# GridWise Alliance Technology Council Meeting Agenda
## **Grid-Forming Inverter Modeling**
October 25, 2023 @ 3:00 PM ET

| | | |
|---|---|---|
| **I.** | Welcome & Antitrust Guidelines | **Josh Steinhardt**, Operations Director |
| | | |
| **II.** | Introduction | **Carl Imhoff**, Manager, Electricity Market Sector, Pacific Northwest National Laboratory |
| | | |
| **III.** | Presentation on Grid-Forming Inverter Modeling and Real-World Demonstration | **Wei Du,** Staff Research Engineer, Pacific Northwest National Laboratory<br><br>**Kevin Schneider**, Laboratory Fellow, Pacific Northwest National Laboratory |
| | | |
| **IV.** | Questions and Discussion | **All** |

# GridWise Alliance
# Antitrust Compliance Program Guidelines

It is the policy of the GridWise Alliance to comply fully with the antitrust laws. The Sherman Act and other applicable antitrust laws are intended to promote vigorous and fair competition and to combat various restraints of trade.

Each person who participates in GridWise Alliance activities has a responsibility to his/her employers and to the GridWise Alliance to avoid any improper conduct from an antitrust standpoint. The following guidelines will assist in meeting this responsibility:

1. GridWise Alliance meetings and discussions generally cover topics related to the generation, transmission and distribution of electricity. Should related discussions ever have any potential for competitive impact, all due care shall be taken to avoid such discussion between competitors.

2. In view of antitrust considerations and to avoid any possible restraints on competition, the following legally sensitive subjects must be avoided during any discussion between competitors:

   (a) Future marketing plans of individual competitors should not be discussed between competitors;

   (b) Any complaints or business plans relating to specific customers, specific suppliers, specific geographic markets or specific products, should not be discussed between competitors;

   (c) Purchasing plans or bidding plans of companies in competition should not be discussed (except privately between two parties with a vertical commercial relationship such as supplier and customer); and

   (d) Current and future price information and pricing plans, bidding plans, refund or rebate plans, discount plans, credit plans, specific product costs, profit margin information and terms of sale should not be discussed between competitors. All of the above are elements of competition.

3. Any question regarding the legality of a discussion topic or business practice should be brought to the attention of the GridWise Alliance legal counsel or a company's individual legal counsel for advice.

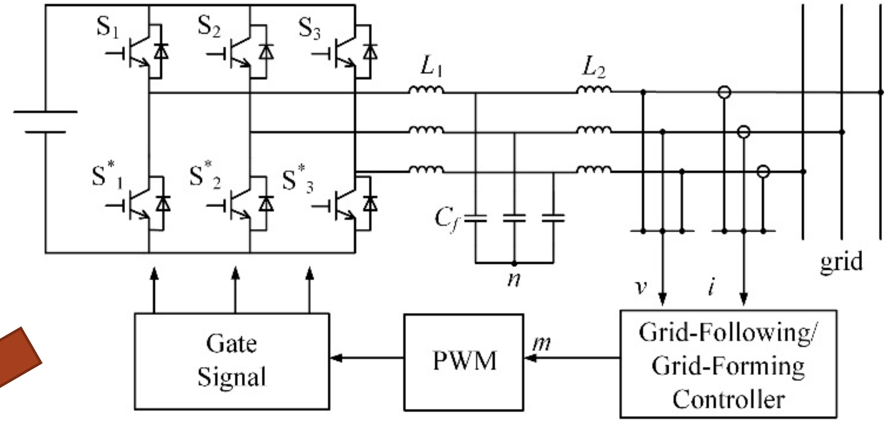
# Grid-Forming Inverter Modeling and Real-World Demonstration

**Wei Du**

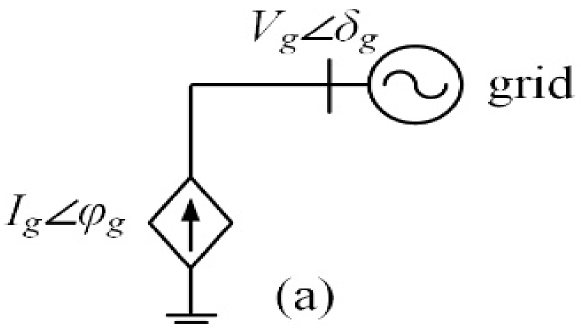
Pacific Northwest National Laboratory

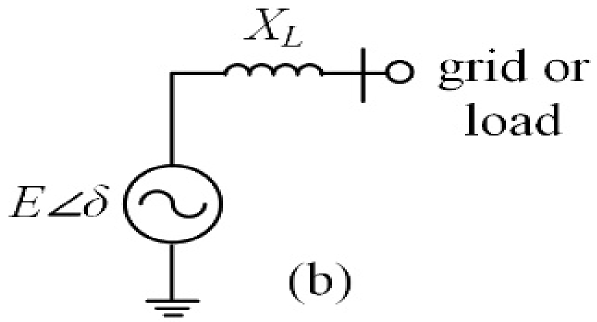
# OUTLINE

- Introduction
- First 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




**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 disturbance, the inverter output current is "approximately" constant, and then external controls adjust $I_{ref}$.

## Grid-Forming (Voltage Source)

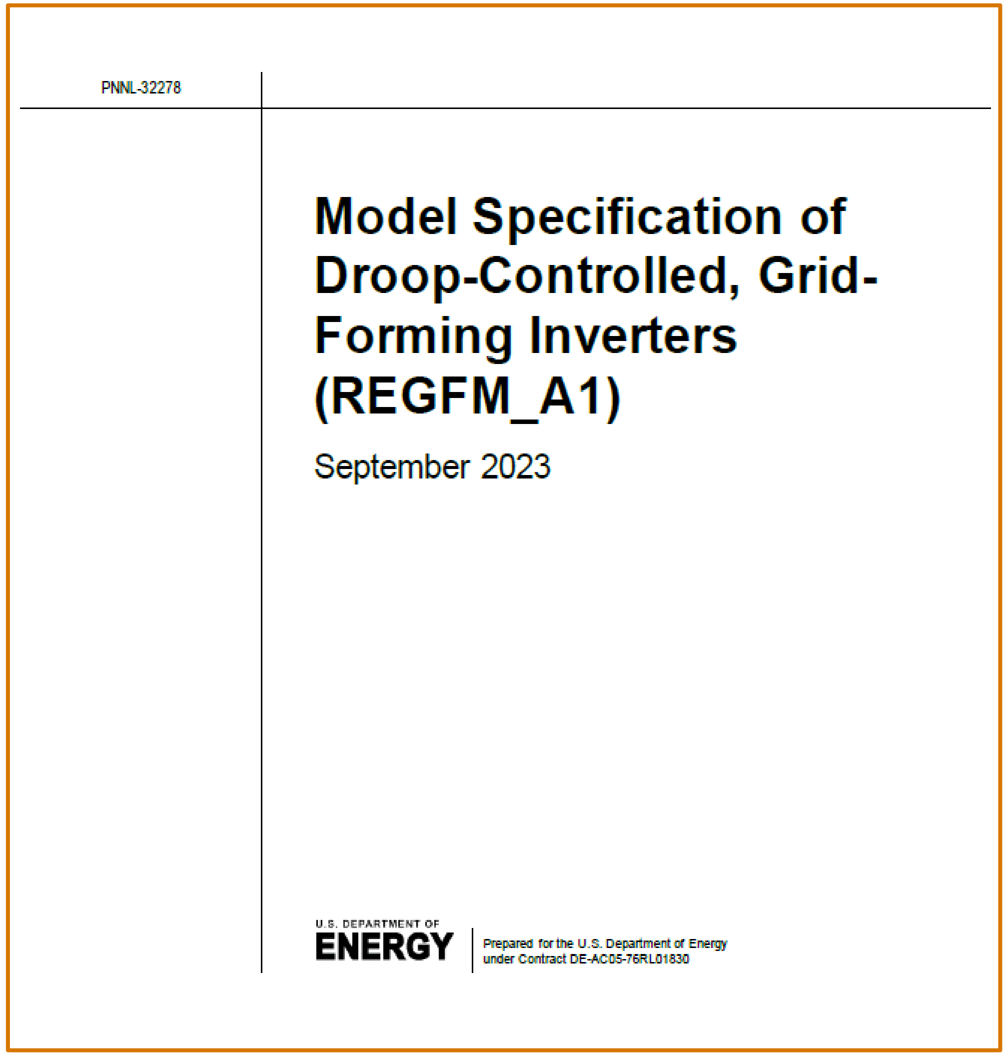
+ Direct Voltage & frequency control
+ Can work in islanded mode

