NREL CGI and PHIL Platform for Validation of Multi-Technology Energy Systems at Scale

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6th Annual International Workshop on
Grid Simulator Testing of Energy Systems and Wind Turbine Power Trains and Other Renewable Technologies

Acronyms

AC	alternating current
AES	Applied Energy Services Corp.
API	application programming interface
BESS	battery energy storage system
CGI	controllable grid interface
CHIL	control hardware in the loop
DC	direct current
DFIG	doubly fed induction generator
DUT	Device Under Test
EV	electric vehicle
F/V	frequency/voltage
FC	Flatirons Campus
FPGA	Field Programmable Gate Array
FRT	frequency ride through
Gb (or Gbit)	gigabit
GE	General Electric
GFM	Grid Forming Mode
GTAI	RTDS Analog Input Card
GTFPGA	RTDS FPGA Card
Hz	hertz
HV	high-voltage
HVRT	High Voltage Ride-through
KIUC	Kaua‘i Island Utility Cooperative
kSps	kilosamples per second
kV	kilovolt
kVDC	kilovolts direct current
kW	kilowatt
LV	low-voltage
Mbit	megabits
µs	microsecond
ms	millisecond
MW	megawatt
MWh	megawatt-hour
MVA	megavolt-ampere
MVDAS	Medium Voltage Data Acquisition System
MVIN	Medium Voltage Impedance Network
NREL	National Renewable Energy Laboratory
PC	Personal Computer
PHIL	power hardware in the loop
PMU	Phasor Measurement Unit
pu	per unit of the baseline value
PV	photovoltaics
RC	Resistive & Capacitive
RLC	Resistive, Capacitive and Inductive
RTAC	Real-time automation controller
RTDS	Real-time digital simulator
s	second
SCR	Short-circuit ratio
SEL	Schweitzer Engineering Laboratories
UDP	User Datagram Protocol
V	volt
VRT	voltage ride through

Agenda

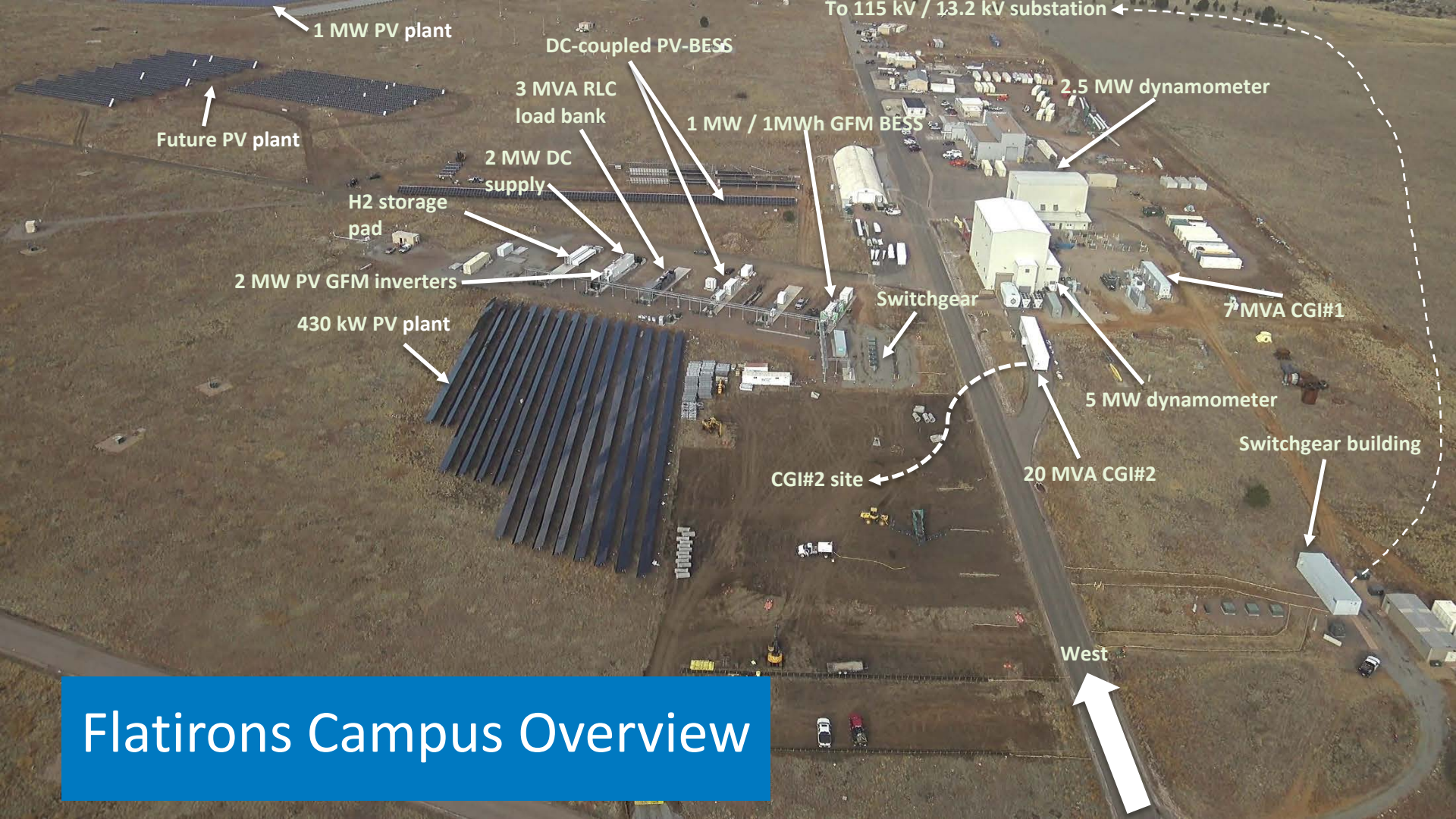
Session 3 (today):

- Status of Flatirons Campus grid integration (CGI 1 and 2, load, Synchronous condenser, BESS, GE)
- CGI#1
  - System overview
  - Recent improvements
  - Not-so-typical CGI tests

- CGI#2
  - System overview

Session 8 (tomorrow)

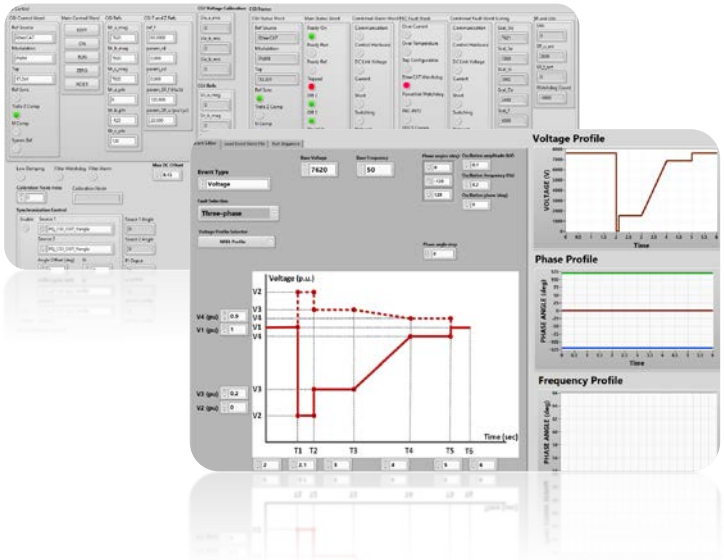
- Power hardware-in-the-loop (PHIL) considerations, virtual impedance, stability, bandwidths…

