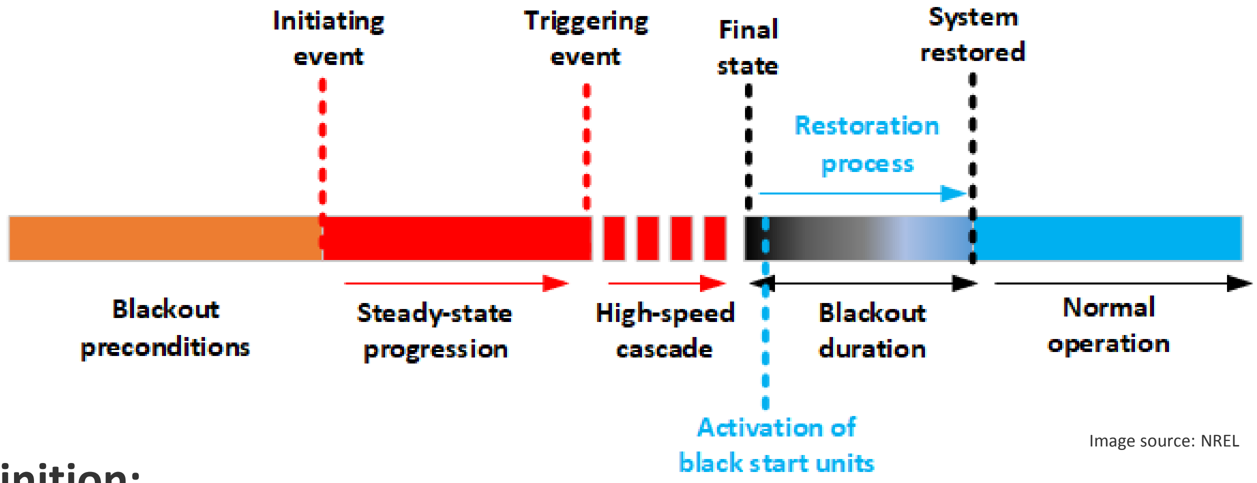


Image source: NREL

<u>NERC definition:</u>

"A generating unit(s) and its associated set of equipment which has the ability to be <u>started without support from the System</u> or is designed to remain energized without connection to the remainder of the System, with the <u>ability to energize a bus</u>, meeting the Transmission Operator's restoration plan needs for <u>Real and Reactive Power capability, frequency and voltage control</u>, and that has been included in the Transmission Operator's restoration plan"

Black Start Stages

The black start process can be divided into three stages:

- **Preparation stage**
- **Network reconfiguring**
- **Load restoration**

A typical restoration plan for bulk power system includes the following essential steps:

- System status identification: blackout boundaries and location in respect to critical loads, status of circuit breakers, capacity of available black start units, etc.
- Starting at least one black start unit to supply critical loads such as nuclear or large thermal power plants
- Progressive restoration: step-by-step supply of other loads avoiding over and under voltage conditions

The restoration strategies:

- Serial – simpler strategy, slower but more stable
- Parallel – quicker but more complex

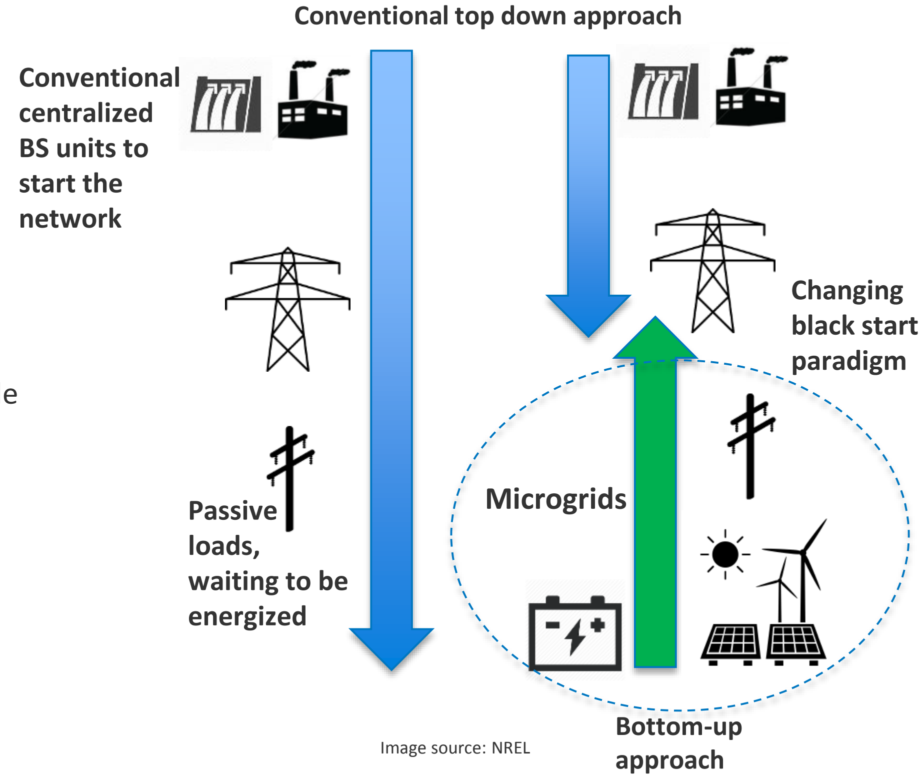
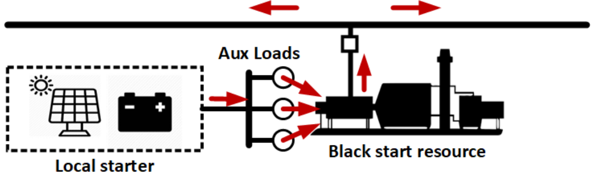