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

At the beginning of a disturbance, the inverter internal voltage is constant, and then external controls adjust $E$ and $\delta$.

# 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*


PNNL-32278

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

September 2023

U.S. DEPARTMENT OF ENERGY

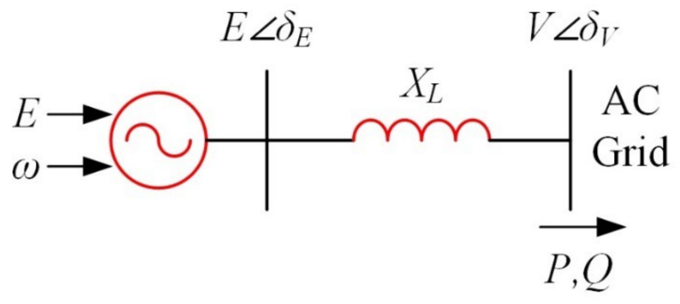
Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830


Twittered by Secretary of Energy Jennifer M. Granholm

This work is funded by the UNIFI consortium under the DOE SETO Award Number 38637, the PNNL Laboratory Directed Research and Development (LDRD) Program, and the OE Microgrid program

# 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%): $P \propto \delta$, $Q \propto E$

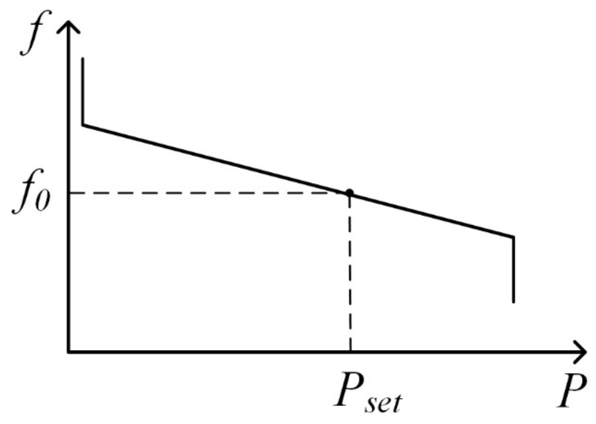



$$\delta_p = \delta_E - \delta_V$$

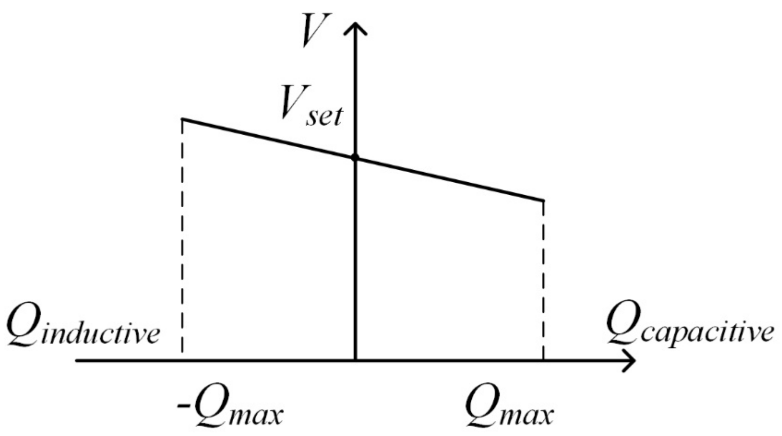
$$P = \frac{EV}{X_L}\sin\delta_p \approx \frac{EV}{X_L}\delta_p \qquad \delta_p = \int(\omega - \omega_0)dt$$

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

- 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

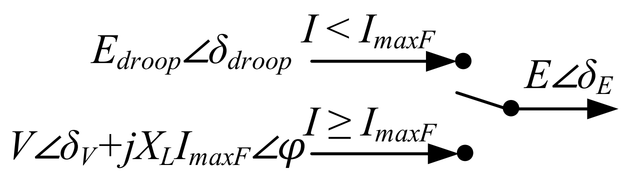



Q vs. V droop

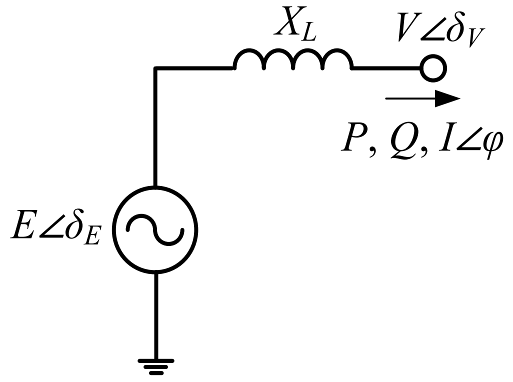
$\delta_P\uparrow \rightarrow P\uparrow \rightarrow \omega\downarrow \rightarrow \delta_P\downarrow$ (Negative feedback control)