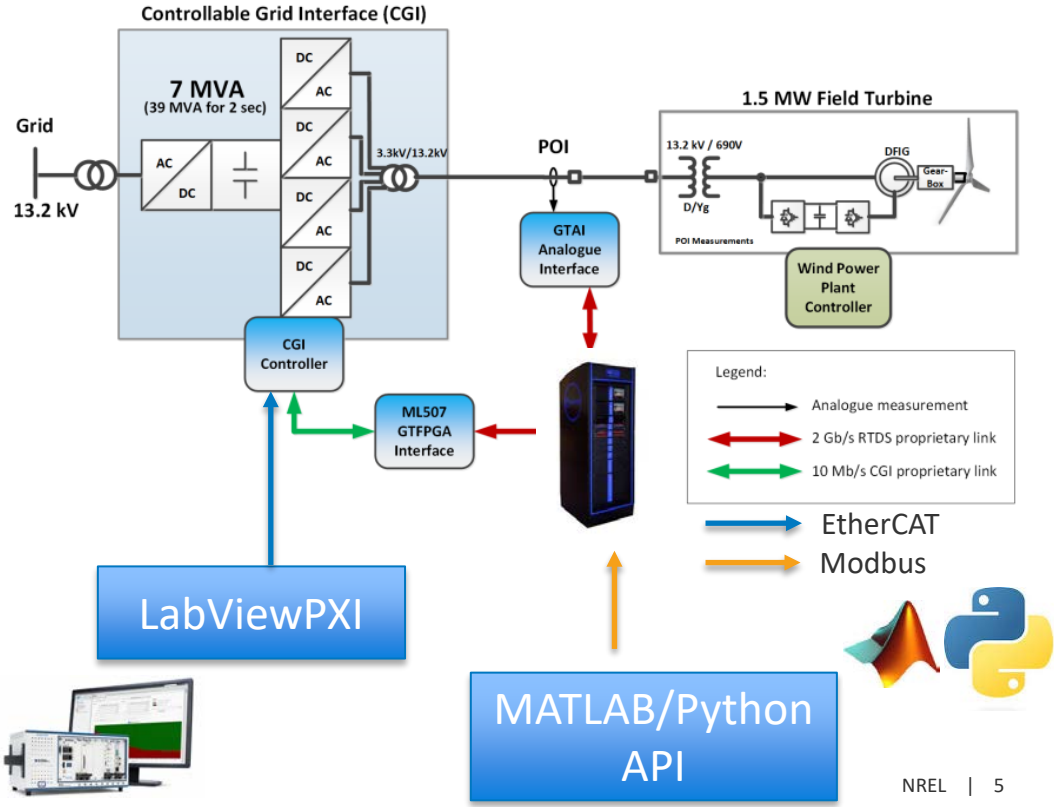


Flatirons Campus Overview

CGI#1 Control System

- LabView – primary supervisory interface
  - Limited to 1-ms sampling
- RTDS – secondary “advanced” interface
  - Uses 2-Gbit/s optical fiber translated to 10-Mbit/s fiber proprietary ABB protocol
  - 25-µs digital communication
  - 40-kSps measurements
  - 25- µs step time processing





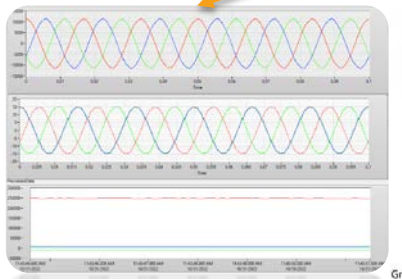
Flatirons Campus Data Acquisition

InfluxDB:
- Big data
- Continuous data acquisition
- Web data viewer

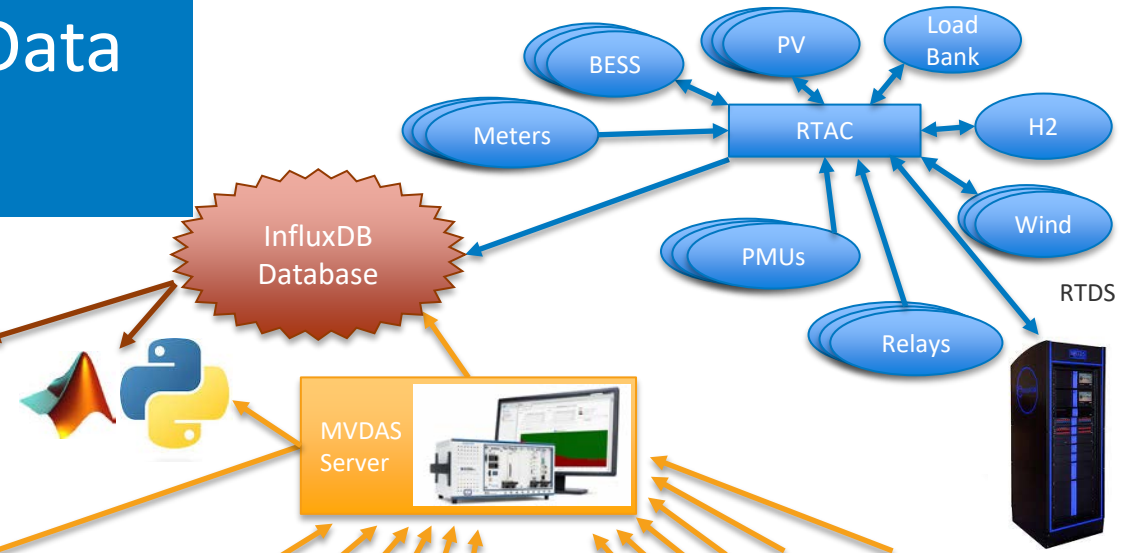
SEL RTAC:
- Controller and data concentrator
- GPS synchronized
- Up to 1 kSps, dependent on device clients

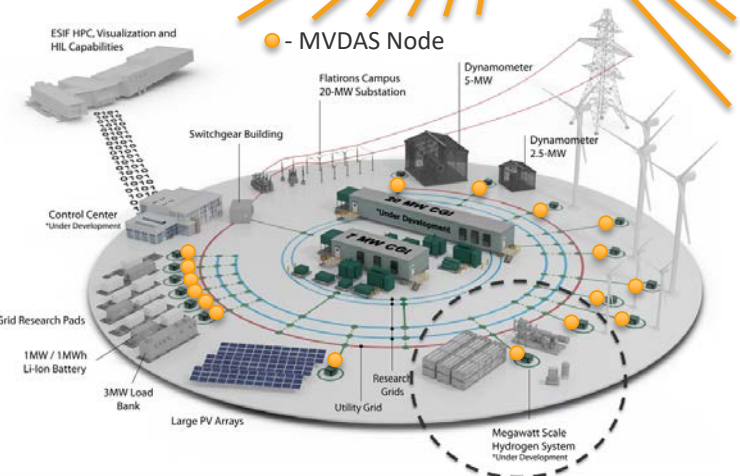
MVDAS:
- 50-kSps user configurable capture length (typical 10 s)
- GPS synchronized
- Multiple nodes observed
- Toolbox for data postprocessing and plotting developed