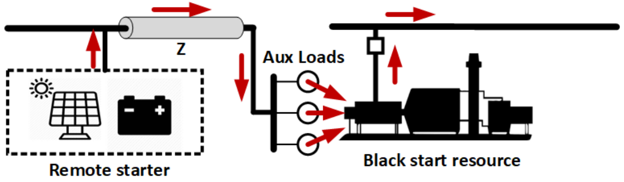
Image source: NREL

Configurations of Integrated PV/BESS Plants for Black Start

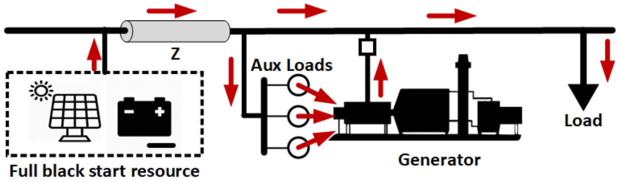
Co-located starter for a black start resource



Remote starter for a black start resource



PV + storage as fully functional black start resource



Collective black start resource

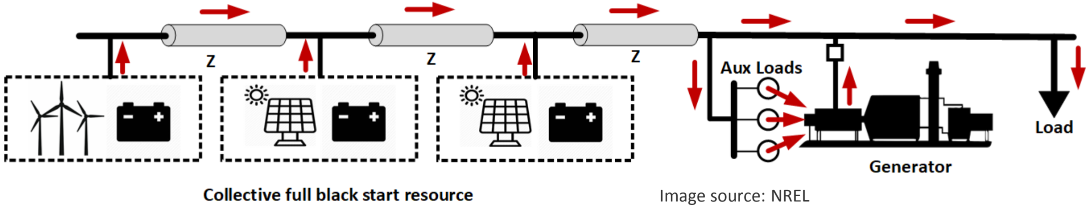


Image source: NREL

PV-BESS Black starting a Gas Turbine Generator

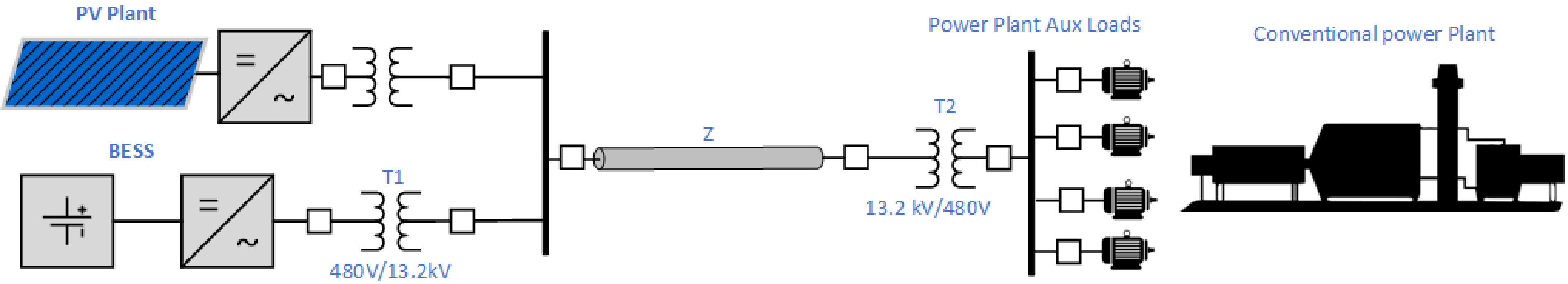


Image source: NREL

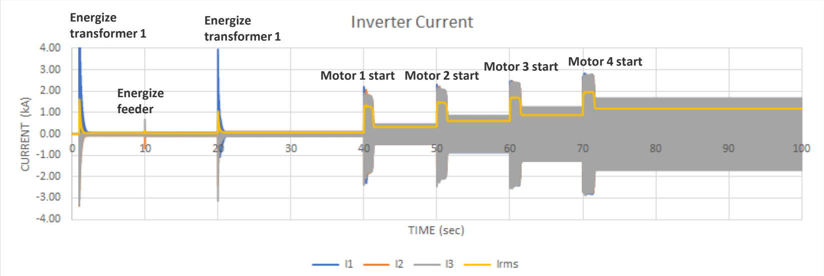
Main challenge:

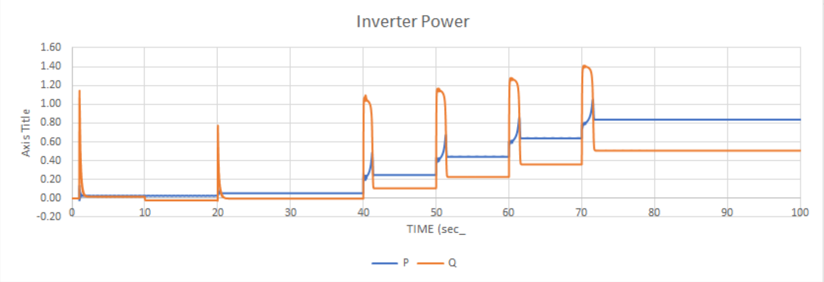
- Energizing transformers and feeders
- Mid-size gas turbines employ starting motors
- Black start inverters need to be sized to provide necessary inrush current

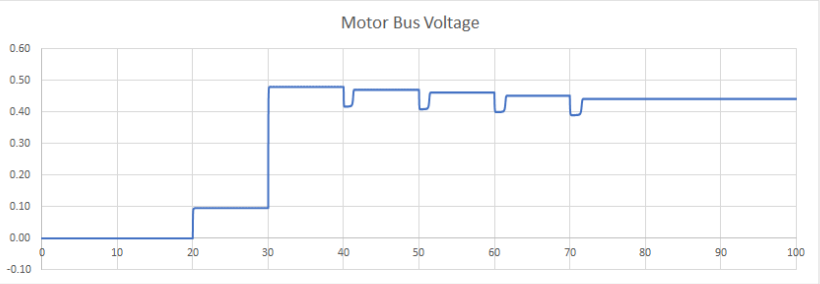
Possible solutions:

- Oversized inverters for inrush current
- Equip all plant motor loads with soft starters of VFDs
- Partial solution – energize transformers with tap positions at highest number of turns

Consecutive Start of Aux Plant Motors







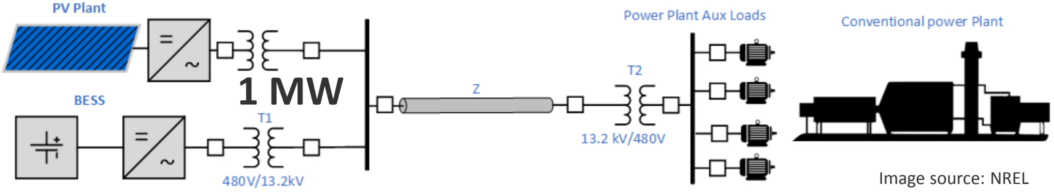
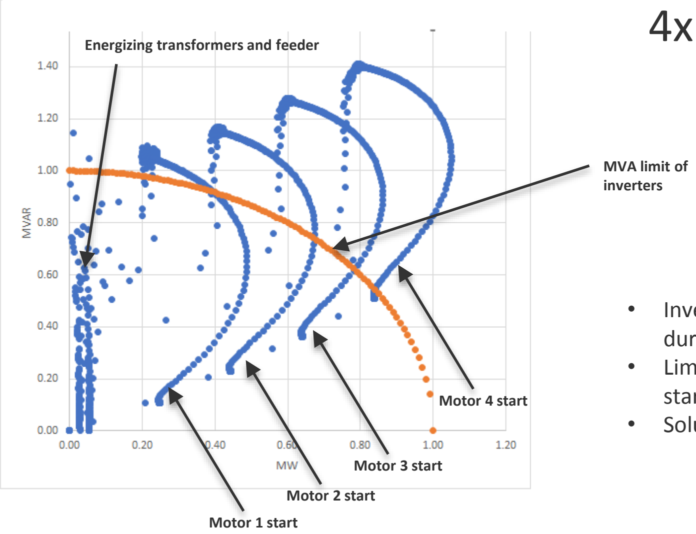


