Grid-Forming Inverter Modeling and Real-World Demonstration

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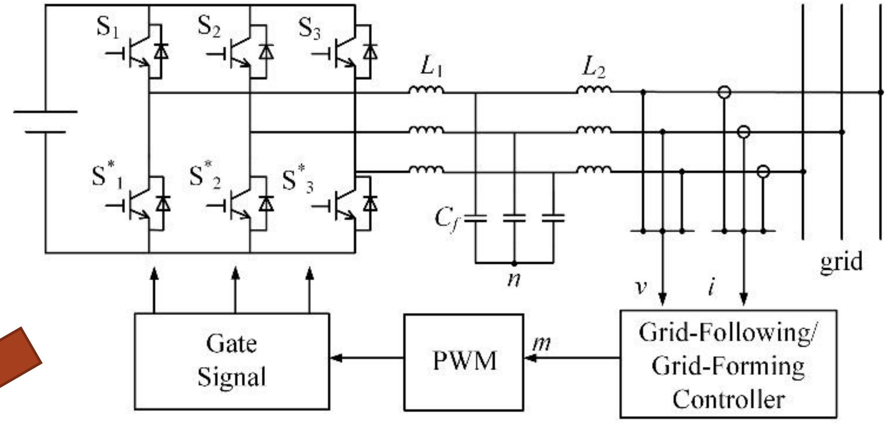
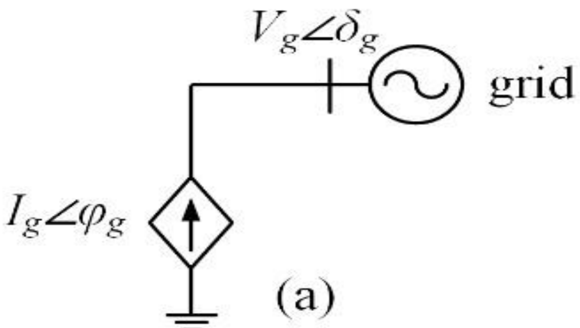
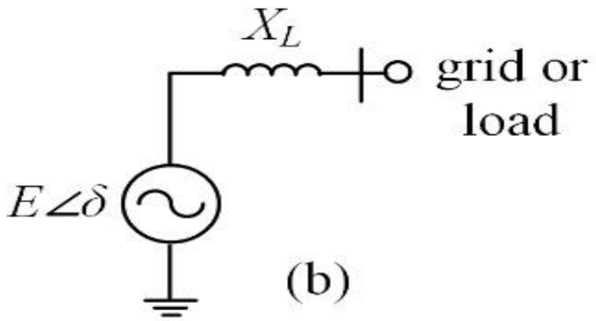
OUTLINE

- Grid-Forming and Grid-Following Concepts
- WECC-Approved Grid-Forming Inverter Model (REGFM_A1)
- Demonstration of Grid-Forming Inverter at a 380 MW Wind, Solar, and Battery Storage Combined Power Plant (led by Portland General Electric)



Voltage-Sourced Inverter





Grid-Following (Current Source)

+ Current control (e.g., PLL+ current loop)
+ Control P & Q

- Do not directly control voltage and frequency
- Cannot work without a grid

At the beginning of a small disturbance, the inverter output current is "approximately" constant, and then external controls adjust I_{ref}.

Grid-Forming (Voltage Source)

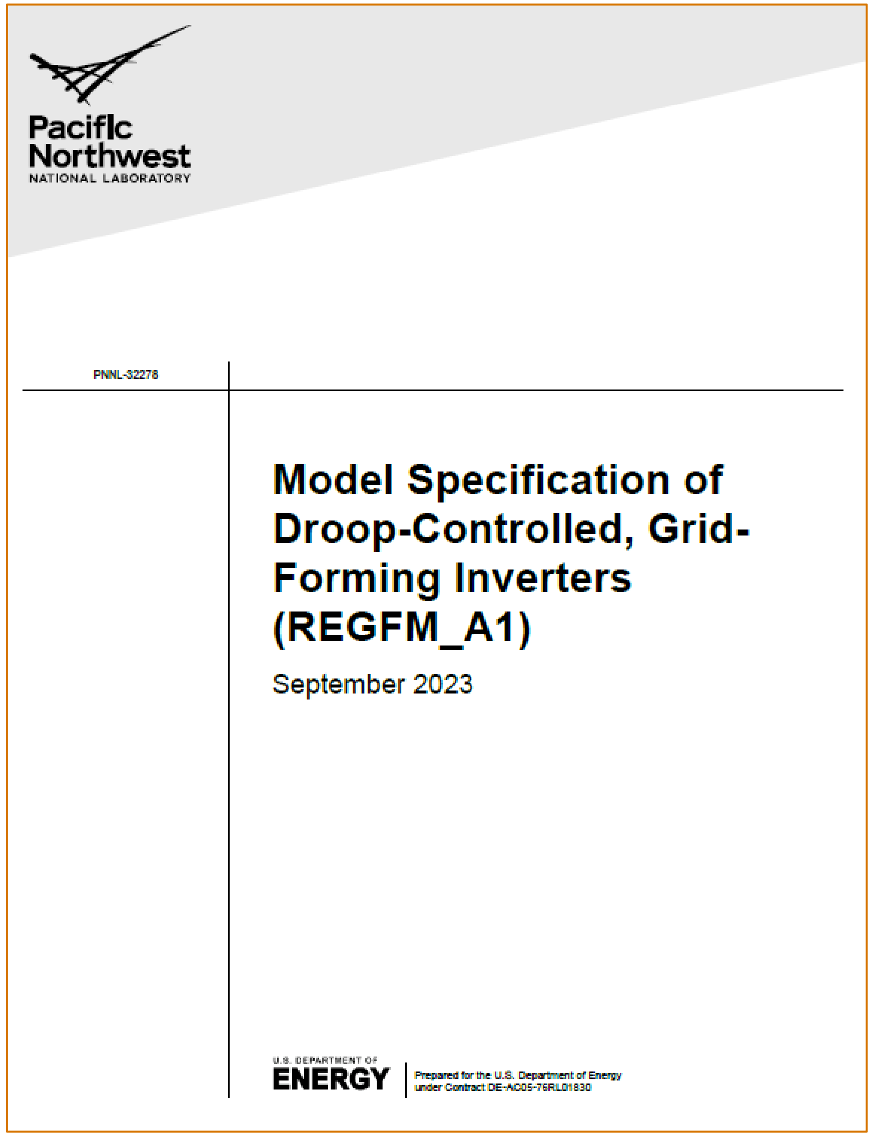
+ Direct Voltage & frequency control
+ Can work in islanded mode

- No direct control of current
- Overload/over-current Issues

At the beginning of a small disturbance, the inverter internal voltage is constant, and then external controls adjust E and δ.

WECC adopted the grid-forming inverter model (REGFM_A1) led by PNNL

- Grid-forming inverters are vital for renewables and energy storage to maintain the stability of power grids
- PNNL-developed model specification of droop-controlled, grid-forming inverters was approved by WECC
- *This is the first WECC-approved grid-forming inverter model*
- *The REGFM_A1 model has been included in the model libraries of PSS/E, PSLF, PowerWorld, and TSAT*



Pacific Northwest NATIONAL LABORATORY

PNNL-32278

Model Specification of Droop-Controlled, Grid-Forming Inverters (REGFM_A1)

September 2023

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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Twittered by Secretary of Energy Jennifer M. Granholm

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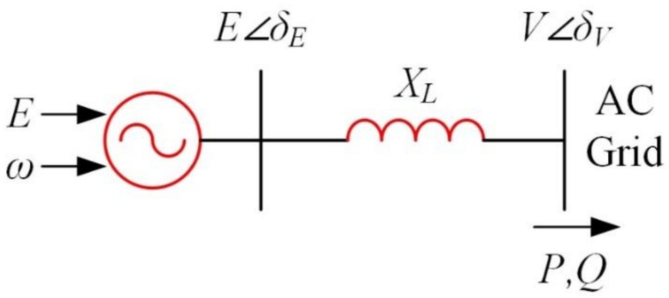
Droop-Controlled, Grid-Forming Inverters

- A grid-forming inverter behaves as a controllable voltage source behind impedance
- Two ideal voltage sources cannot be paralleled. The coupling reactance X_L is very important for controller design
  - ➢ If X_L is well designed (e.g., 5%-20%): $P \propto \delta$, $Q \propto E$