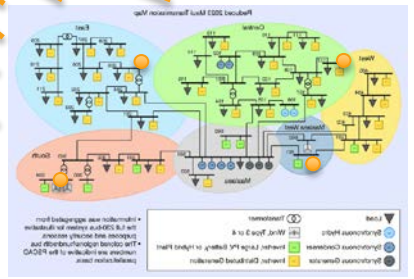
Grafana Web App



MVDAS Client



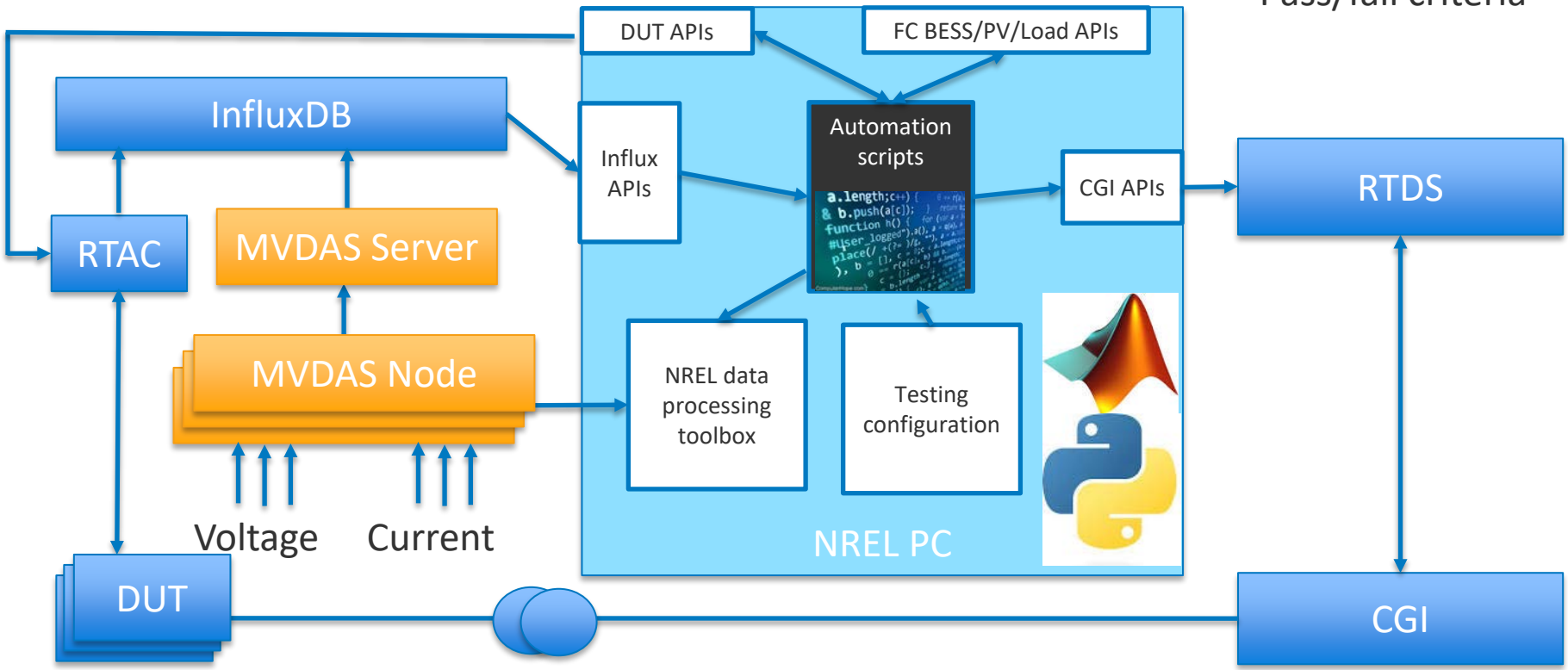




Automation

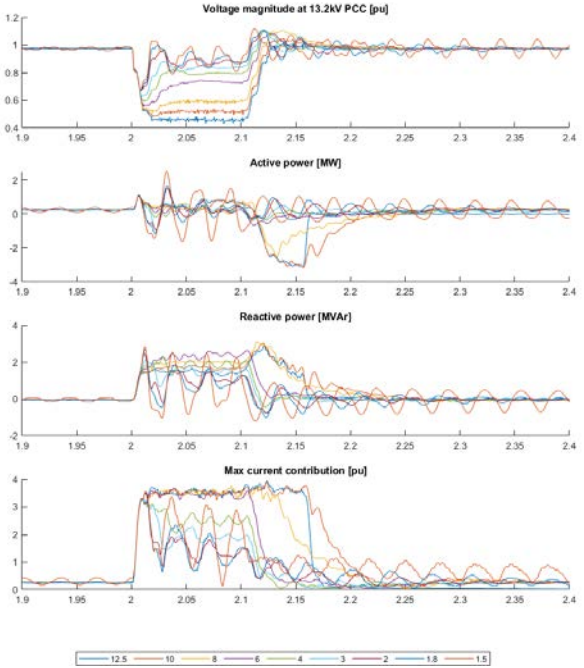
Test automation:

- MATLAB and Python
- Thousands of cases
- Pass/fail criteria



Example of Use of Test Automation

Characterization of inverters in wide range of operating points, VRT/FRT depths, SCRs, etc.

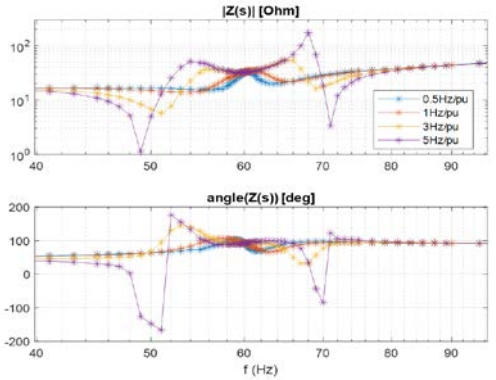


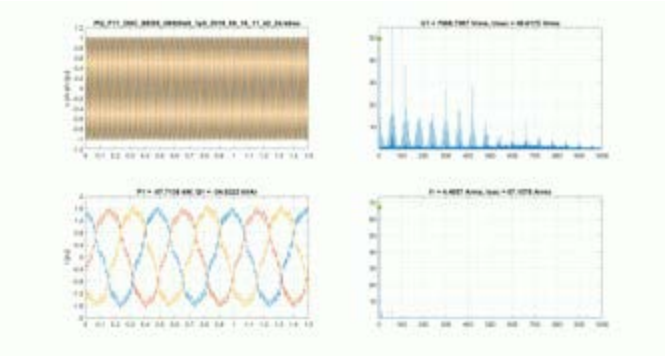
AES VRT/FRT testing with islanding for KIUC grid code