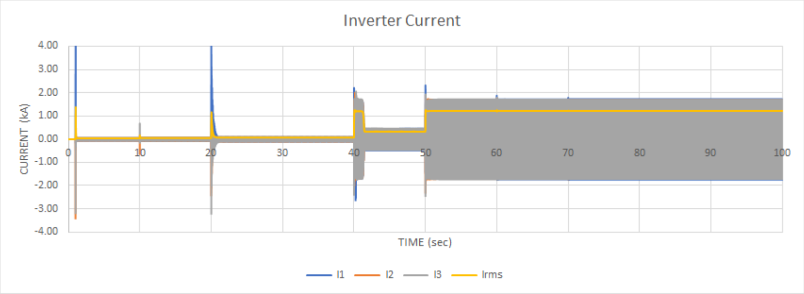
Image source: NREL

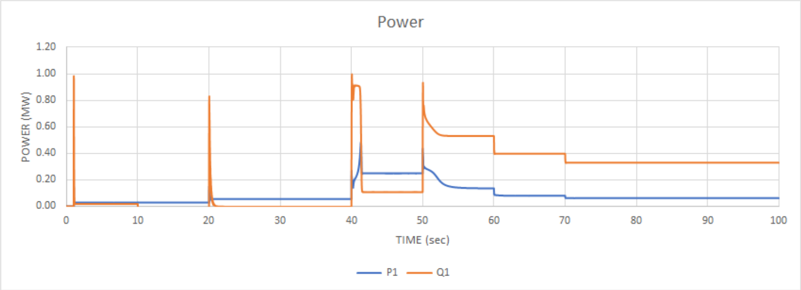
4x250 kW

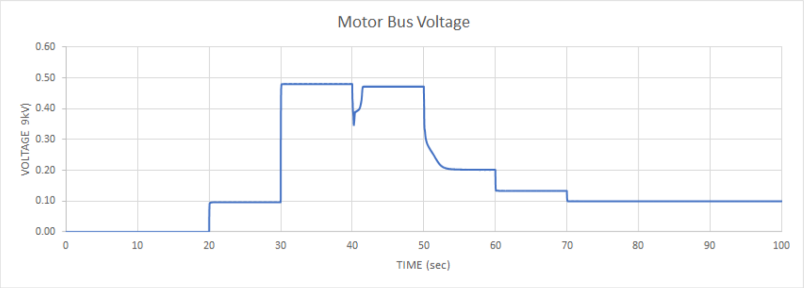


- Inverter current limit is exceeded during motor starting
- Limits capacity of motors that can be started with inverters
- Solutions:
  - Oversized inverters
  - Soft starters or VFDs for all motors

Inverters in Current limiting Mode







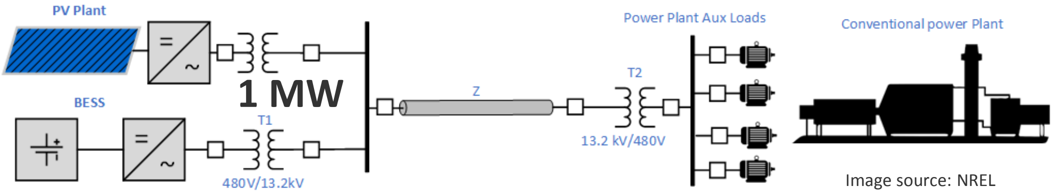
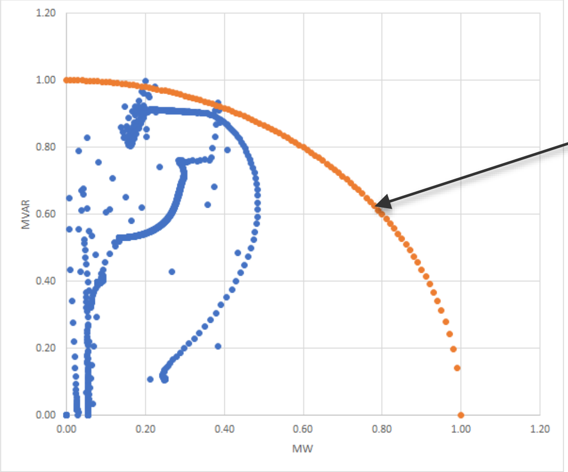