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

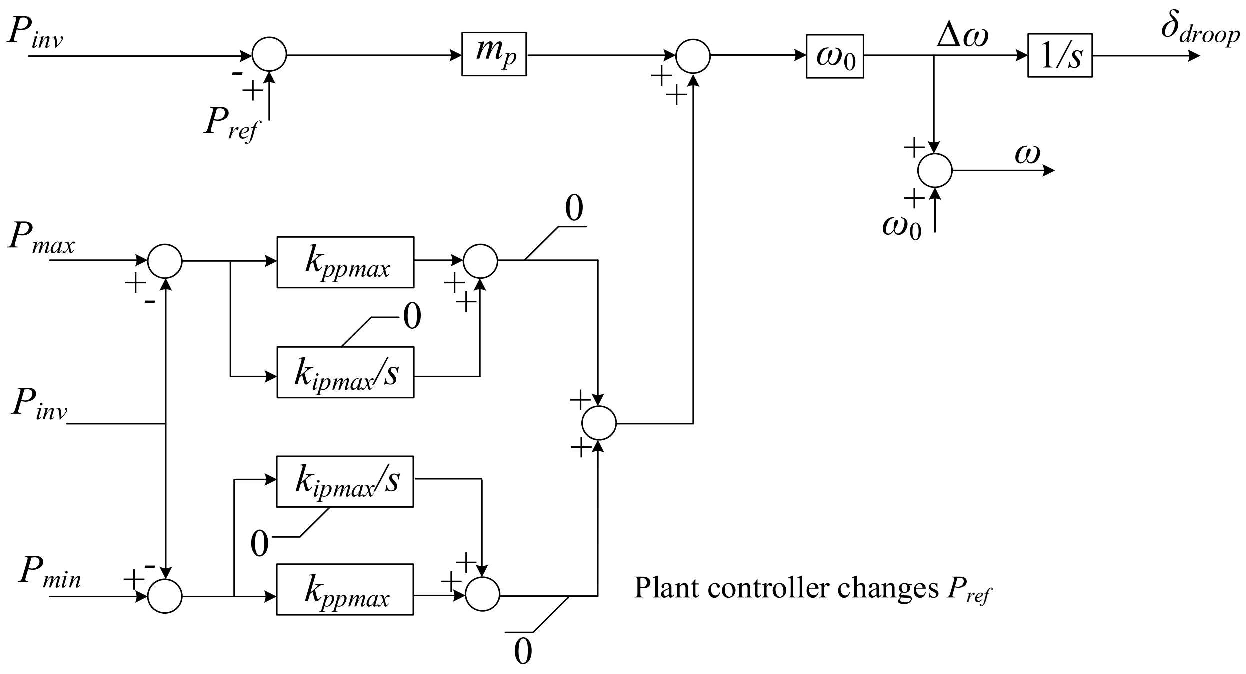
- The model includes a voltage source representation, *P-f* and *Q-V* droop controls, *P/Q* limiting controls, and a transient fault current limiting function
- Most of the control blocks came from the CERTS Microgrid Project funded by DOE
- SMA suggested to add the $Q_{max}/Q_{min}$ control block, and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