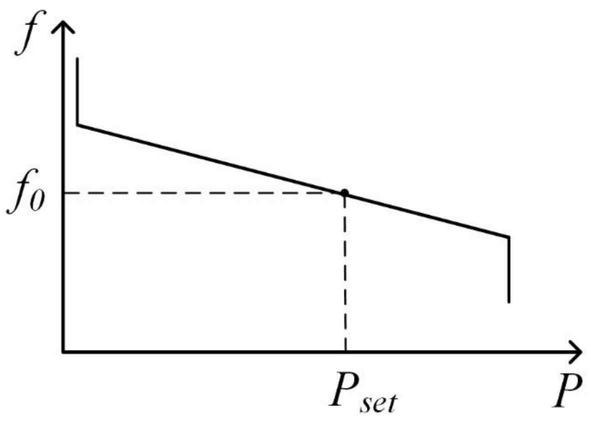


$$\delta_p = \delta_E - \delta_V$$

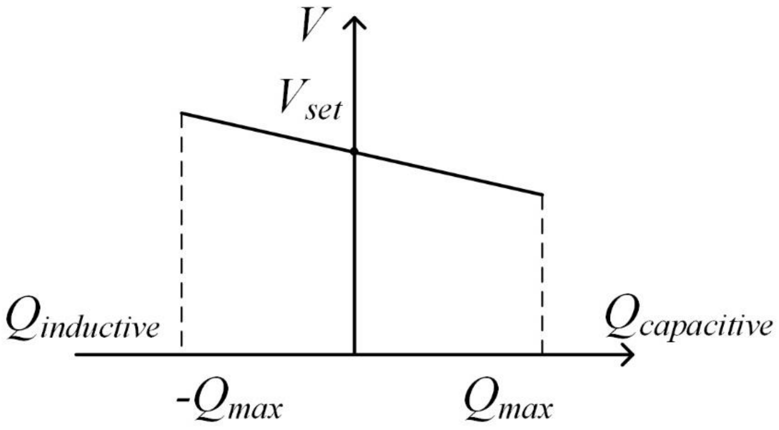
$$P = \frac{EV}{X_L}\sin\delta_p \approx \frac{EV}{X_L}\delta_p \qquad \delta_p = \int(\omega - \omega_0)dt$$

$$Q = \frac{E^2 - EV\cos\delta_p}{X_L} \approx \frac{E(E-V)}{X_L}$$

- Droop Control: Parallel multiple voltage sources in a system
  - ➢ *P* vs. *f* droop ensures the phase angles of multiple voltage sources are synchronized
  - ➢ *Q* vs. *V* droop avoids large circulating vars between voltage sources



P vs. f droop

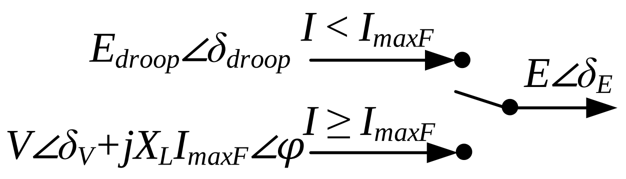


Q vs. V droop

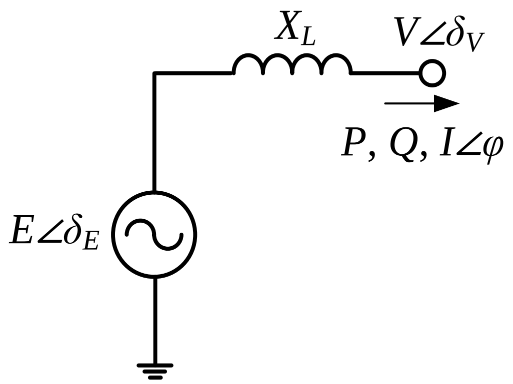
$\delta_P \uparrow \rightarrow P \uparrow \rightarrow \omega \downarrow \rightarrow \delta_P \downarrow$ (Negative feedback control)

Model Specification of a Droop-based Grid-Forming Inverter (REGFM_A1)

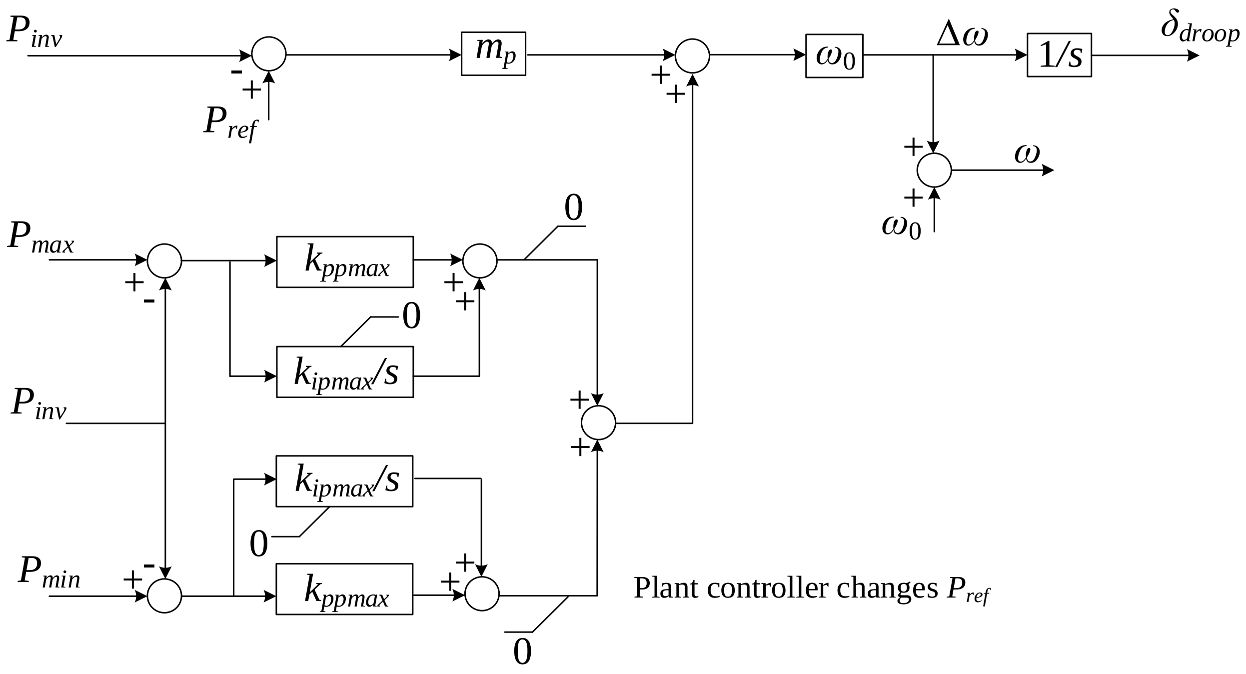
- The model includes a voltage source representation, *P-f* and *Q-V* droop controls, *P/Q* limiting controls, and a transient fault current limiting function
- Most of the control blocks came from the CERTS Microgrid Project funded by DOE
- SMA suggested to add the Q_{max}/Q_{min} control block, and the *Vflag*=0 option