- Hundreds of tests a day – multiple reps
- Random combinations of F/V events to increase test coverage

Impedance scans

- Improved scanning times and overhead
- 3–5 s per frequency
- Parallel data processing

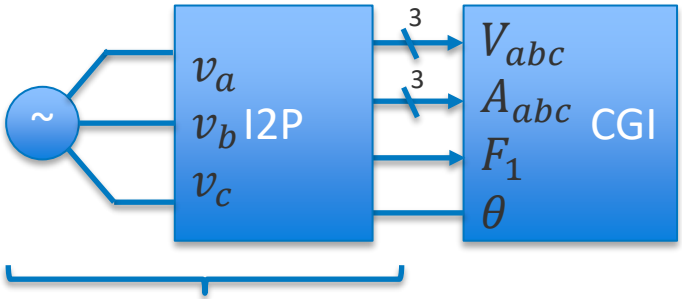




Extended F/V Range – Dynamic Vector Control

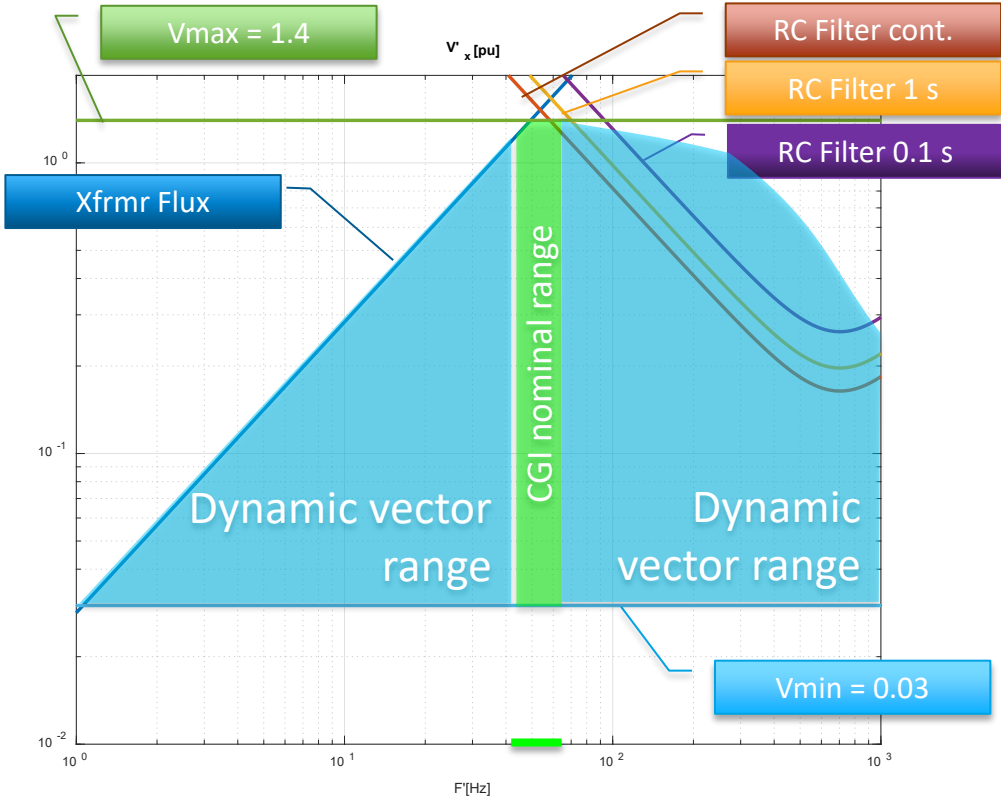
Instantaneous interface

Phasor interface



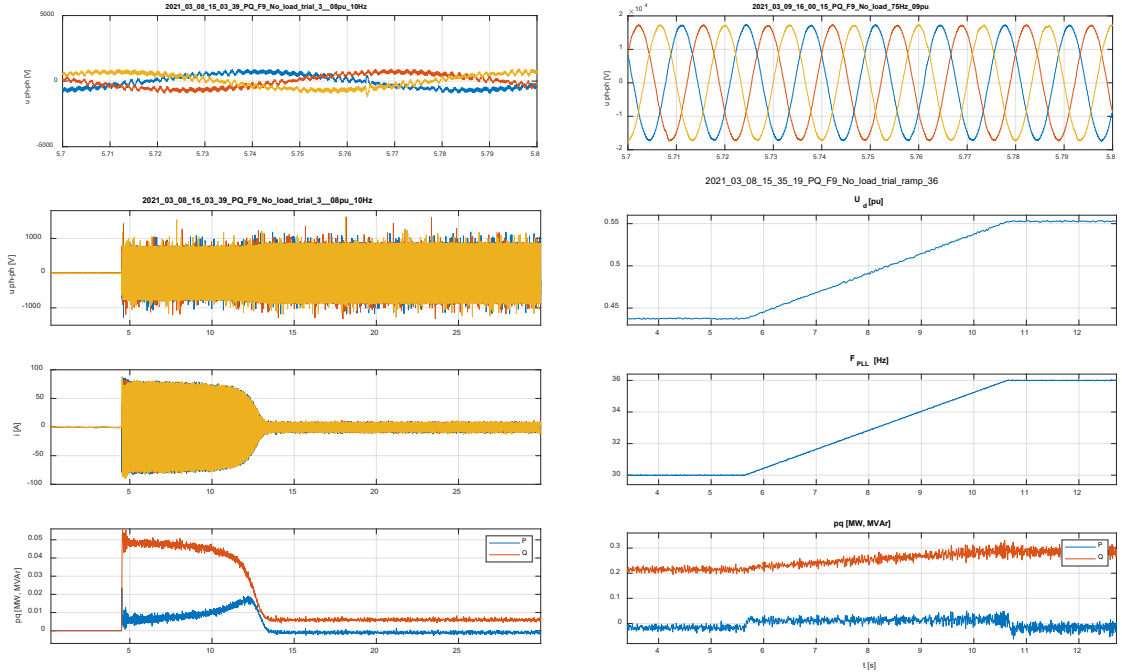
$$F' \neq F_1$$
$$V_x' \neq V_x$$

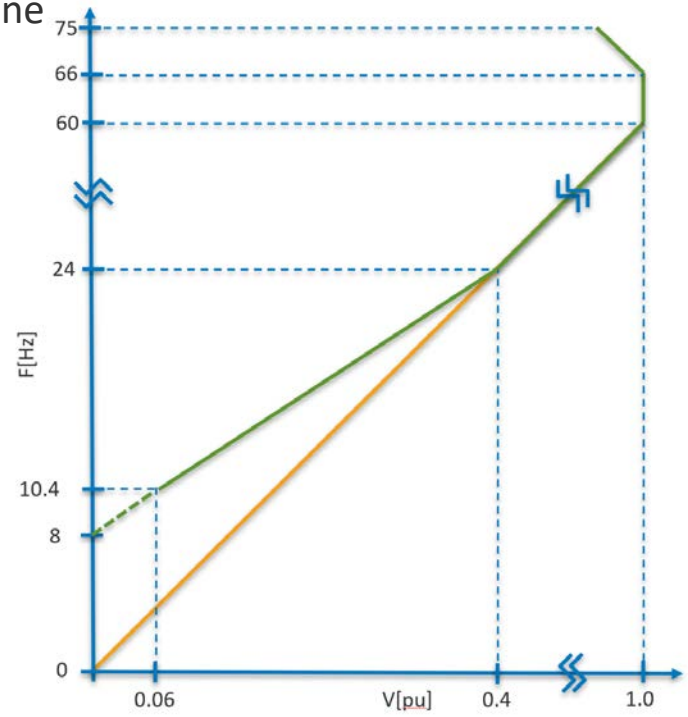
$$v_x = V_x' \cos(2\pi F' t + \theta_x')$$