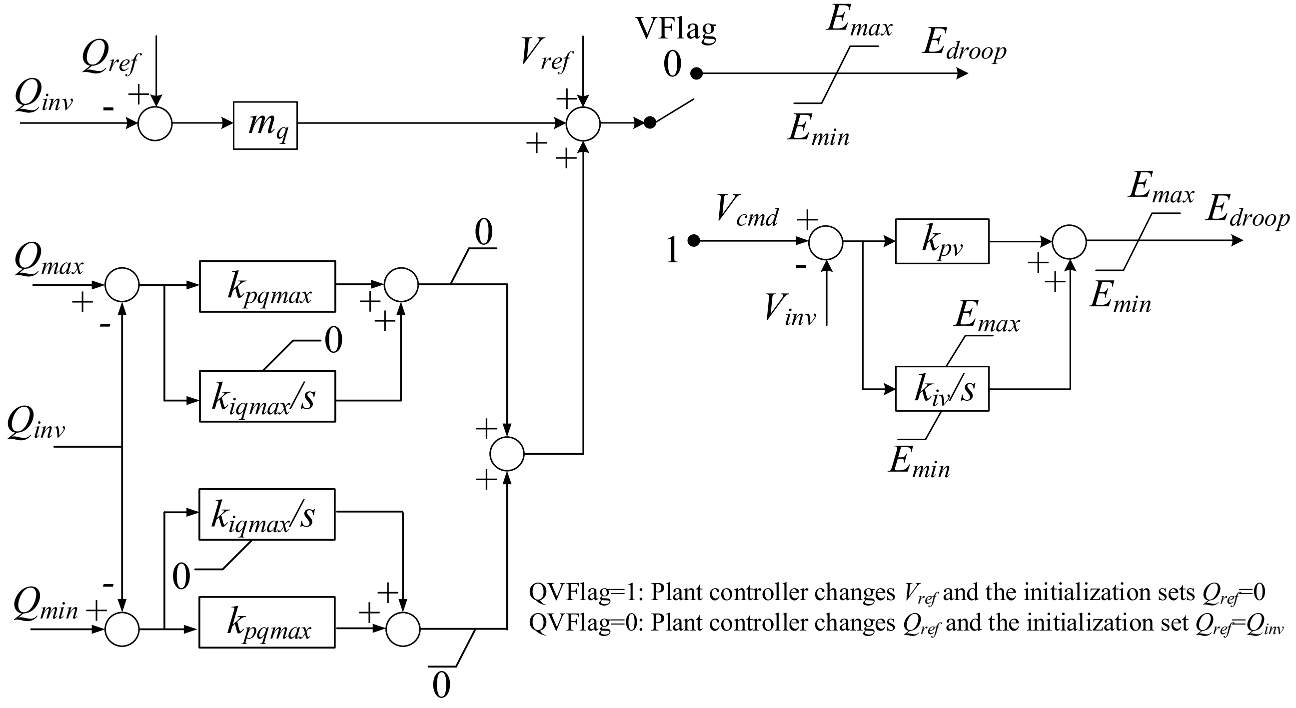

Fault current limiting




Voltage source behind impedance




P-f droop and P Limiting



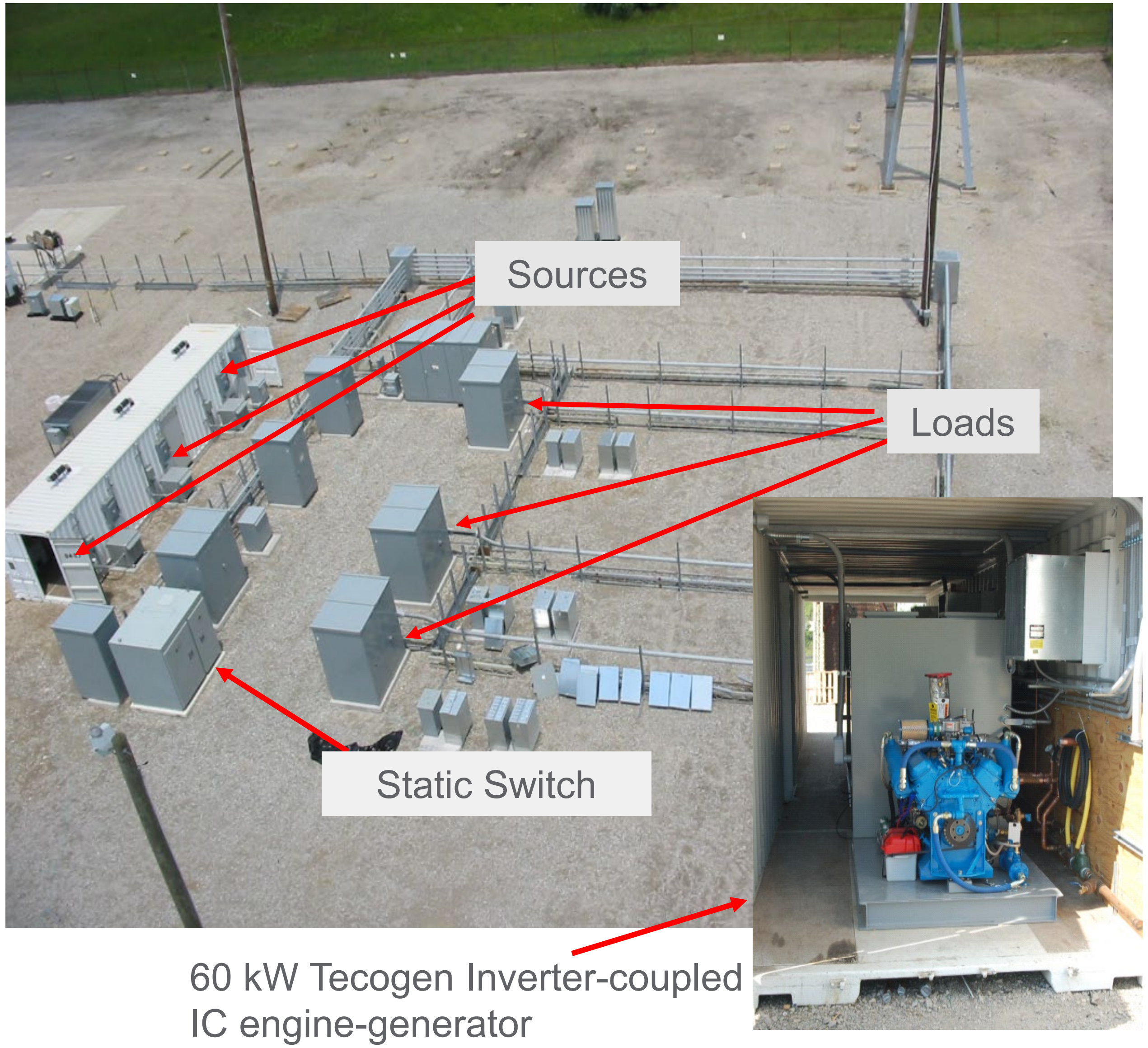

Q-V droop and Q Limiting

# Model Validation

# 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

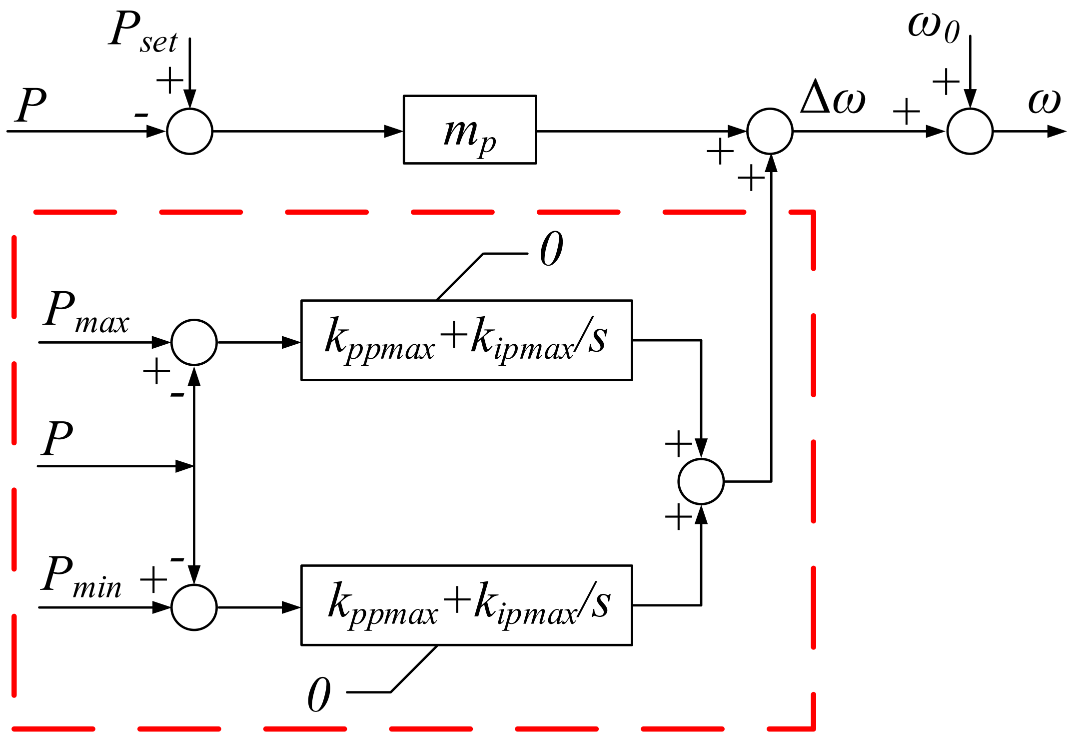
CERTS CONSORTIUM for ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

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

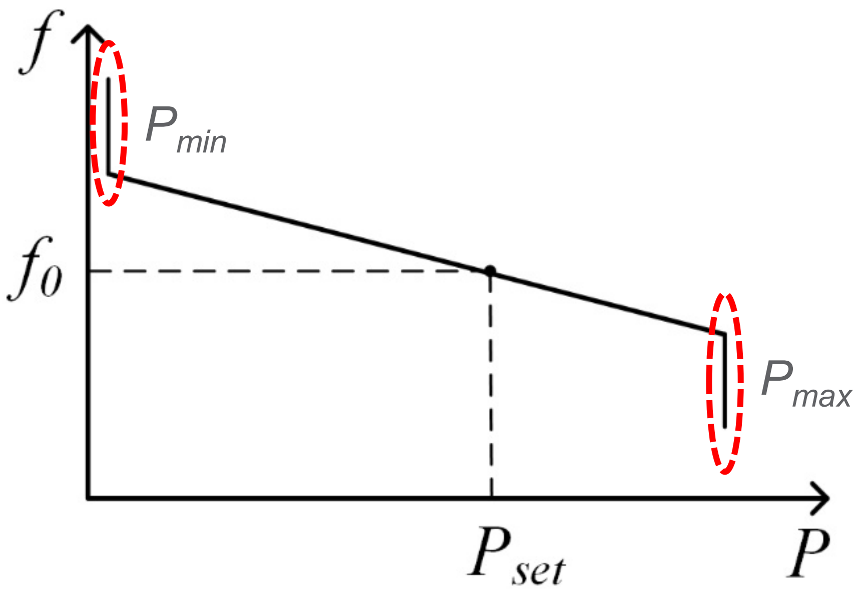

[1] Lasseter, R.H., Eto, J.H., Schenkman, B., Stevens, J., Vollkommer, H., Klapp, D., Linton, E., Hurtado, H. and Roy, J., 2010. CERTS microgrid laboratory test bed. IEEE Transactions on Power Delivery, 26(1)