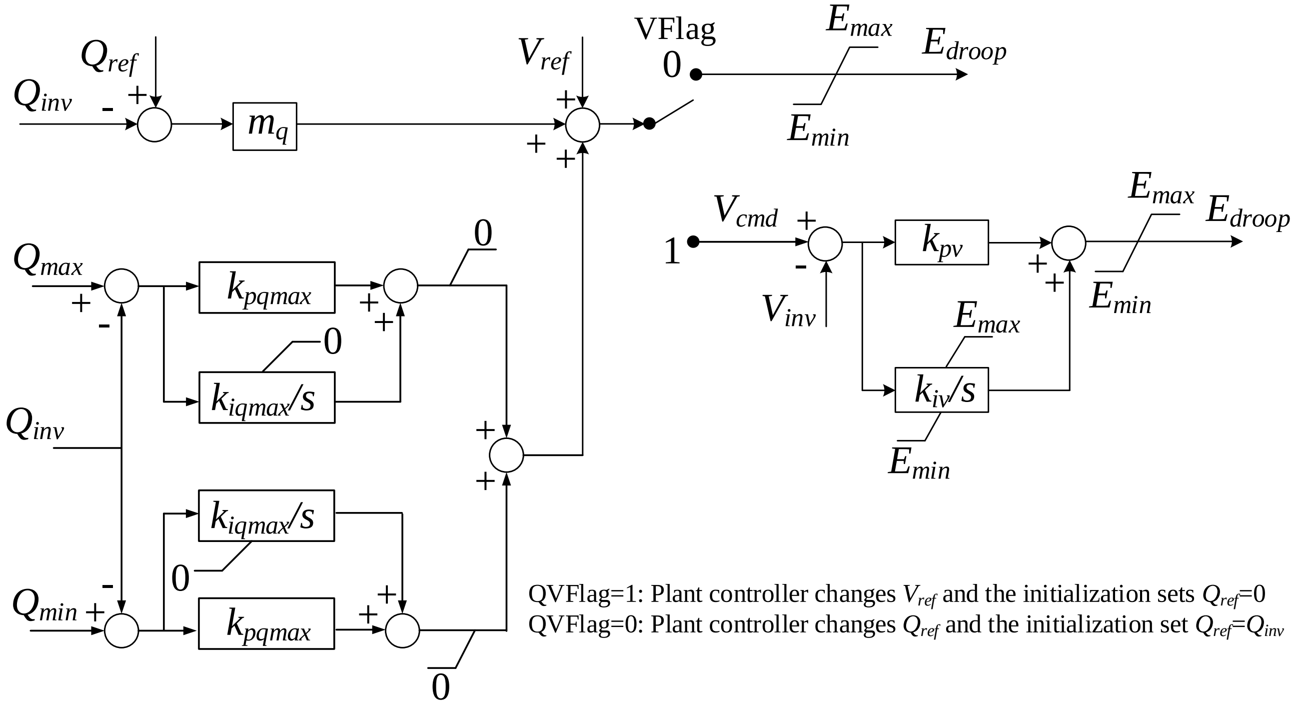
Transient fault current limiting



Voltage source behind impedance



P-f droop and P Limiting



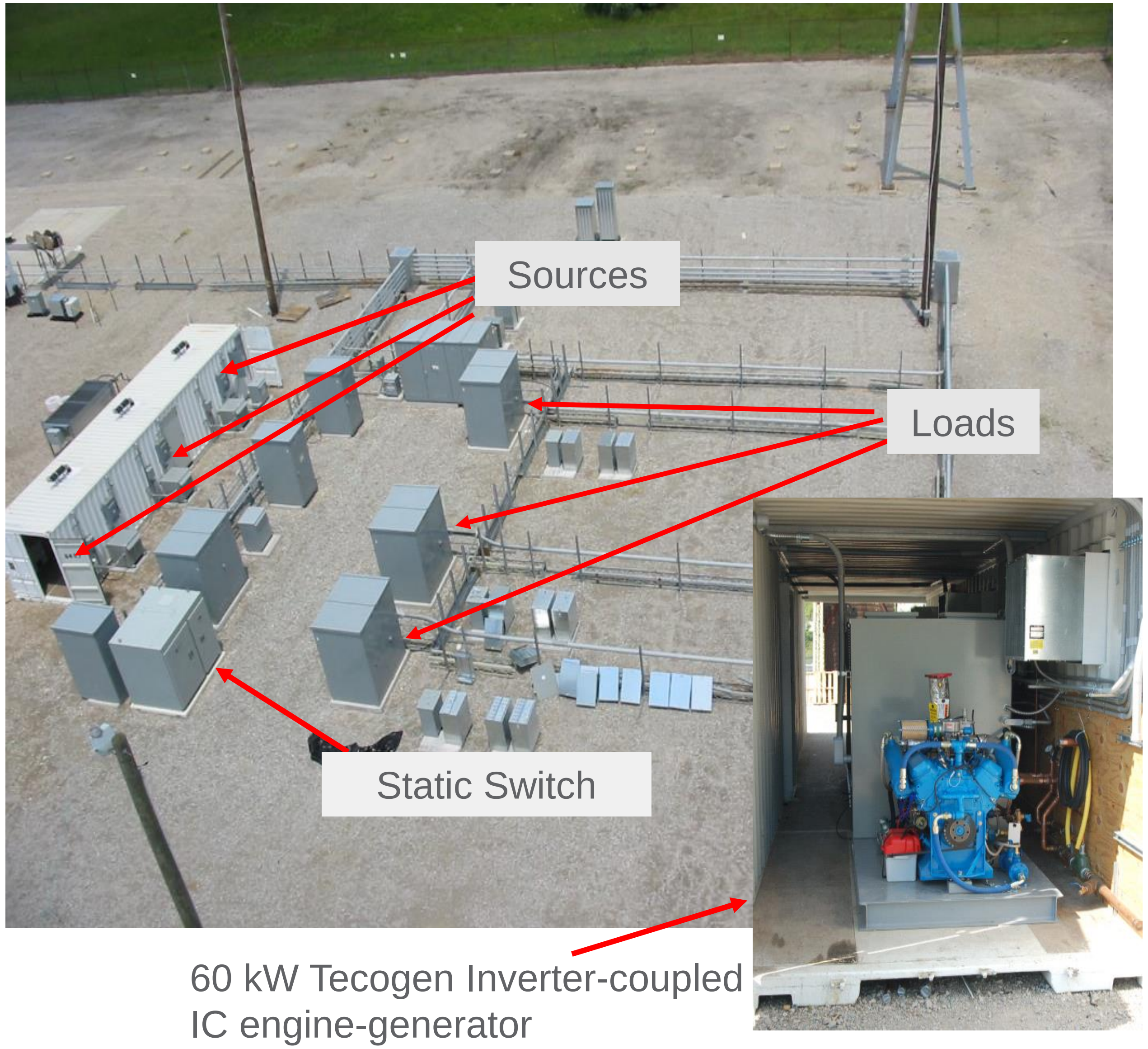
Q-V droop and Q Limiting

Model Validation against Field Test Results

CERTS/AEP Microgrid Testbed

- AEP/CERTS testbed: one of the earliest inverter-based microgrids in the world, funded by DOE
- *Principle Investigator: Prof. Bob Lasseter from University of Wisconsin-Madison*
- The CERTS Microgrid Program has been running for almost 20 years

A 100% Grid-Forming-Inverter-based testbed



60 kW Tecogen Inverter-coupled IC engine-generator

CERTS/AEP Testbed

Wisconsin Energy Institute
UNIVERSITY OF WISCONSIN–MADISON

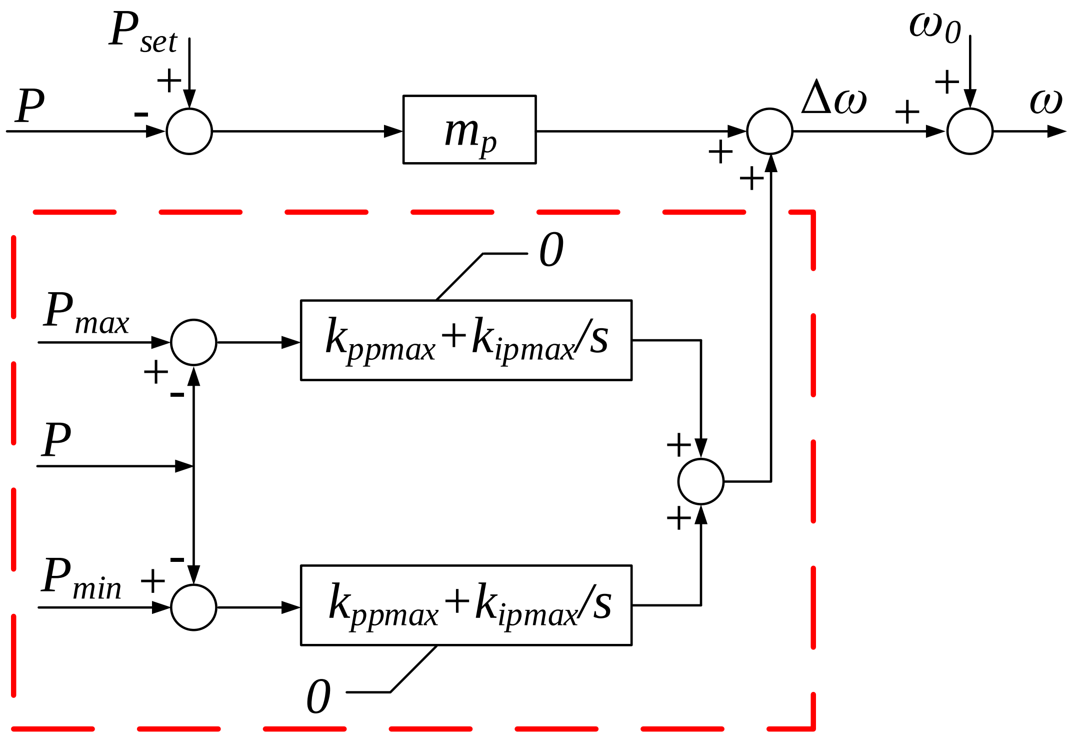
CERTS CONSORTIUM for ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

http://certs.lbl.gov/certs-der-pubs.html

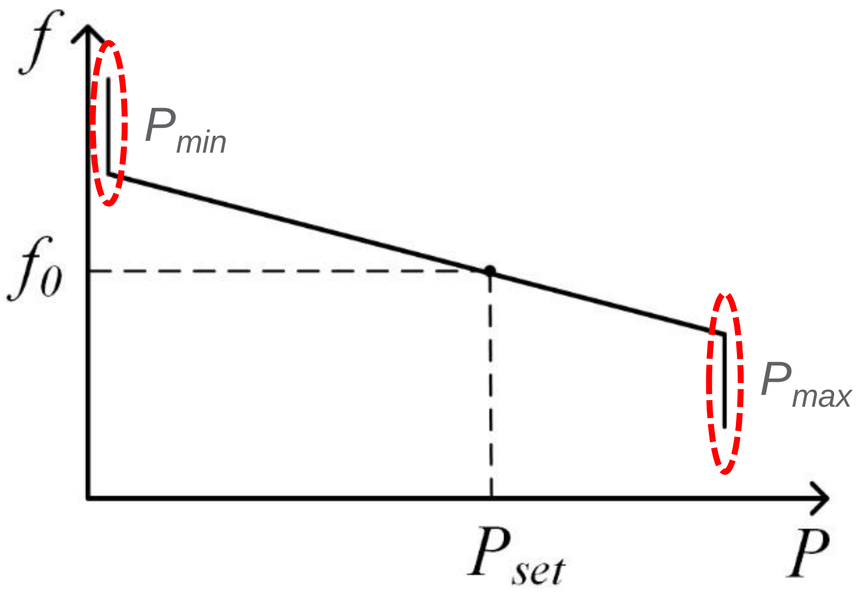
[1] Lasseter, R.H., Eto, J.H., Schenkman, B., Stevens, J., Vollkommer, H., Klapp, D., Linton, E., Hurtado, H. and Roy, J., 2010. CERTS microgrid laboratory test bed. IEEE Transactions on Power Delivery, 26(1)