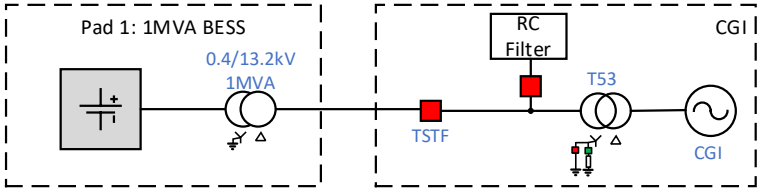
Extended F/V Range – CGI as Motor Drive

- Experiment to precisely measure winding losses of 3-MVA machine
- Wide F/V range needed: 10–75 Hz / 8%–110% voltage

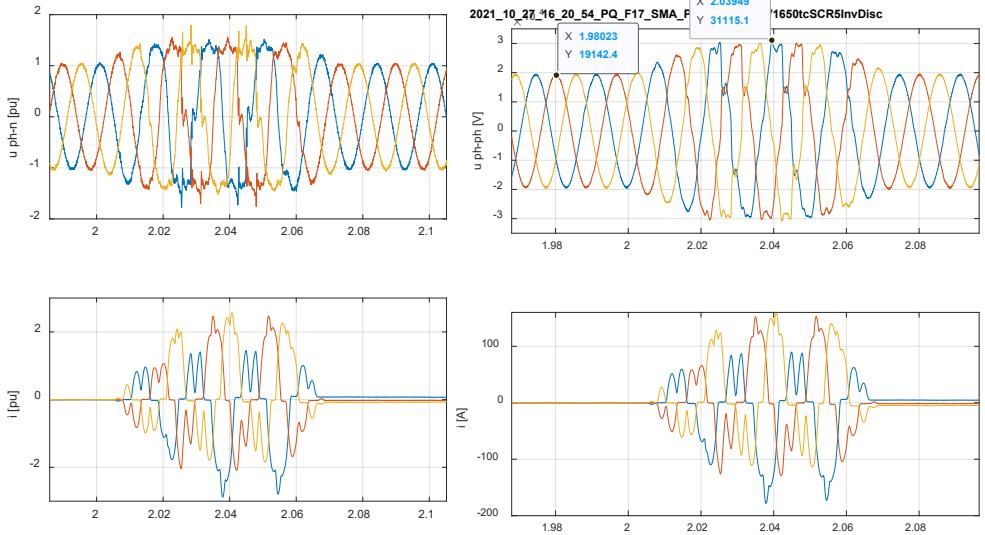


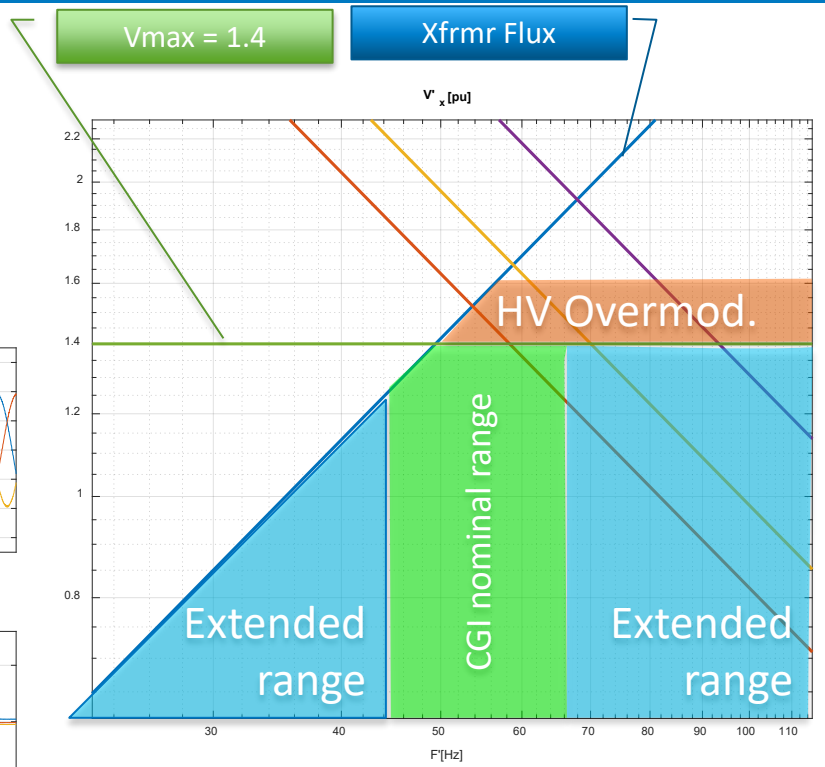


High Voltage Range Extension – Overmodulation



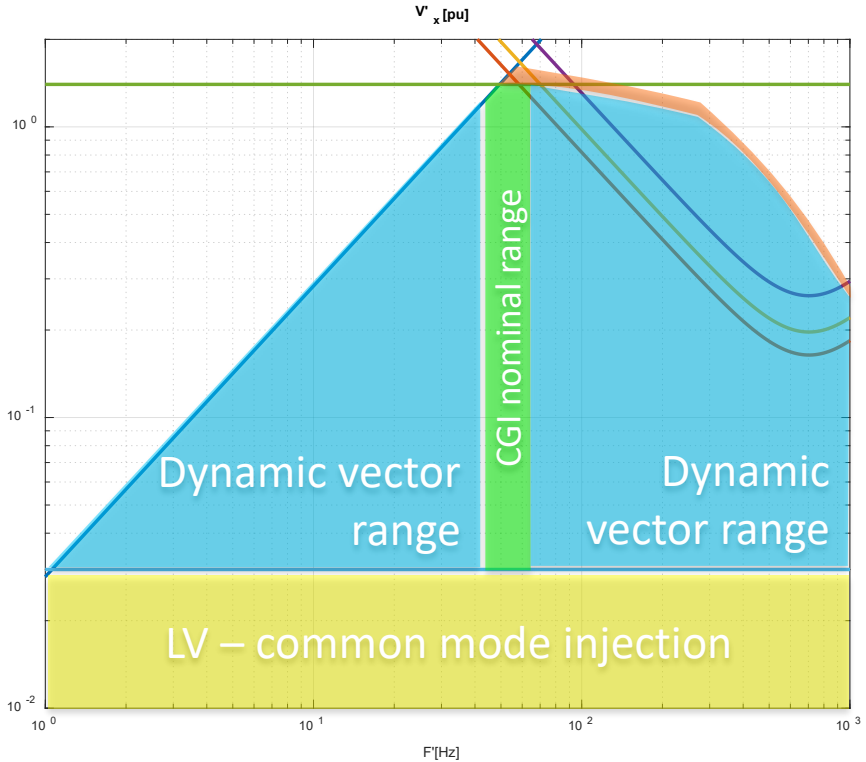
Vmax – Line to Line – 1.16*1.4 = 1.62 pu
21.3 kVrms / 30.2 kVpeak