Image source: NREL

4x250 kW

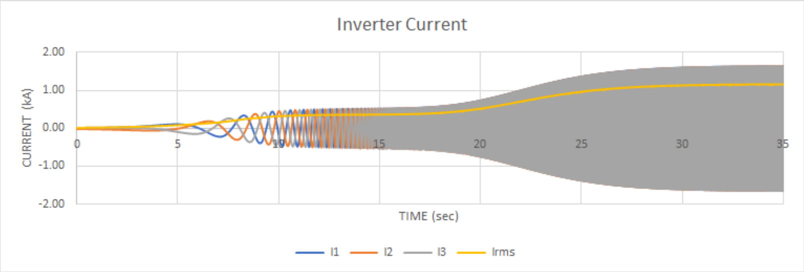


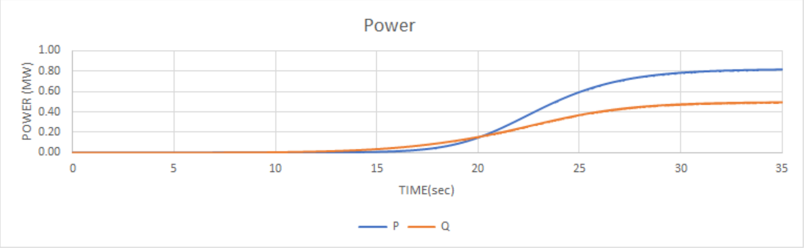
MVA limit of inverters

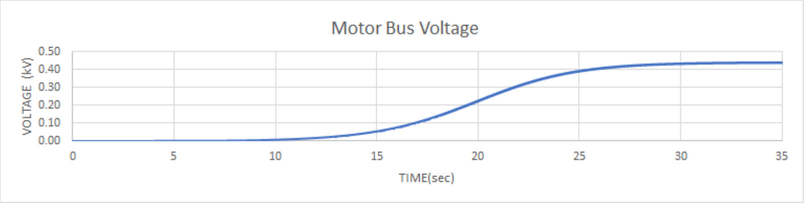
- Inverter current limit is not violated but lack of inrush current causes voltage collapse
- Motors fail to start

Constant V/Hz Soft Start

Inverters operate as VFDs with constant V/Hz ratio


Inverter Current


Power


Motor Bus Voltage

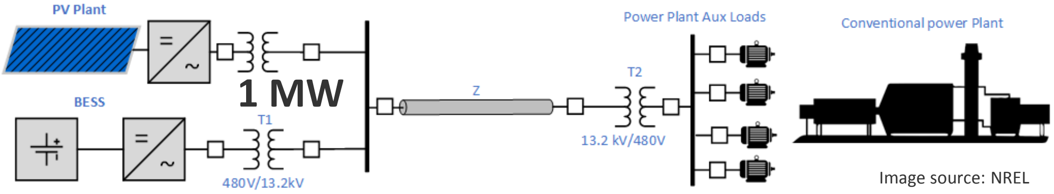
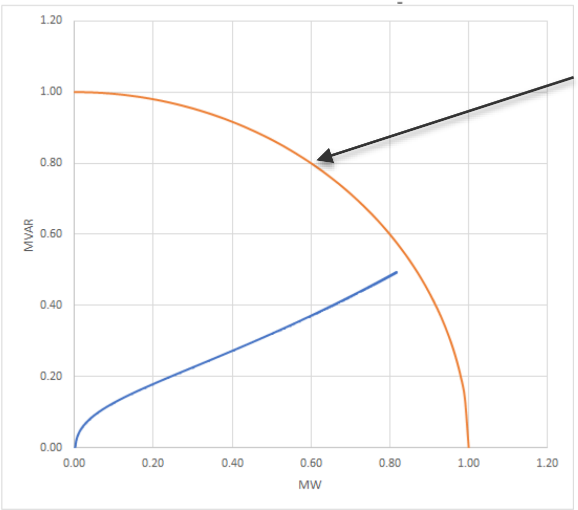


Image source: NREL

4x250 kW



MVA limit of inverters

- The whole circuit is started as a single VFD with constant V/Hz ratio
- Smooth start of all motors
- No overcurrent conditions during energizing/start up
- No need to oversize inverters

HPP / Supercapacitor Energy Storage for Improved Restoration Process

- **Black start of the feeder circuit with a fully black-start capable hydro power plant (slow governor)**
- **Supercapacitor energy storage is used to assist in frequency stabilization during system restoration**