Overload Issues in Microgrids and the Overload Mitigation Controller

- Grid-forming inverters can be overloaded during large step changes in loads
- CERTS Microgrid address the overload issue by actively controlling the inverter' frequency
- When some of the inverters are overloaded: Overload Transfer
- When all the inverters are overloaded: Under Frequency Load Shedding



Overload Mitigation Controller

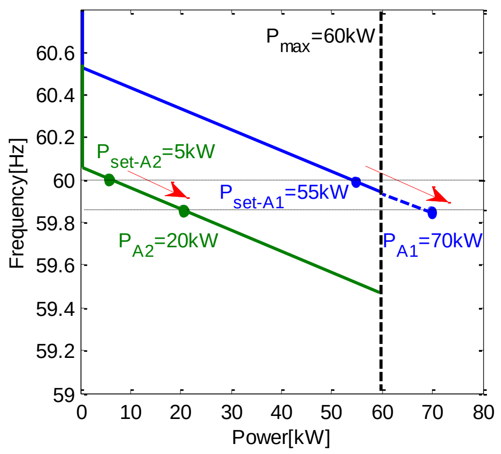


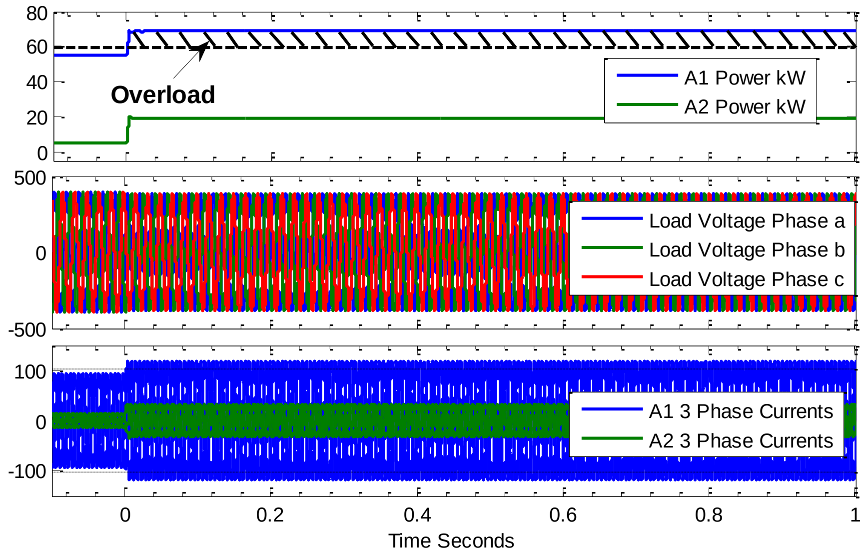
P-f droop

Function 1: When Some of the Inverters are Overloaded (*Overload transfer*)

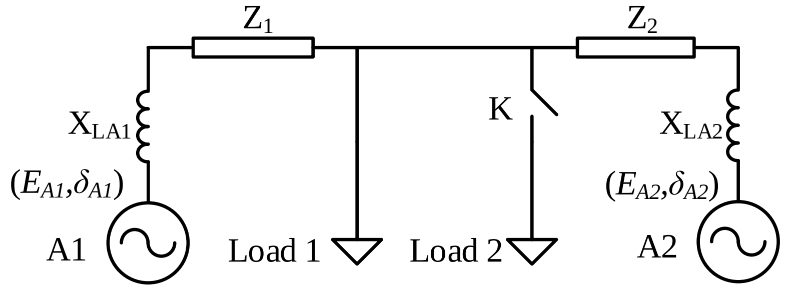
- When one grid-forming inverter is dispatched near its maximum generation, a load step can result in overload
  - Overload can collapse the dc bus of inverters, stall the synchronous generators, etc.

Without P_{max} Controller





Without P_{max} Controller



A Two-Source System

Function 1: When Some of the Inverters are Overloaded (*Overload transfer*)

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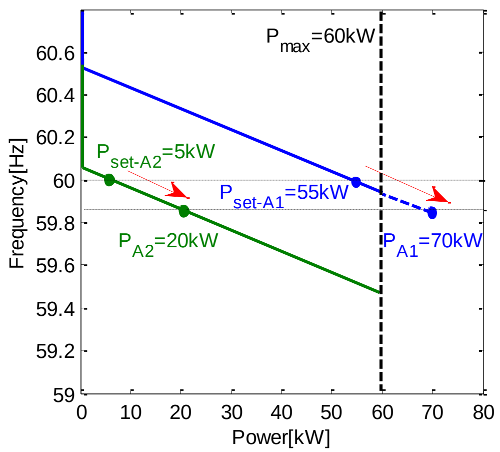
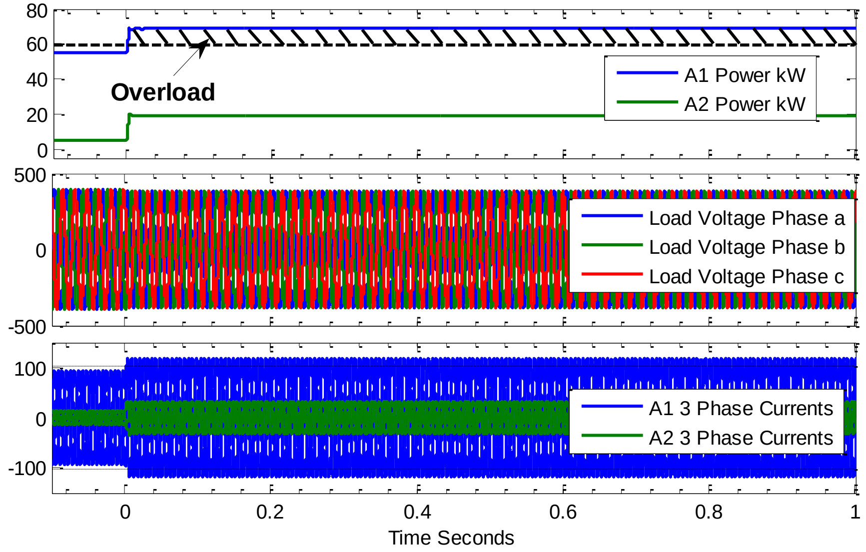
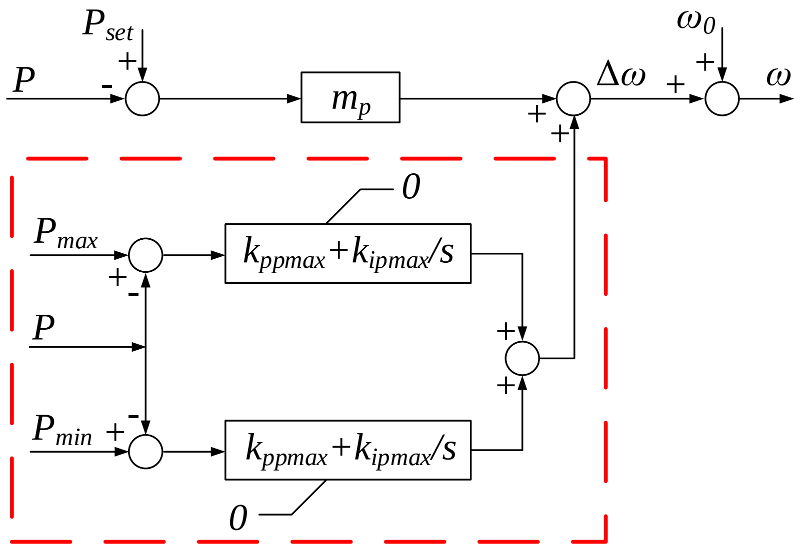
Without P_{max} Controller