Low Voltage Extension – Common Mode Injection

- CGI automatically adds common mode if approaching LV limit
- CGI keeps modulating down to 0.0 pu allowing
- Only enable if DUT has Delta input transformer

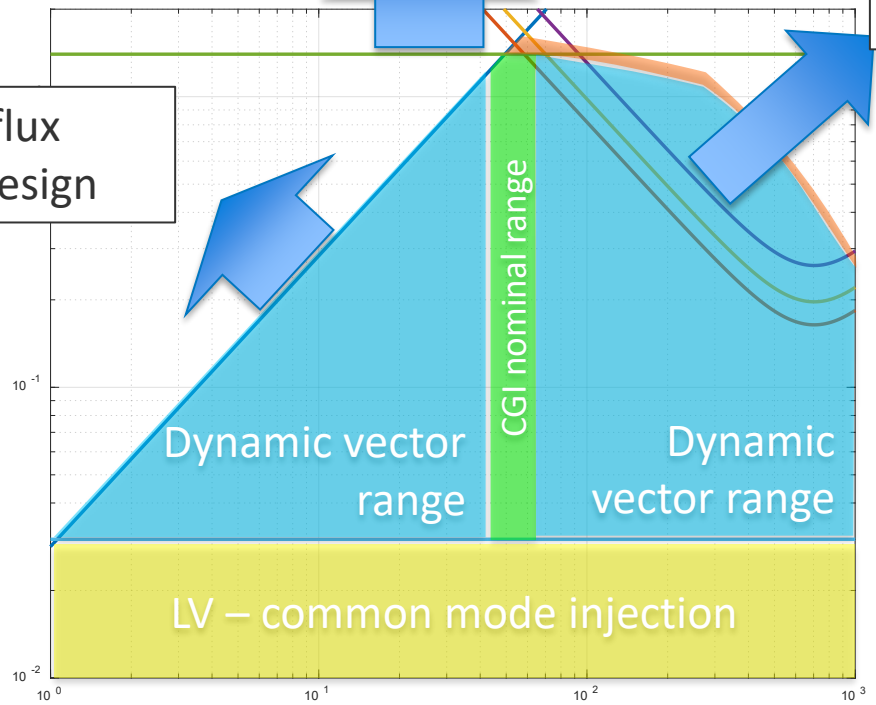


CGI2

Lower nominal modulation index Vmax: 1.4 -> 1.5

New filter design: Higher Fr

Low nominal flux transformer design



Using CGI With Other GFM Sources

CGI = Voltage Source GFM = Voltage Source

Yes, we can use CGI for them:

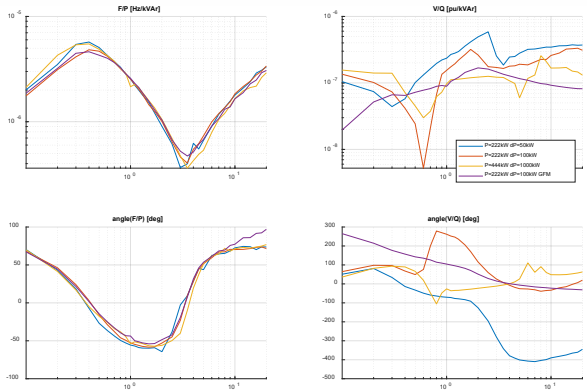
- 2 x GFM BESS systems campaigns
- 1 x GFM DFIG Wind
- 1 x GFM PV
- 1 x Sync condenser

Special case GFM that is not intended to be operating parallel to grid (e.g., backup diesel generator)

Had to add frequency droop to CGI to connect

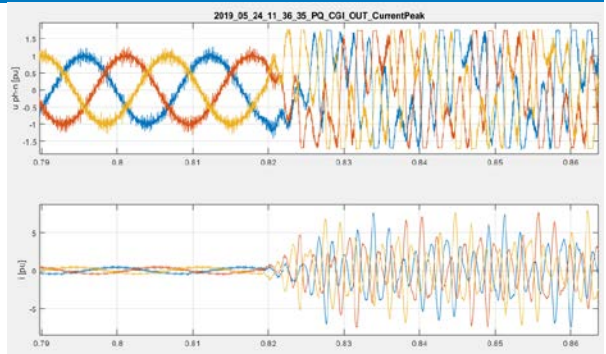
2-MW Diesel Genset

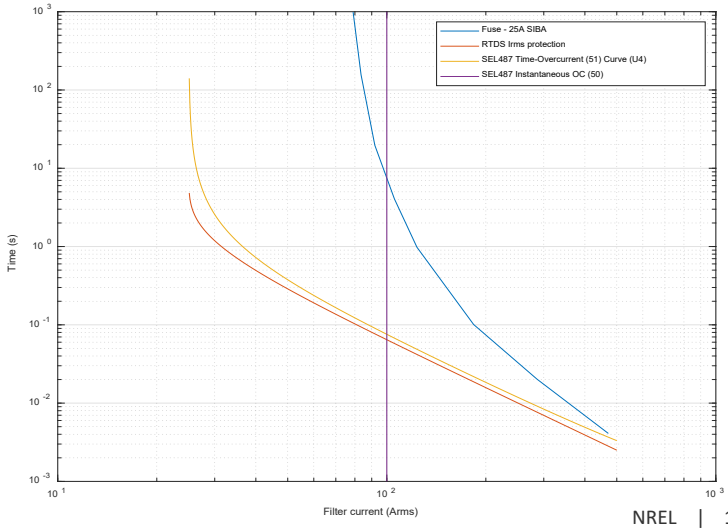
Impedance characterization:



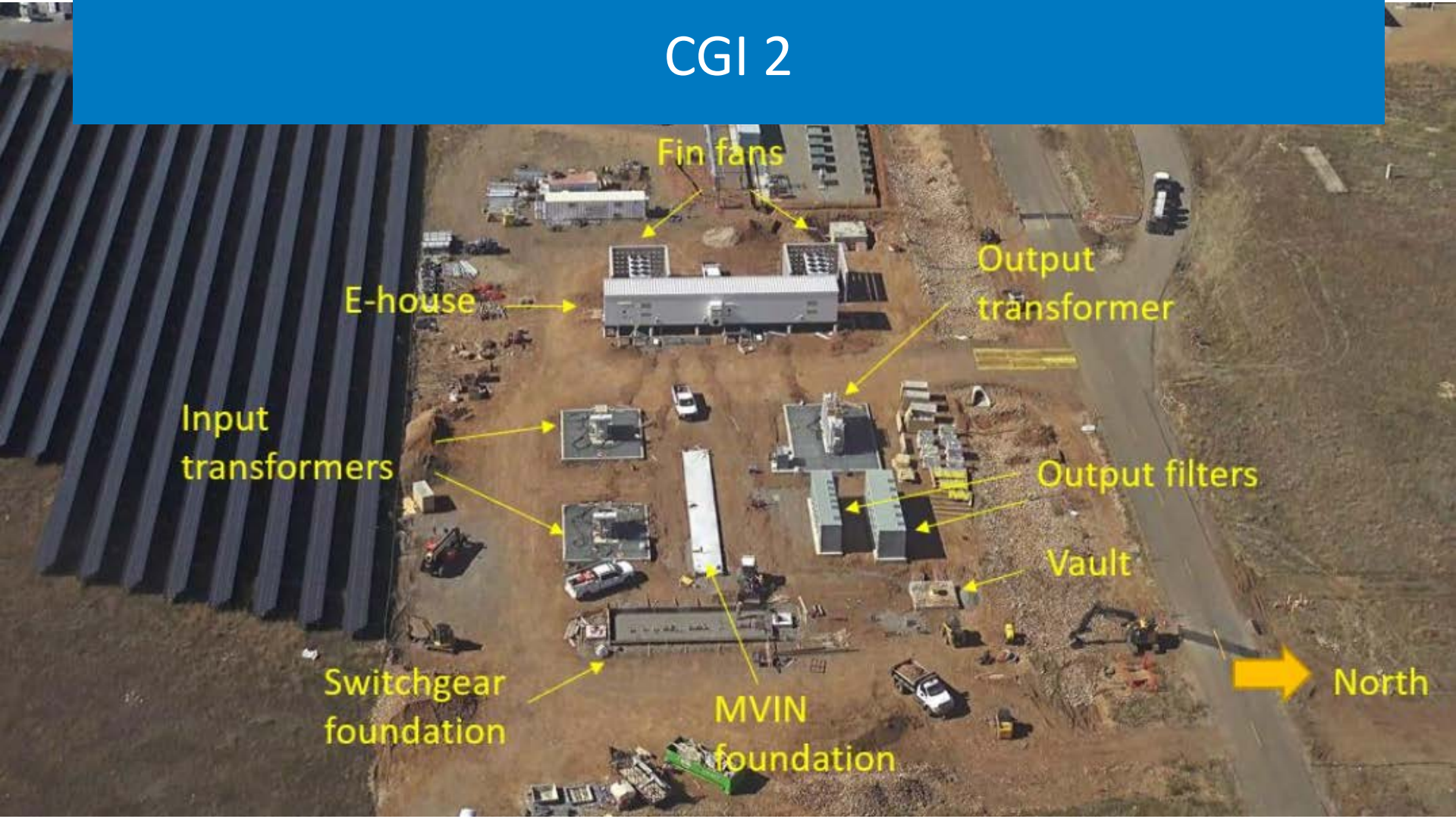
Extra Protections

- PHIL -> risk of high-frequency oscillations!
- Damaged: expensive voltage sensors, filter fuses, common mode resistor
- Protective relays don't handle high-frequency oscillations very well
- We developed our own elements in RTDS that trip CGI in <100 µs
  - 51 (time overcurrent)
  - 59 (overvoltage)





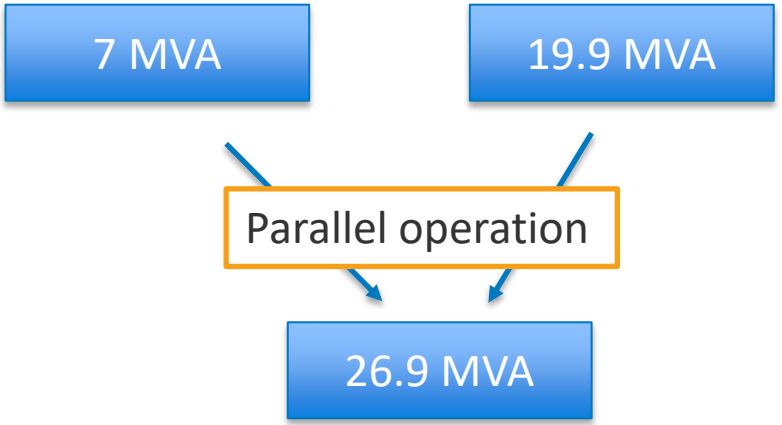
CGI 2


Fin fans
E-house
Output transformer
Input transformers
Output filters
Vault
Switchgear foundation
MVIN foundation
North

CGI2 Updates

- **Increase in power 7 MVA -> 19.9 MVA**
- Smaller nominal flux of transformer
- 34.5-kV output
- MV series impedance
- Configurable grounding
- Reduced latency
- DC output -> 5 kV @ 10 MW
- Better dynamics in active power transients
- New controller
- High-fidelity CHIL CGI#2 emulator

- Bigger DUT capacity
- Lower impedance for strong grid simulation
- Parallel operation -> 26.9 MVA



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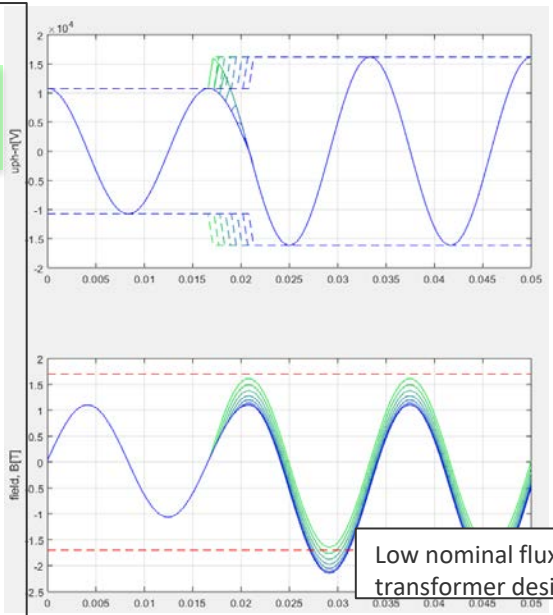
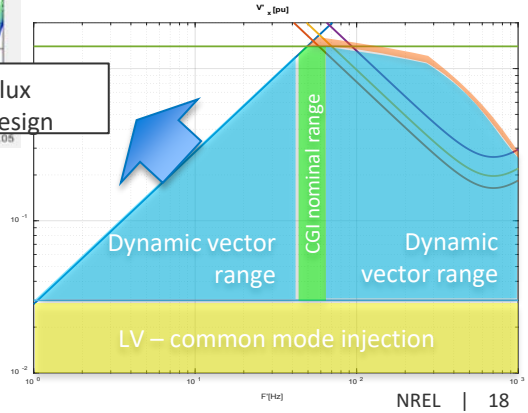


- Lower risk of saturation during HVRT
- Much lower than typical DUT transformer



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Working on 34.5-kV site infrastructure for higher power devices (e.g., tall tower wind turbines)