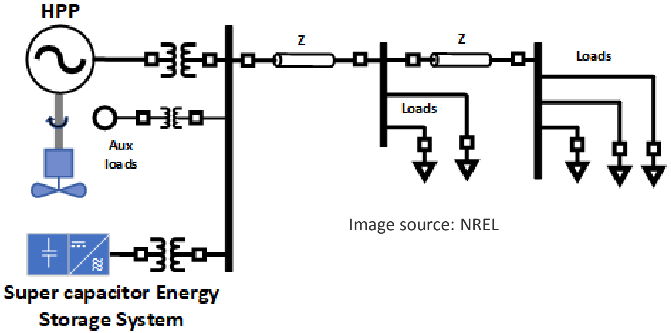
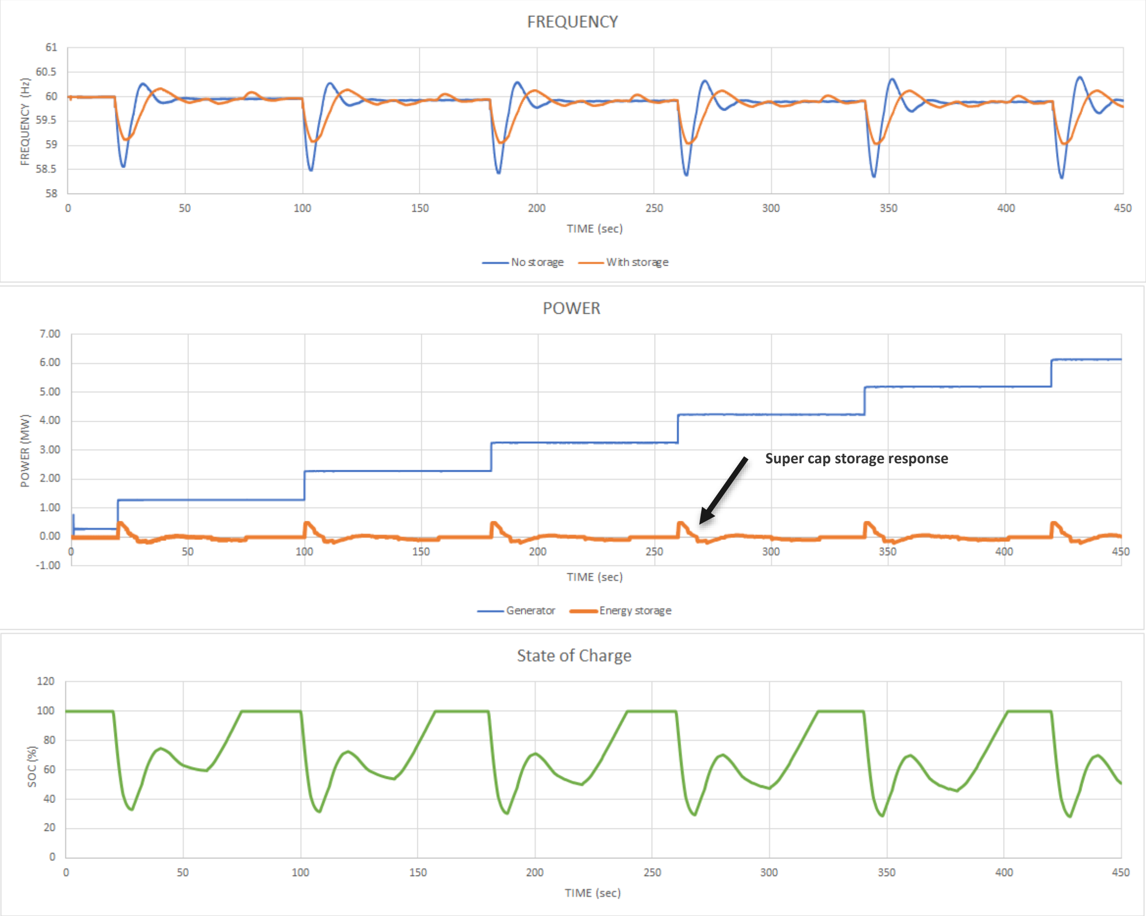


Image source: NREL

- INL-NREL project
- Industry partners:
  - Idaho Falls Power
  - Siemens
  - Maxwell



Challenges, Conclusions

- Today and future restoration strategies should align with the changing network paradigm
- Modern grid forming inverters can contribute into black start / restoration with more superior reactive power capabilities compared to conventional synchronous generators
- Inherent inverter current limit is one most important factor for black start applications