# 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

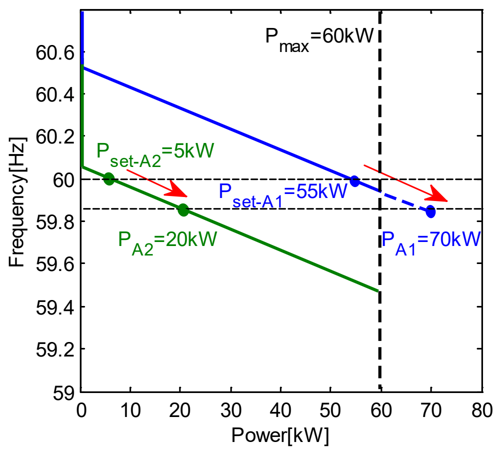


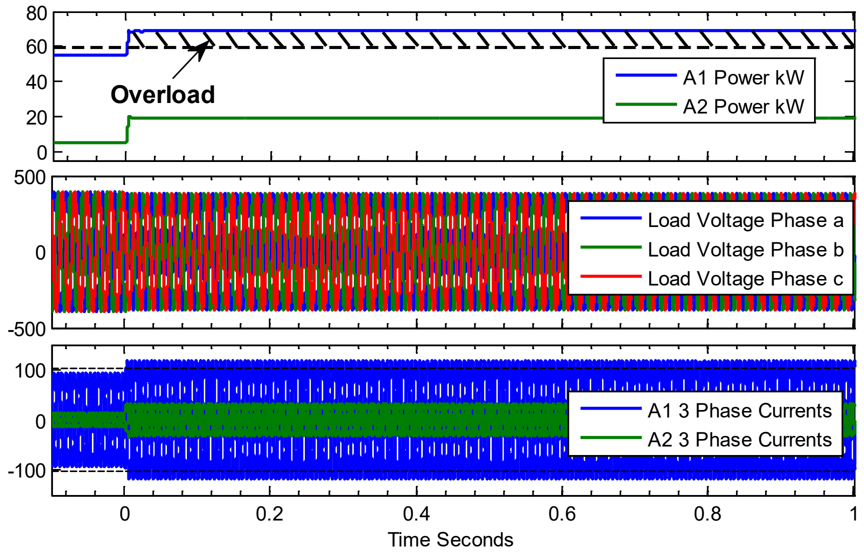

P-f droop

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

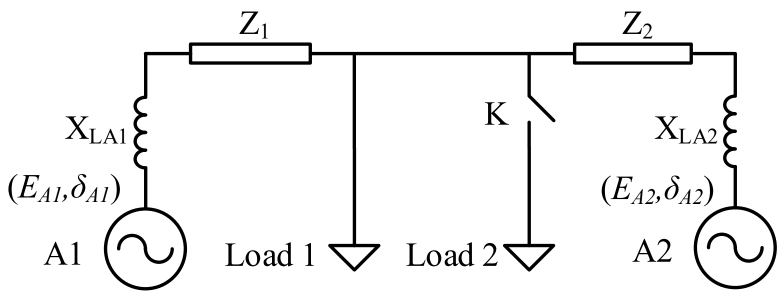
- When one grid-forming inverter is dispatched near its maximum generation, a load step can result in overload
  - Overload can collapse the dc bus of inverters, stall the synchronous generators, etc.

Without $P_{max}$ Controller




Without $P_{max}$ Controller

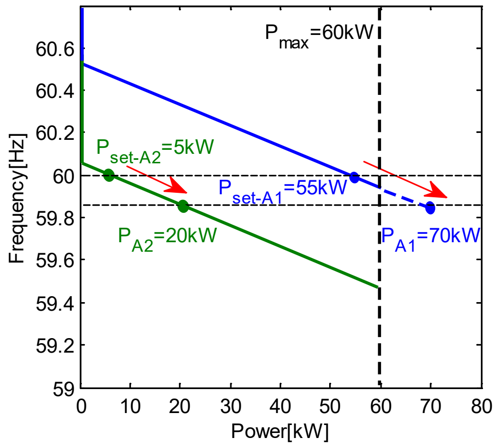


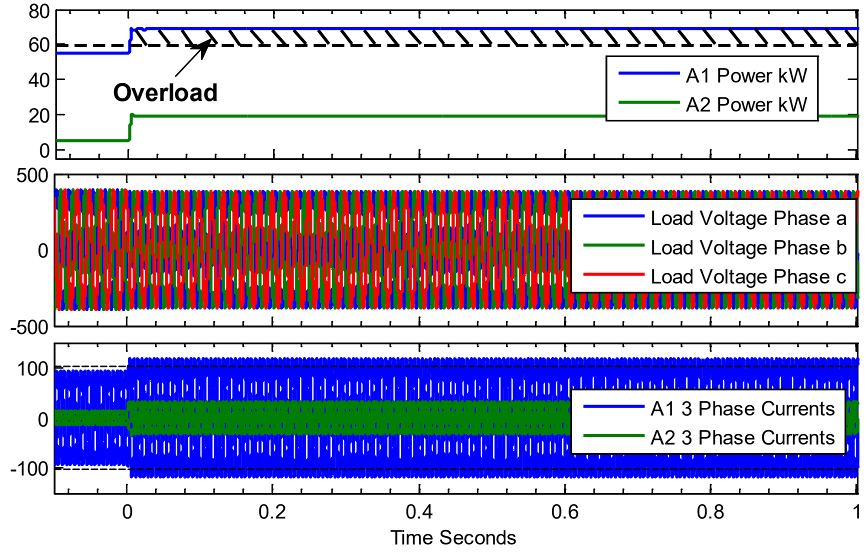

A Two-Source System

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

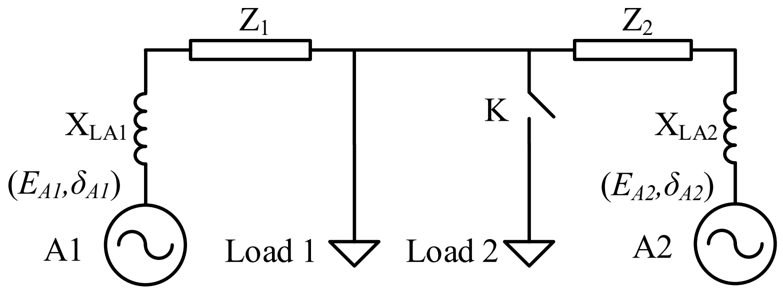
- When one grid-forming inverter is dispatched near its maximum generation, a load step can result in overload
  - Overload can collapse the dc bus of inverters, stall the synchronous generators, etc.