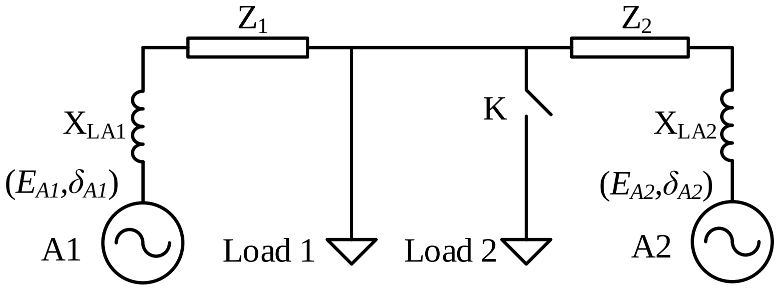




Without P_{max} Controller



Overload Mitigation Controller:
Change the phase angle between sources: $\Delta\delta$

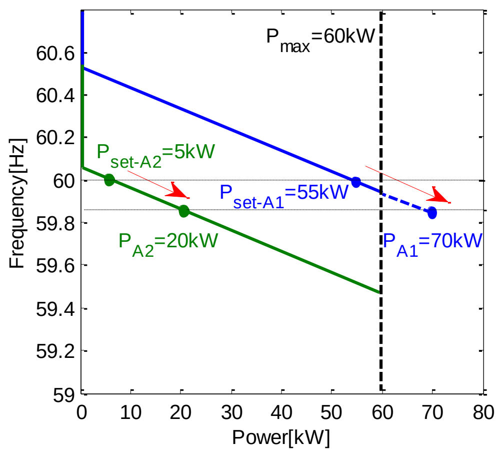


A Two-Source System

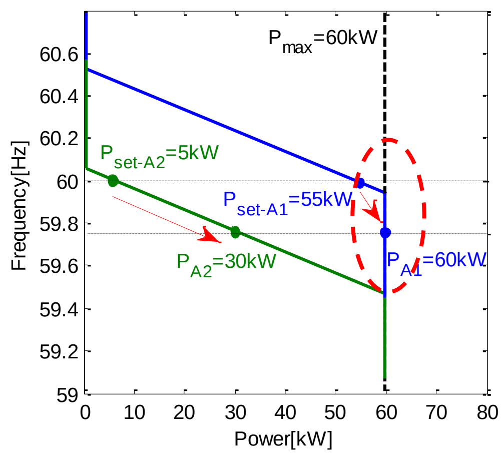
Function 1: When Some of the Inverters are Overloaded (*Overload transfer*)

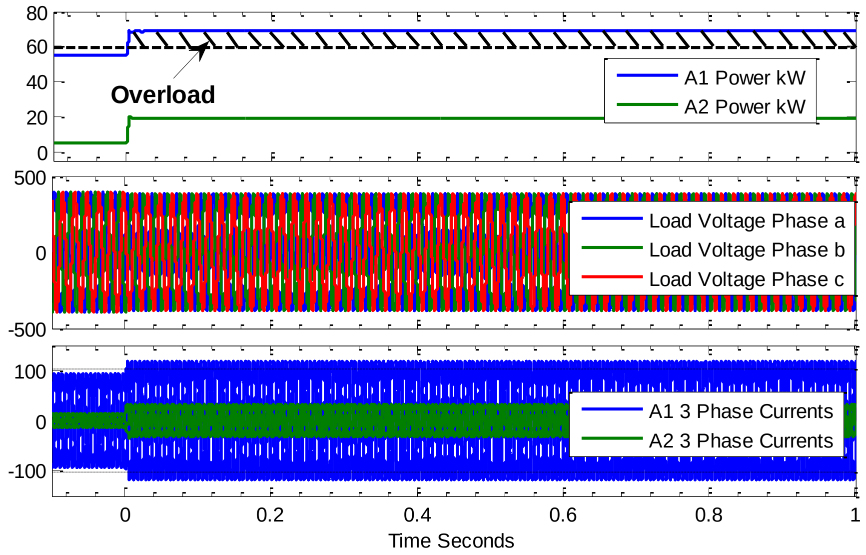
- Transfer the extra load to non-overloaded sources by reducing the frequency rapidly
- The change of phase angle redistributes power flow between inverters