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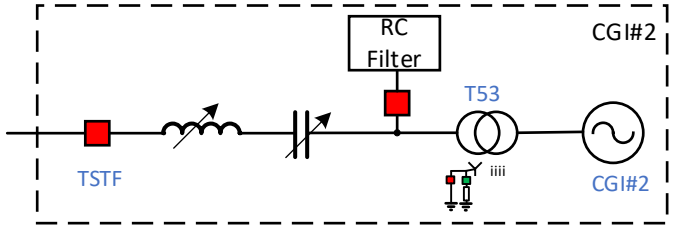
- Real inductive and capacitive series impedance
- Reducing the need for virtual impedance
- Increase of dynamic bandwidth in low SCR scenarios



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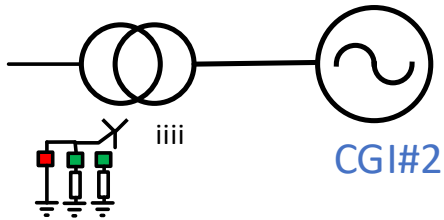
- Allows various grounding configuration studies
- Reduces common mode resonance with cables' capacitance



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CGI#1 approximate transfer function:

$$G(s) = e^{-sT_d} \frac{1-e^{-sT_s}}{sT_s} \frac{1}{\frac{s}{\omega_c}+1}$$

Transport delay
T_d = 220 µs

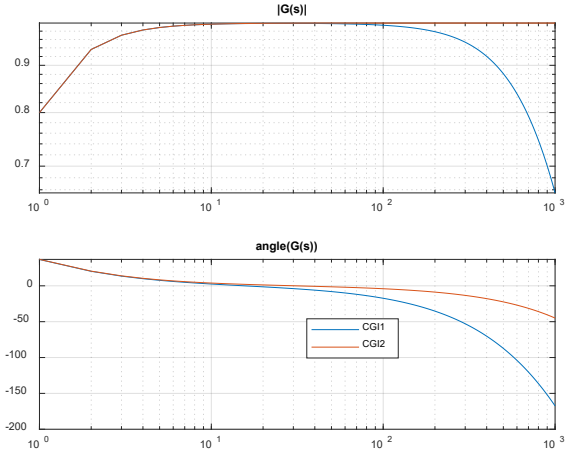
Sampling
T_S = 250 µs

Low-pass
F_c = 1 kHz

<75 µs

<200 µs (TBD)

Removed



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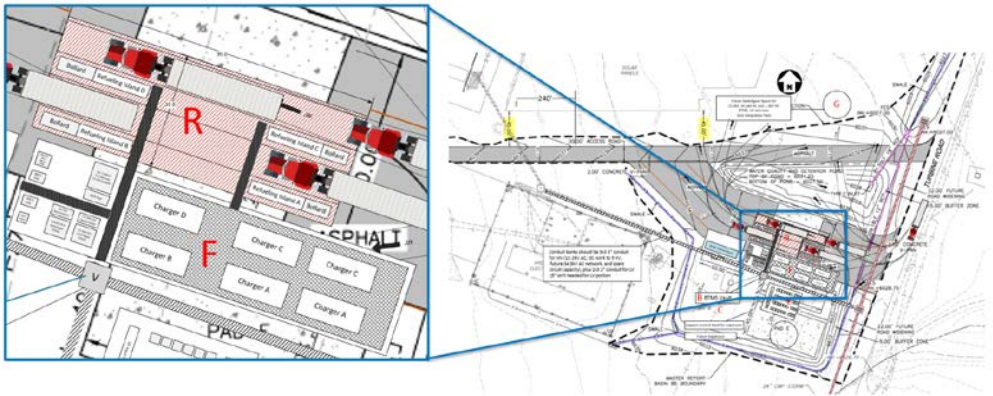
- 10-MW bidirectional DC output
- 0–5 kVDC
- 1st use case: multi-MW EV charging
  - 4 -> 1.5-kV isolation DC/DC 8-MW converter under design
  - CGI to emulate battery or charger up to 4-MW per charge port



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Improvement of CGI internal DC link control:

- More grid side inverters
- Bigger DC capacitor bank
- High power voltage limiting resistor

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Communication Protocols:
UDP, Modbus, EtherCAT, etc…

Simulink-Based Protection Scheme

CGI 2

Use Simulink HDL Coder to Generate FPGA

Speedgoat RT Target Machine

Custom Printed Circuit Board Powerlink
25 µs

Aurora 8b/10b
25 µs

Analog I/O
Digital I/O

CGI2 Controls

RTDS

OPAL RT

Typhoon HIL

Typhoon HIL

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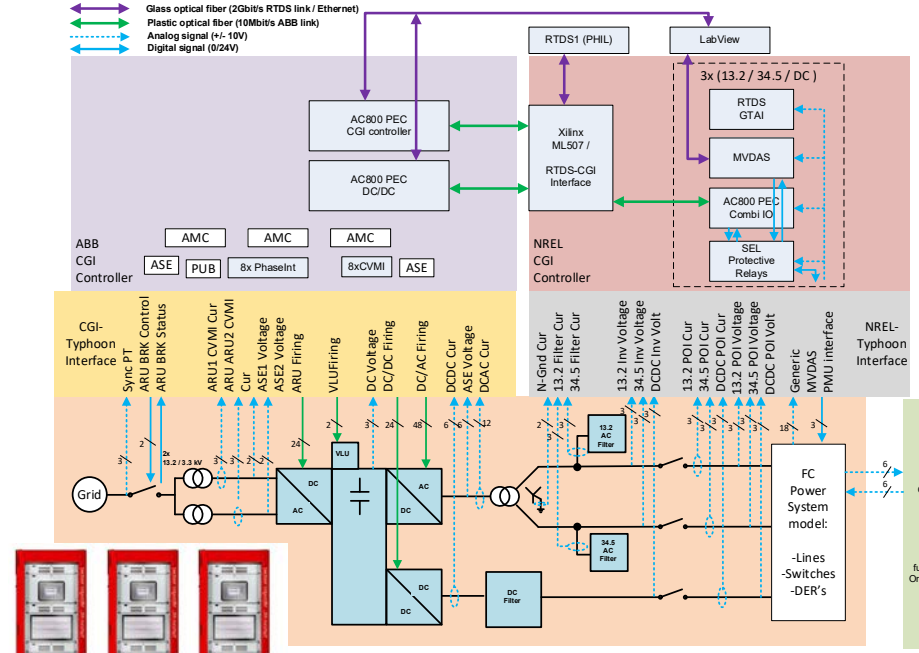
- **High-fidelity CHIL CGI#2 emulator**

- High-fidelity CHIL system for entire CGI#2 lineup
- 3x Typhoon 604
- Allow validation of new functionalities and systems integrations before power (e.g., DC/DC)



Typhoon HIL

Conclusions

- CGI#1 well-vetted platform for validation of Multi-Technology Energy Systems at Scale
- Looking forward to CGI#2 – will become a great addition to Flatirons Campus

Thank You / Q&A

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NREL/PR-5000-84716

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