Without $P_{max}$ Controller

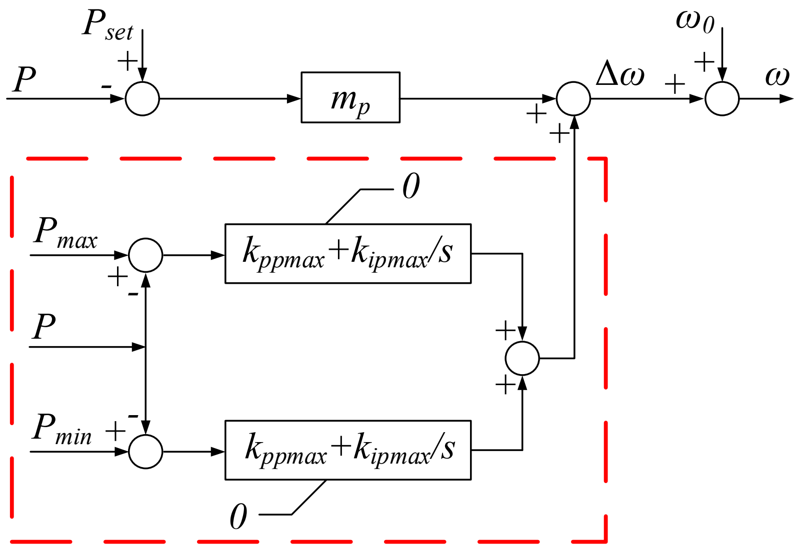



Without $P_{max}$ Controller




A Two-Source System



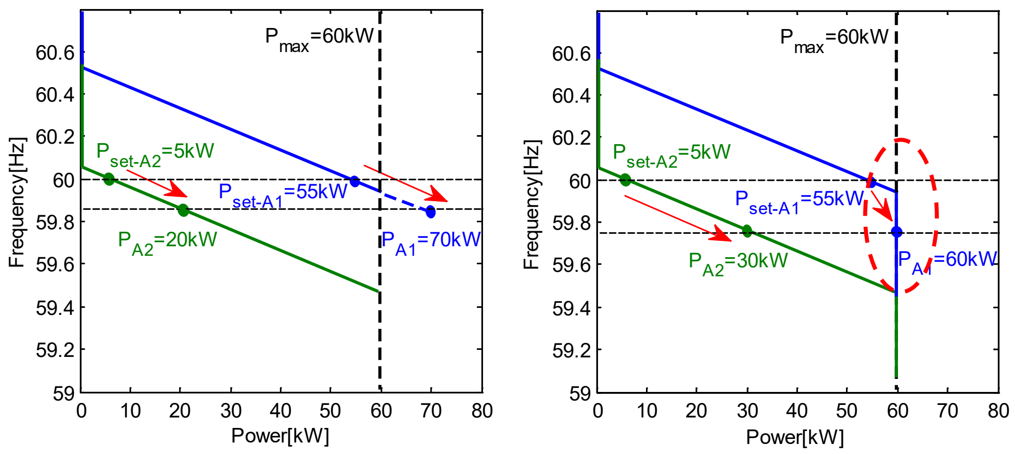

Overload Mitigation Controller:

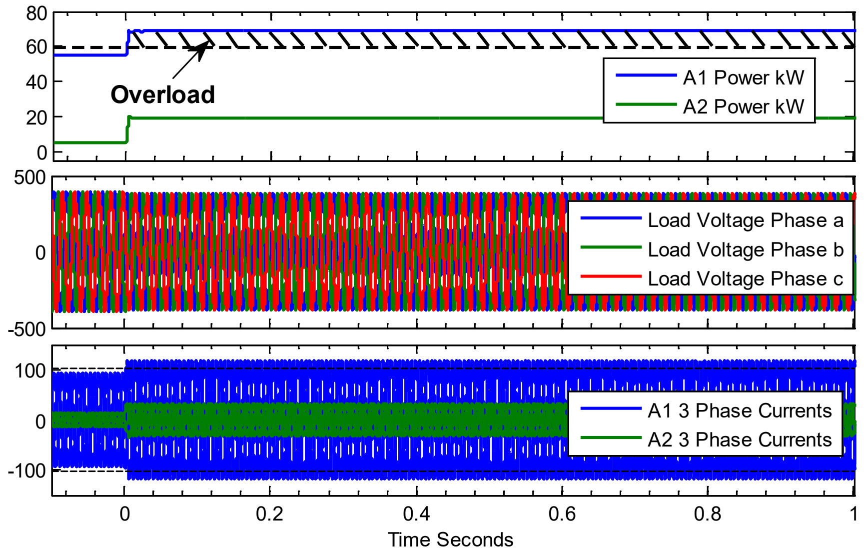
Change the phase angle between sources: $\Delta\delta$

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

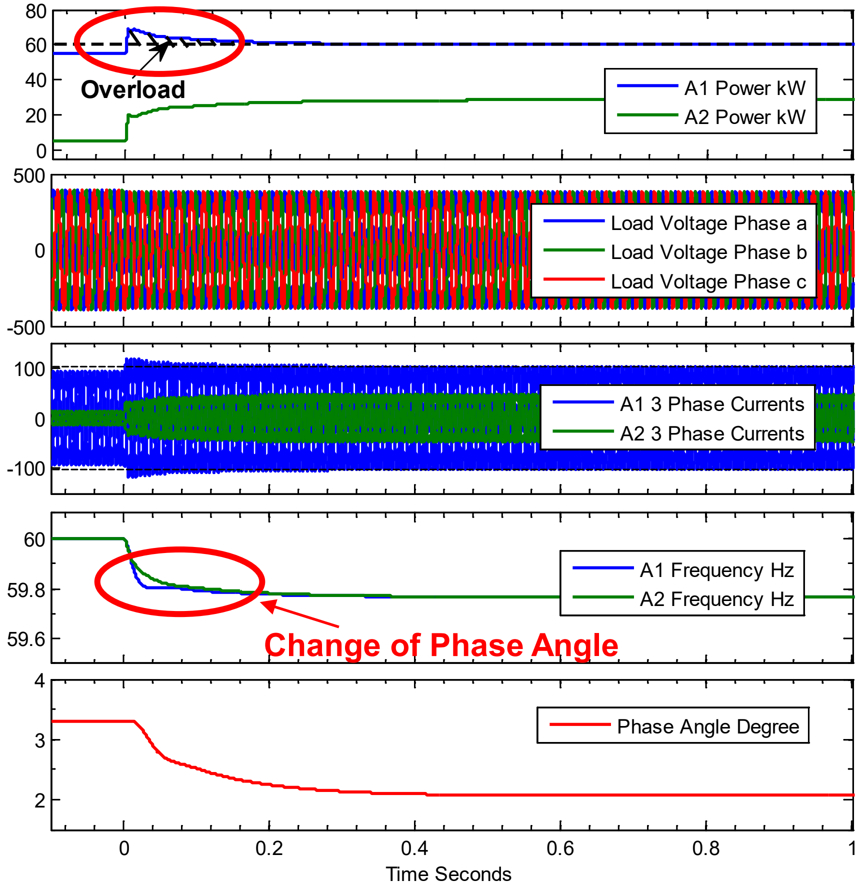
- Transfer the extra load to non-overloaded sources by reducing the frequency rapidly
- The change of phase angle redistributes power flow between inverters