Without P_{max} Controller

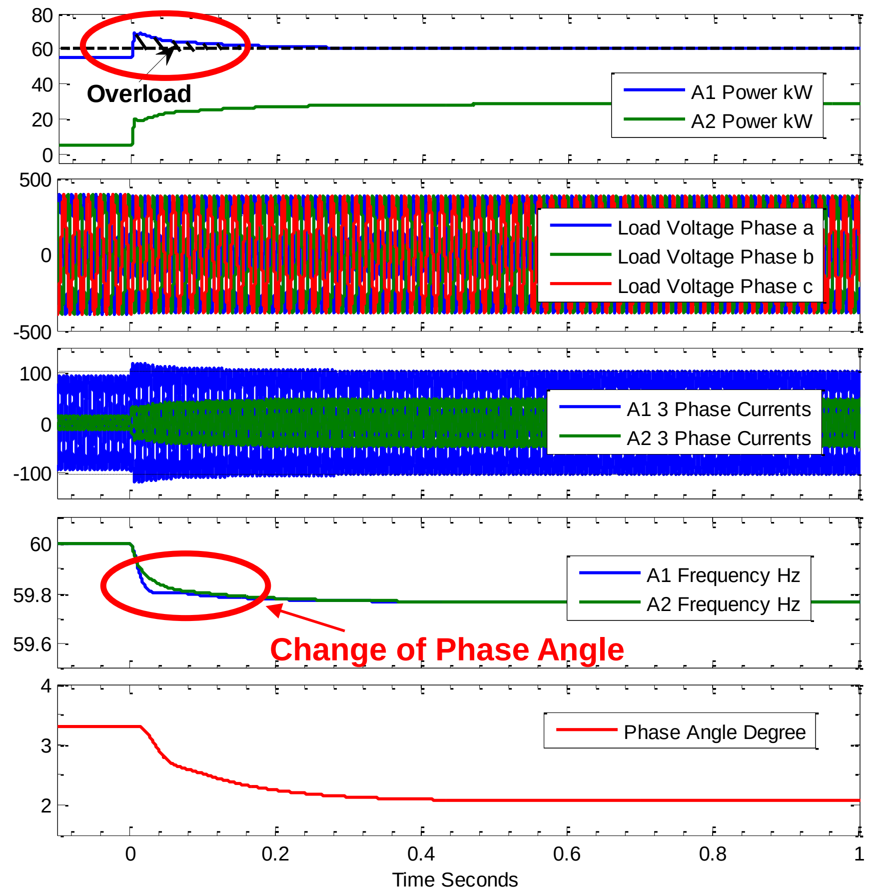


With P_{max} Controller

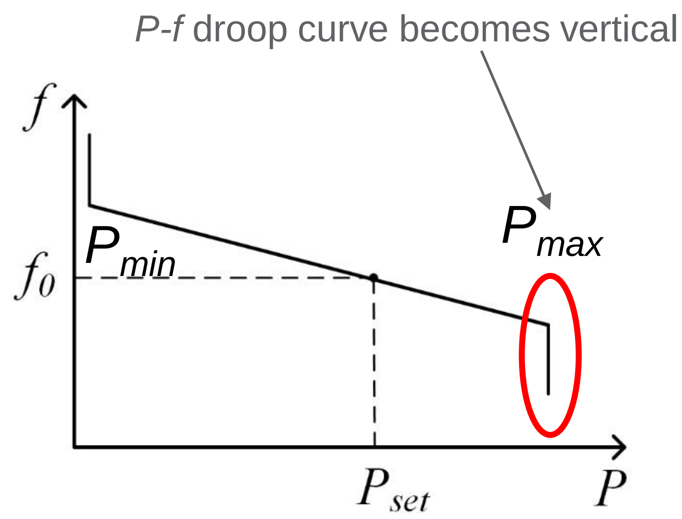


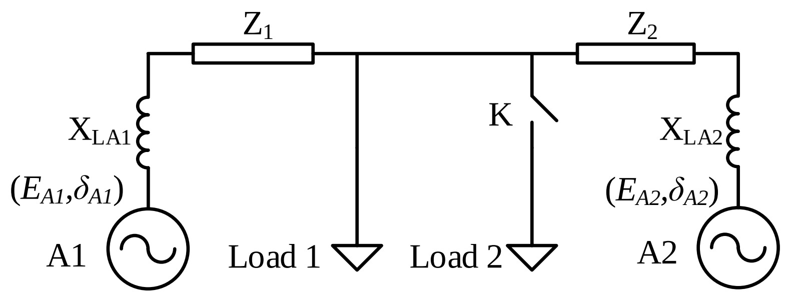


Without P_{max} Controller



With P_{max} Controller



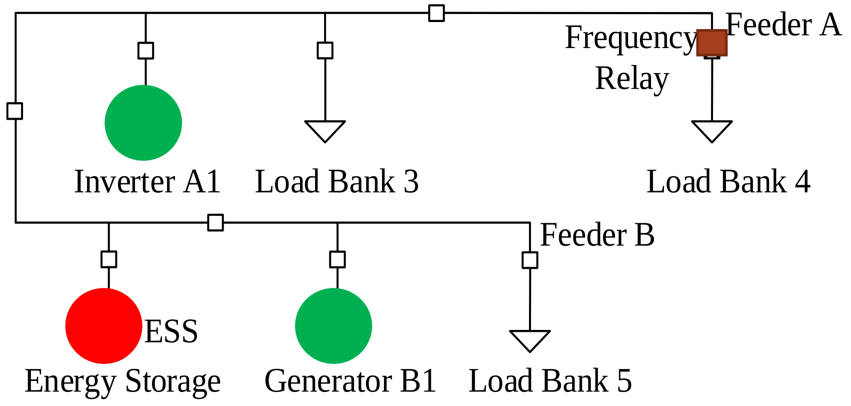


A Two-Source System

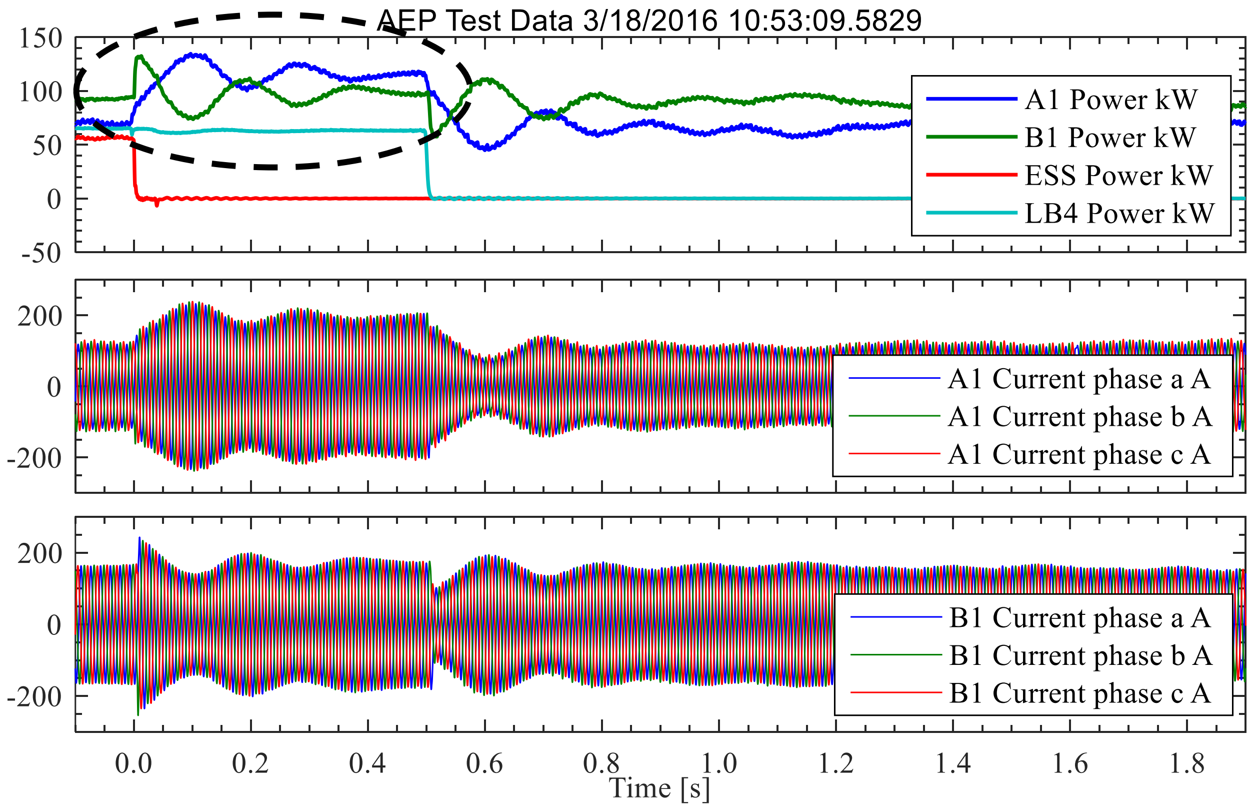
[1] Du, Wei, Robert H. Lasseter, and Amrit S. Khalsa. "Survivability of autonomous microgrid during overload events." *IEEE Transactions on Smart Grid* 10, no. 4 (2018): 3515-3524.

Function 2: When the entire system is overloaded (under-frequency load shedding)

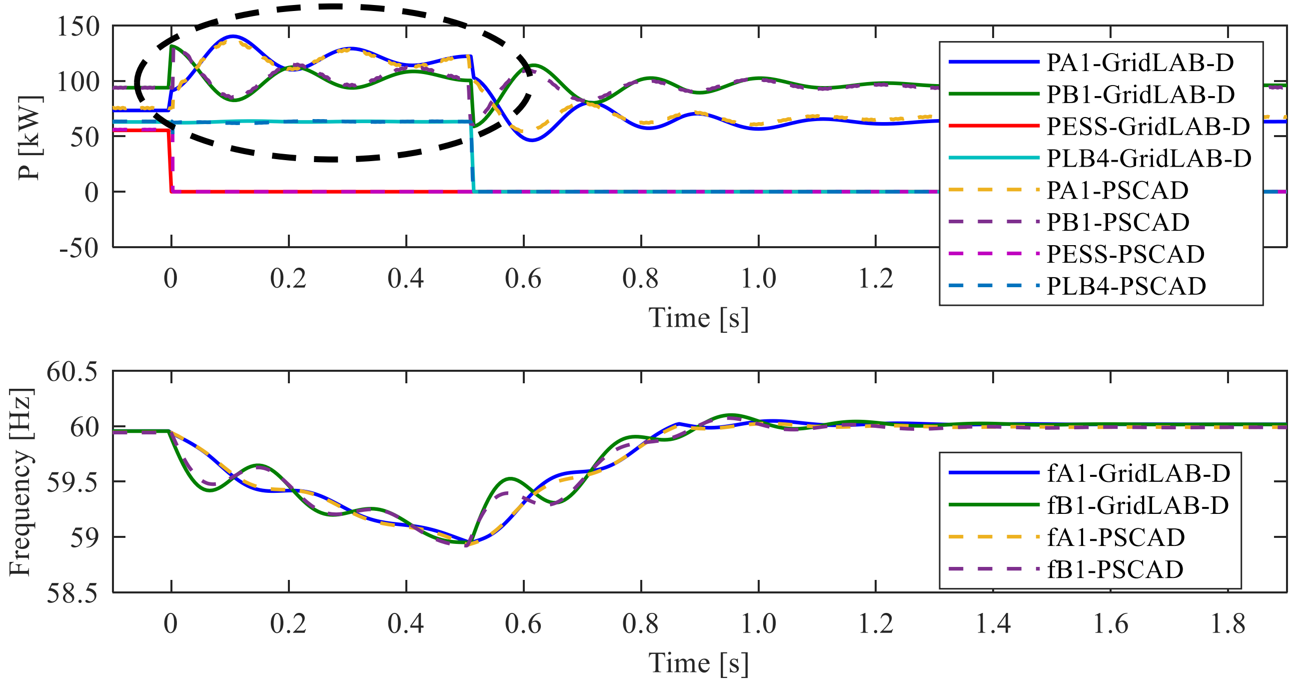
- The loss of ESS results in the overload of the entire microgrid
- All sources' droop curves become vertical, triggering under-frequency load shedding
- GridLAB-D simulation, PSCAD simulation, and field test results match well with each other



CERTS/AEP Testbed



Field test results from CERTS/AEP testbed



EMT and phasor simulation results

EMT

Positive-sequence

[1] Du, Wei, Robert H. Lasseter, and Amrit S. Khalsa. "Survivability of autonomous microgrid during overload events." *IEEE Transactions on Smart Grid* 10, no. 4 (2018): 3515-3524.