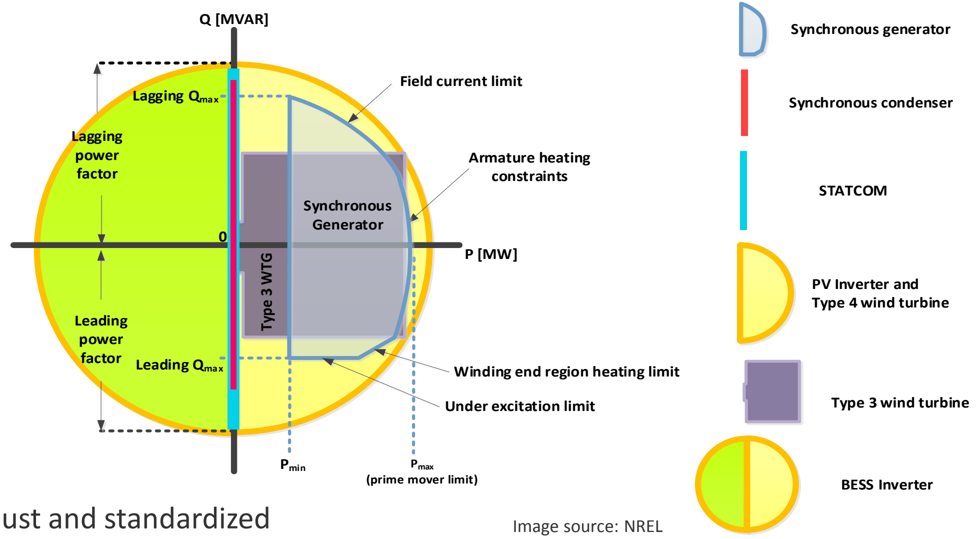
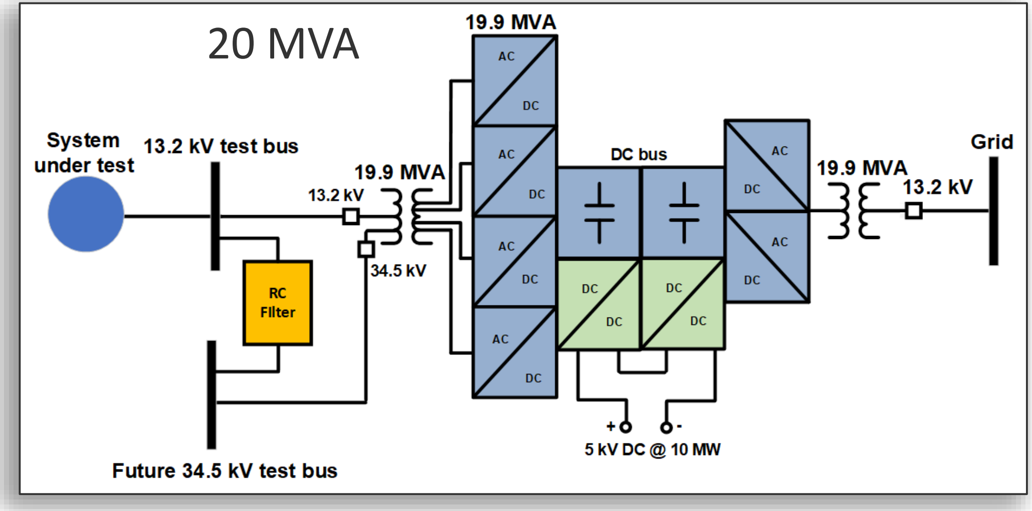


Image source: NREL

Recommendations for future studies

- Fault performance of grid forming inverters – needs to be robust and standardized
- Robust seamless transition between grid forming and grid following
- If grid forming is present, do we really need grid following anymore? If so, what shares of GM and GFL are optimal?
- Impedance characterization of grid forming inverters
- Grid stability impacts of grid forming
- Validated grid forming inverter models are needed for various renewable and storage technologies for successful black start studies
- At scale PHIL testing of black start-capable renewable resources is an important tool to discover potential issues, test mitigating solutions and validate models

Summary of CGI#2 Specifications



Power rating

- Continuous AC rating - 19.9 MVA at 13.2kV and 34.5 KV
- Overcurrent capability (x5.7 for 3 sec, x7.3 for 0.5 sec)
- 4-wire 13.2 kV or 35.4 kV taps
- Continuous operational AC voltage range: 0 - 40 kVAC
- Continuous DC rating – 10 MW at 5 kVDC

Possible test articles

- Types 1, 2, 3 and 4 wind turbines
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies / hybrid systems
- Responsive loads

Voltage control (no load THD <1%)