Without $P_{max}$ Controller — With $P_{max}$ Controller

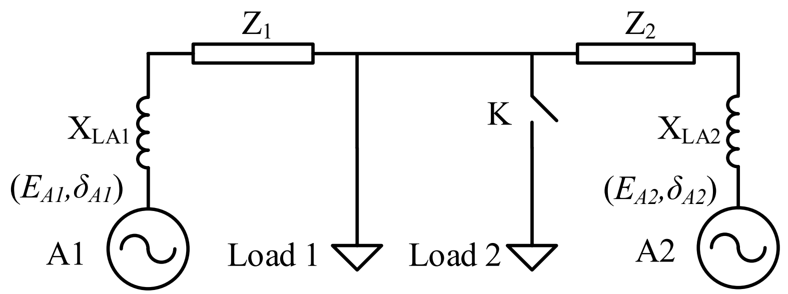



Without $P_{max}$ Controller

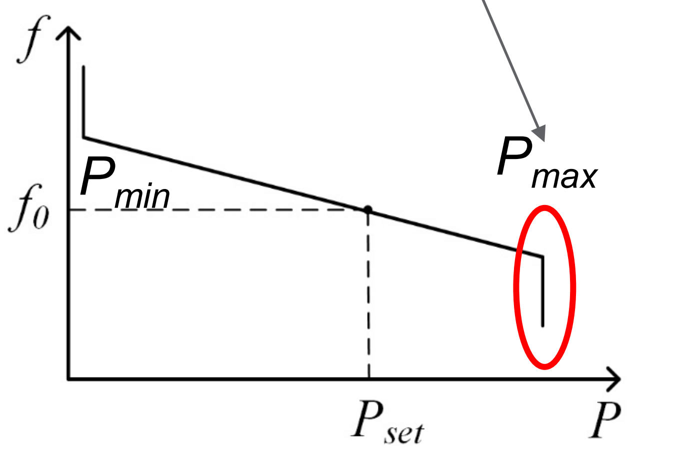



With $P_{max}$ Controller




A Two-Source System

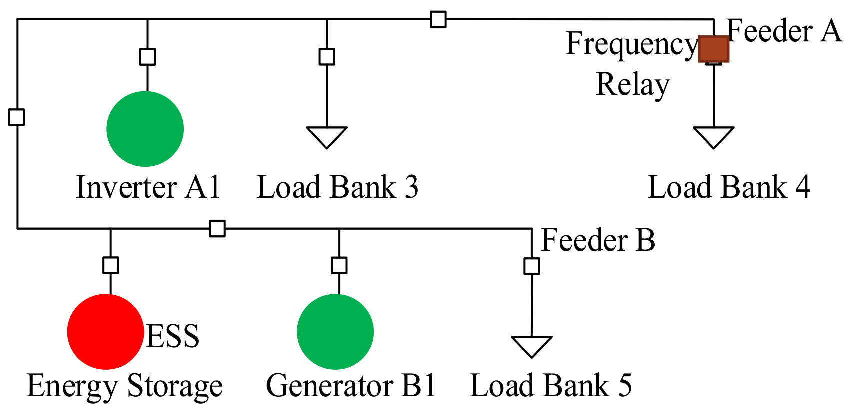
*P-f* droop curve becomes vertical



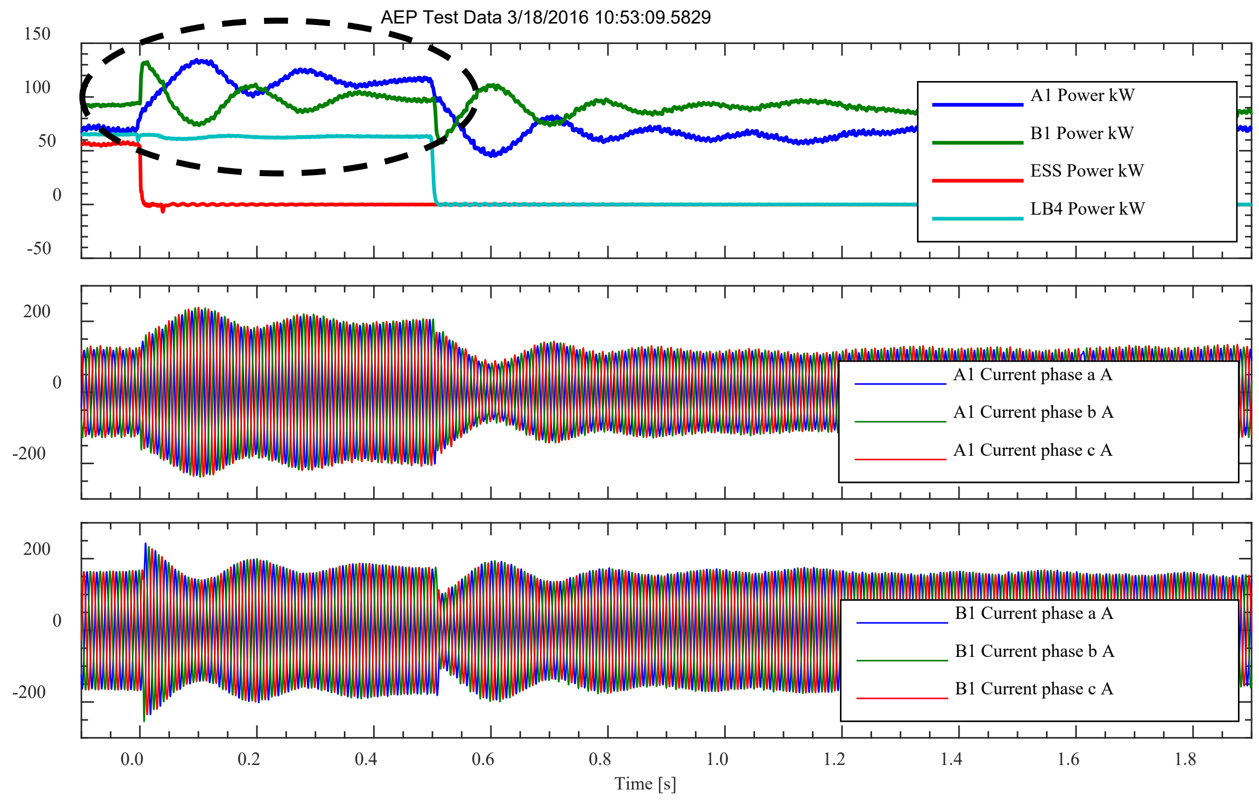

[1] Du, Wei, Robert H. Lasseter, and Amrit S. Khalsa. "Survivability of autonomous microgrid during overload events." *IEEE Transactions on Smart Grid* 10, no. 4 (2018): 3515-3524.

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

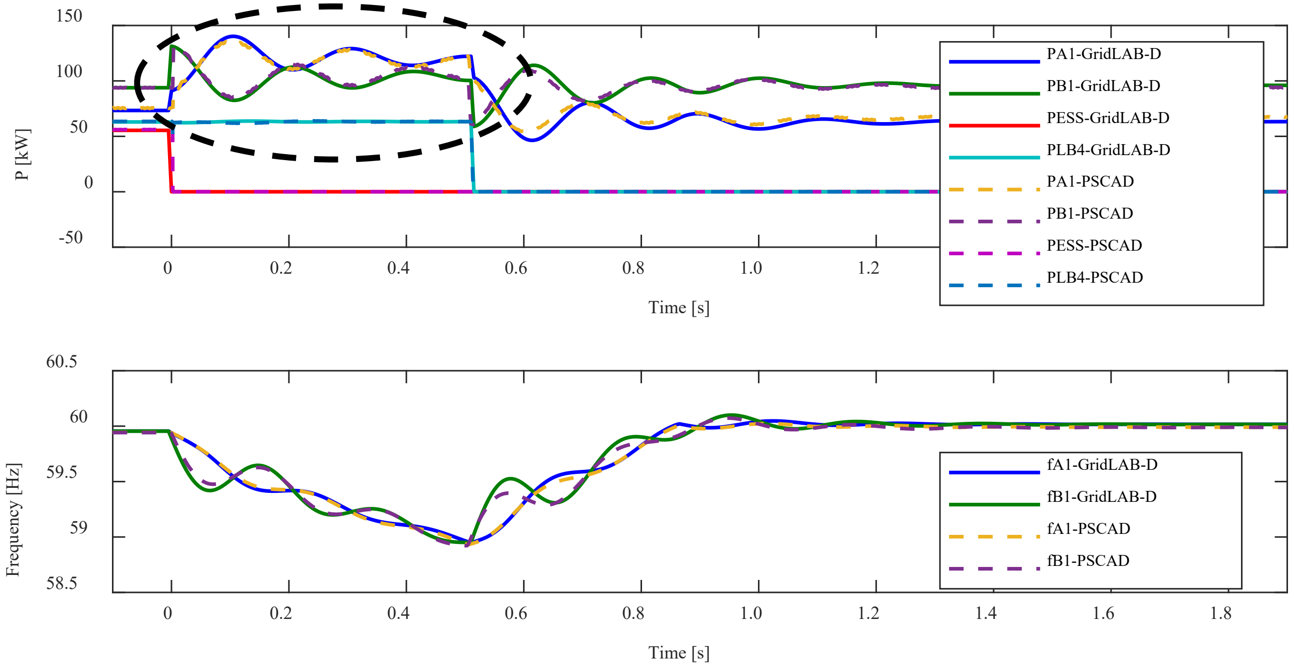
- The loss of ESS results in the overload of the entire microgrid
- All sources' droop curves become vertical, triggering under-frequency load shedding
- GridLAB-D simulation, PSCAD simulation, and field test results match well with each other