Industry Engagement and Use Case Study

--*Transmission Level Simulation and Analysis*

Industry Engagement

- The generic/standard library GFM model development received significant supports from OEMs, WECC MVS, and software vendors
- The models have been used by many utilities and ISOs to evaluate how the grid-forming technology will impact their power grids

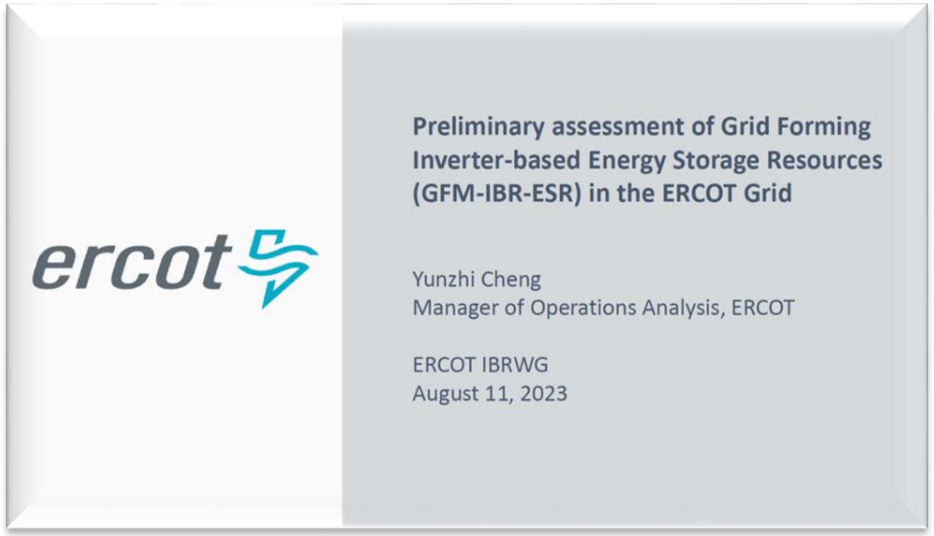
<Public>

WECC

Grid Forming Inverters

Grid Forming Advisory Group 7/17/2023

WECC Report of GFM technology using the model provided by PNNL



ercot

Preliminary assessment of Grid Forming Inverter-based Energy Storage Resources (GFM-IBR-ESR) in the ERCOT Grid

Yunzhi Cheng
Manager of Operations Analysis, ERCOT

ERCOT IBRWG
August 11, 2023

ERCOT presentation using the GFM model provided by PNNL

cigre Canada

CIGRE-646 2023 CIGRE Canada Conference
Vancouver, British Columbia, September 25-28, 2023

Value and Gain of Grid-Forming Inverters for ROCOF and Frequency Regulation in Island Grids

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[1]Quanta Technology
[2]LUMA Energy
[3]Pacific Northwest National Laboratory

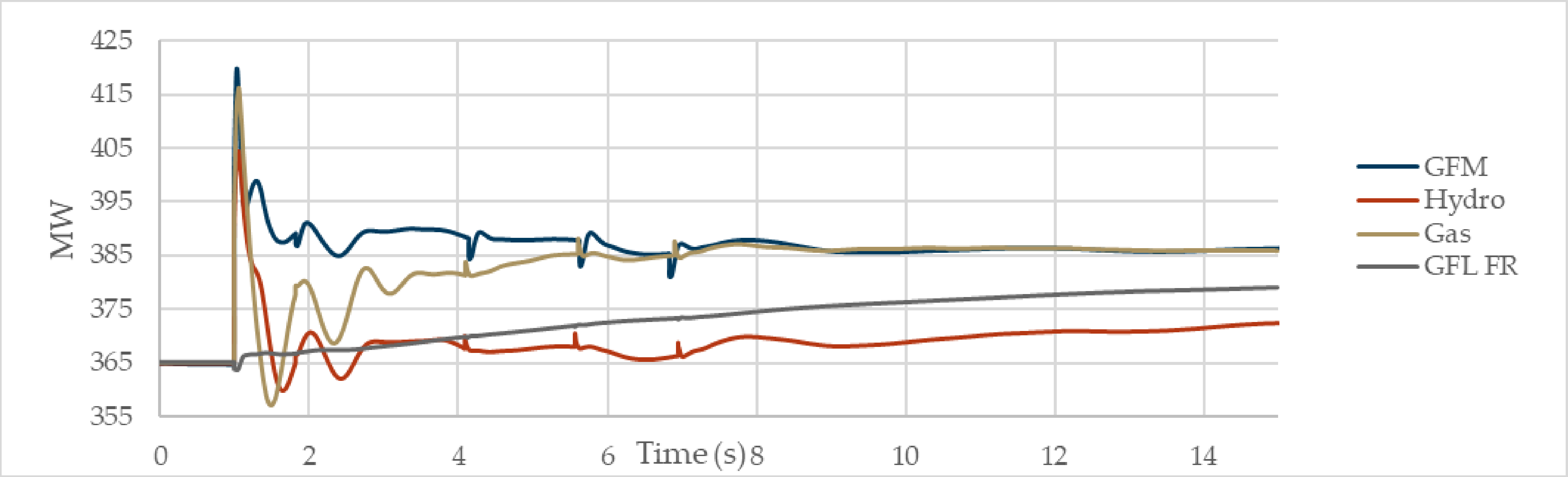
PNNL's GFM model is used to support the **Puerto Rico** work

Industry Engagement

Utilities/ISOs	OEMs
• NERC • WECC • ERCOT • PGE • PG&E • LUMA • ISO-NE • MISO • ComEd • BPA • HECO	• GE • SMA • SGRE

Dynamic Response of GFMs

- A GFM approximately behaves as a voltage source behind impedance, which is much like a synchronous generator.
- Because of the voltage source characteristic, the GFM responds to disturbances almost instantaneously, which is much faster than traditional grid-following inverters (GFLs).

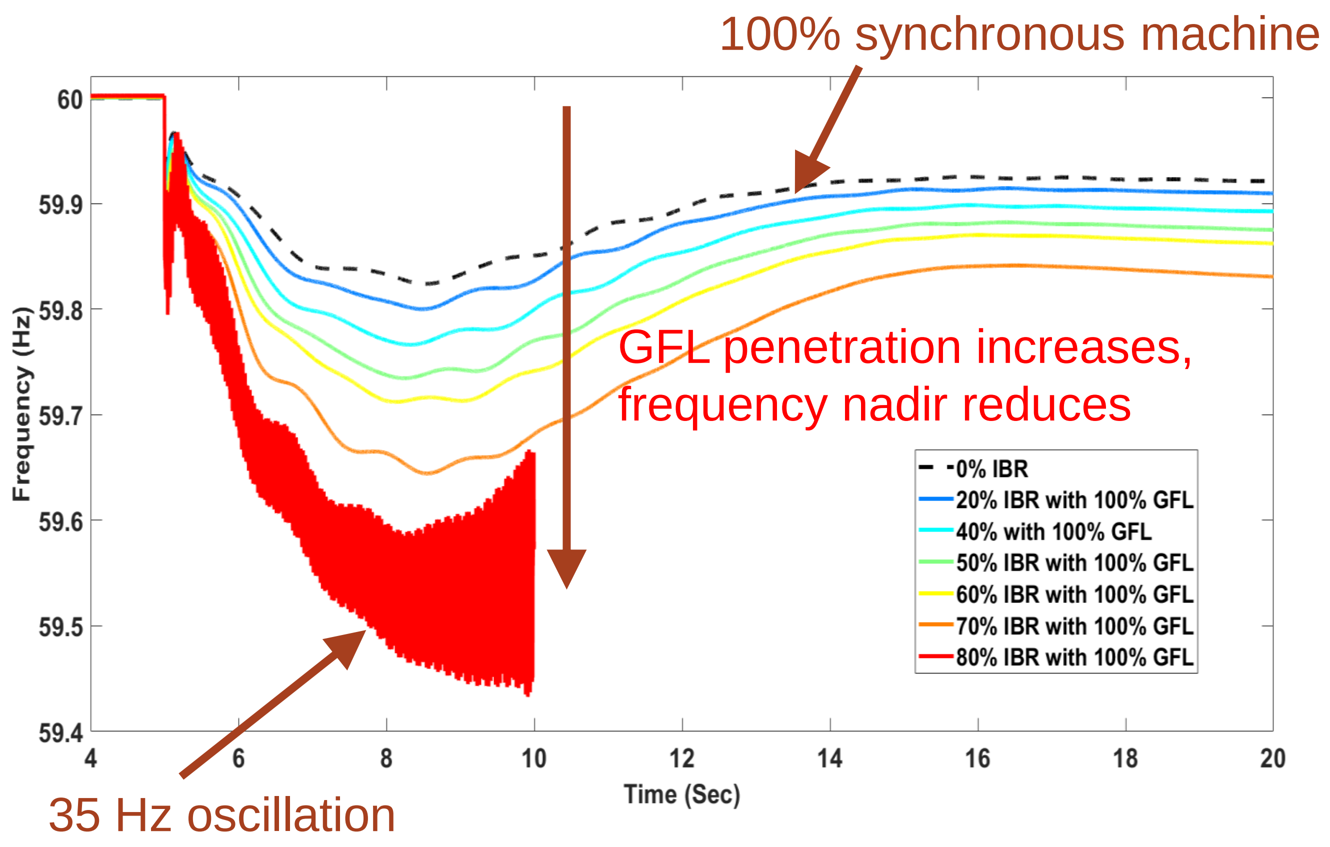


Response of gas generators, hydro generators, grid-forming and grid-following inverters near outage (*source: WECC report of the grid-forming inverter*)

System Frequency Response Study

Question 1: How many GFLs can synchronous-machine-dominated T&D system hold?