- Balanced and unbalanced voltage fault conditions (ZVRT, LVRT and 140% HVRT) – independent voltage control for each phase on 13.2 kV and 34.5 kV terminals
- Response time – less than 1 millisecond (from full voltage to zero, or from zero back to full voltage)
- Programmable injection of positive, negative and zero sequence components
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0-10 Hz) – SSR conditions
- Programmable impedance (strong and weak grids, wide SCR range corresponding to a POI with up to 250 MVA of short circuit apparent power)
- Injection of controlled voltage distortions
- Wide-spectrum (0-2kHz) impedance characterization of inverter-coupled generation and loads
- All-quadrant reactive power capability characterization of any system

Frequency control

- Fast output frequency control (3 Hz/sec) within 45-65 Hz range
- 50/60 Hz operation
- Can simulate frequency conditions for any type of power system
- PHIL capable (can be coupled with RTDS, Opal-RT, Typhoon, etc.)
- Coupled with PMU-based wide-area stability controls validation platform

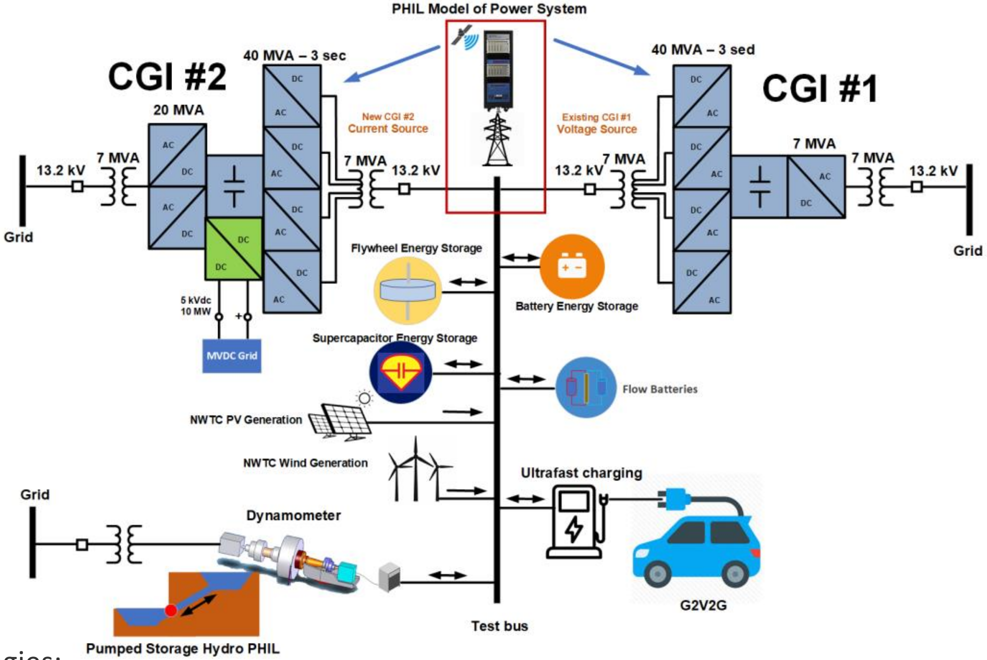
New features

- 5 kV MVDC grid simulator (PHIL capable)
- Voltage or current source operation
- Seamless transition between voltage and current source modes
- Emulation of full set of resiliency services:
    - Black start
    - Power system restoration schemes
    - Microgrids
- Flexible configurations are possible when combined with CGI#1:
    - Two independent experiments
    - Parallel operation
    - Back-to-back operation
    - Emulation of isolated, partially or fully grid-connected microgrids

Variable Generation with Storage

Ongoing PV, wind, hydro + storage projects (DOE and industry funded):

- WETO – storage to enhance APC by wind power
- GE – wind storage, hybrid wind/solar/storage
- SETO - First Solar hybrid solar PV/storage systems
- WPPTO – integrated storage with ROR hydro plants
- PG&E EPIC project – synthetic inertia, grid forming, distributed applications
- AES – DC-coupled PV-storage peaker plant



Main current areas of research for storage integration:

- Essential reliability services
- Co-optimized controls development
- Grid stability issues
- Resiliency: Grid forming/black start/microgrids
- Storage value streams

New research enabled by Flatirons Campus:

- Fundamental operational characteristics of other storage technologies:
  - SMES, Supercaps, Flywheels, BESS, Flow batteries
- Multi-POI PHIL experiments up to 20MW with CGI#1 and CGI#2 – 13.2kV, 34.5 kV
- Virtually interconnected experiments for 100s of MWs – What are the limits of scalability?
- PSH and CAES emulation using by-directional dynamometers
- Fast EV charging
- Thermal storage, hydrogen / CH4 storage
- DC and MVDC microgrids

Thank you

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