- When the penetration of GFLs increases in the T&D system, the frequency nadir decreases after tripping the two Palo Verde generation units
- When the GFL penetration reaches 80%, the system cannot maintain stability

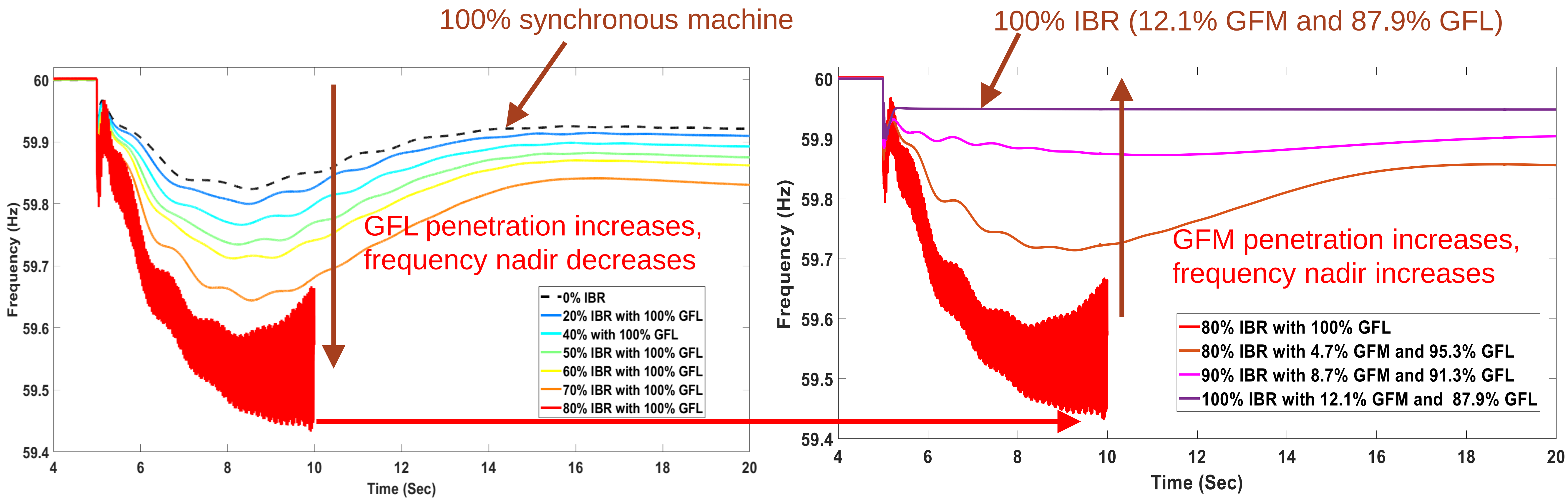


[1] Y. Liu, R. Huang, W Du*, *et al.*, "Highly-Scalable Transmission and Distribution Dynamic Co-Simulation with 10,000+ Grid-Following and Grid-Forming Inverters", IEEE Transactions on Power Delivery, 2023

System Frequency Response Study

Question 2: How many GFMs are needed to maintain the stability of future IBR-dominated T&D systems?

- For the 80% IBR penetration case, if we replace 4.7% GFLs with GFMs, the system becomes stable
- As the penetration of GFMs continues to increase, the frequency nadir is significantly improved
- For the 100% IBR case, the primary frequency response is even much better than the 100% synchronous machine case.



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New GFM Model Development
Virtual Synchronous Machine GFM Model (REGFM_B1)

Virtual Synchronous Machine GFM Model (REGFM_B1)

- PNNL is working with GE, Siemens, EPRI, and others to develop another type of generic grid-forming inverter model—VSM GFM model (REGFM_B1)
- The model is also expected to be included in the model libraries of commercial tools including PSS/E, PSLF, PowerWorld, and TSAT in collaboration with WECC
- *The generic GFM model development work will be a multi-year effort to support industry better understand/evaluate this technology*

unifi consortium

Virtual Synchronous Machine Grid-Forming Inverter Model Specification (REGFM_B1)

DRAFT

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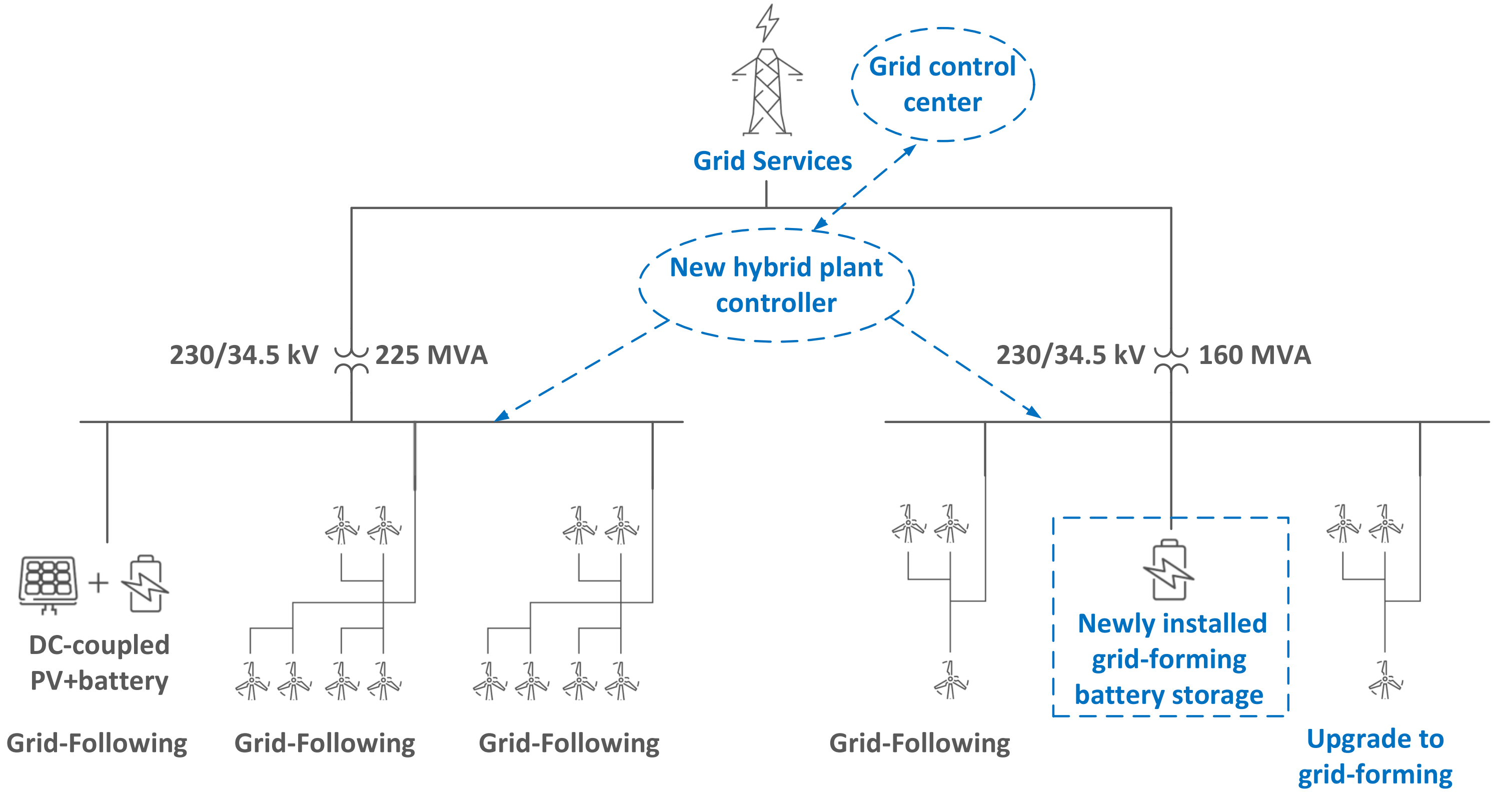
Real-World Demonstration of Grid-Forming Inverter

Demonstration of Grid Services by a 380 MW Wind, Solar, and Battery Storage Combined Power Plant

- Wheatridge Renewable Energy Facility is ***North America's first energy center to combine wind, solar, and battery storage in one location***, with 300 MW of wind, 50 MW of solar, and 30 MW of energy storage systems
- This will be ***the first time that grid forming IBRs, including both wind and battery storage, are connected to the US bulk power systems,*** and demonstrated at the same site for grid services

380MW Wheatridge wind, solar and battery storage power plant



One line diagram

Portland General Electric | GE Research | GE Renewable Energy | Pacific Northwest National Laboratory | Bonneville Power Administration | NextEra Energy | The University of Texas at Austin | Portland State University

The project is funded by the solar and wind grid services and reliability demonstration funding program by the DOE SETO

Conclusions and Future Work

- As the penetration of IBRs continue to increase in power systems, GFMs will play a critical role in maintaining the system stability
- The WECC-approved GFM model (REGFM_A1) led by PNNL helps transmission planners understand the GFM technology and its potential impacts on their grids
- As the GFM technology continues to evolve, PNNL will continue leading the work on developing and enhancing generic grid-forming inverter models for industry use in collaboration with our partners

Thank you

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