CERTS/AEP Testbed



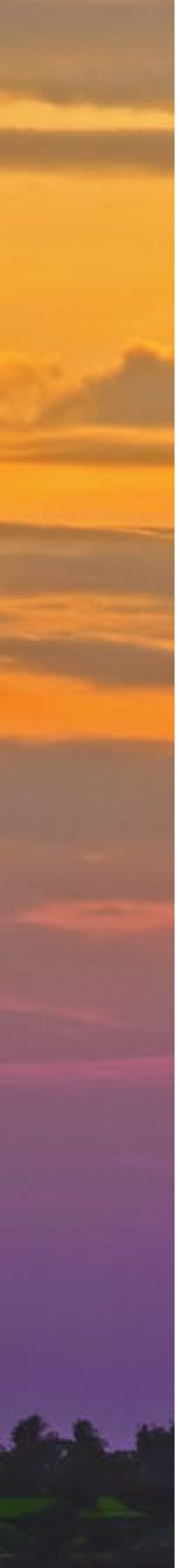

Field test results from CERTS/AEP testbed




EMT and phasor simulation results

---- EMT
—— Phasor

[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

# 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

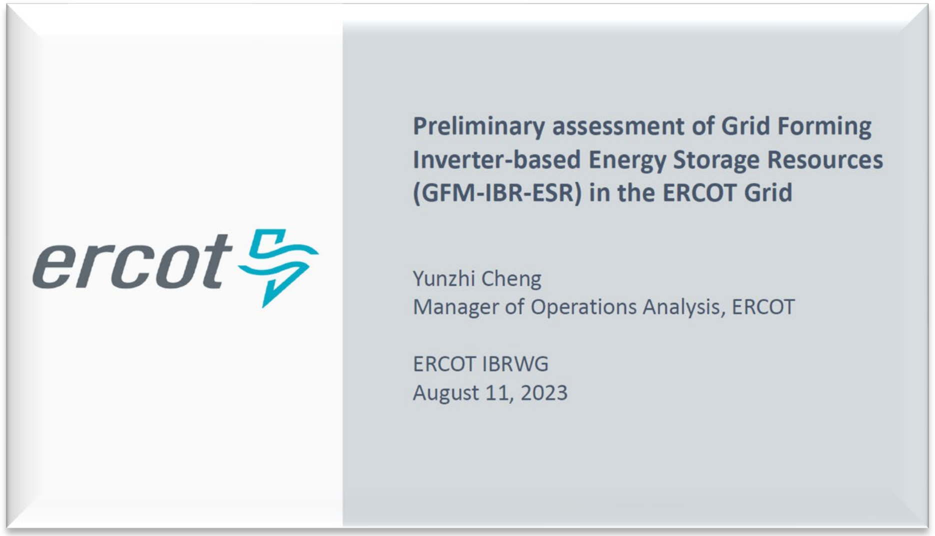
<Public>

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

Matin Rahmatian[1], Alexandre Nassif[2], Xiaoyuan Fan[3], Marcelo Elizondo[3], Wei Du[3], Hisham Othman[1]
[1]Quanta Technology
[2]LUMA Energy
[3]Pacific Northwest National Laboratory

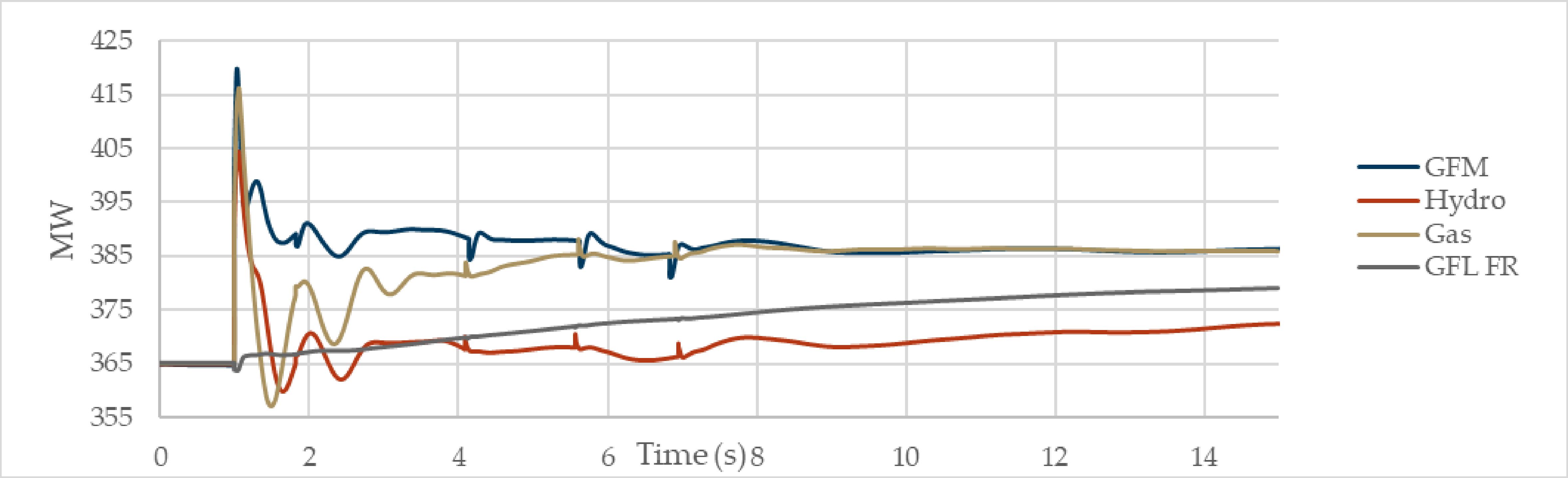
PNNL's GFM model is used to support the **Puerto Rico** work

## Industry Engagement

| Utilities/ISOs | OEMs |
| --- | --- |
| • NERC<br>• WECC<br>• ERCOT<br>• PGE<br>• PG&E<br>• LUMA<br>• ISO-NE<br>• MISO<br>• ComEd<br>• BPA<br>• HECO | • GE<br>• SMA<br>• 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 fault events almost instantaneously, which is much faster than traditional grid-following inverters (GFLs).

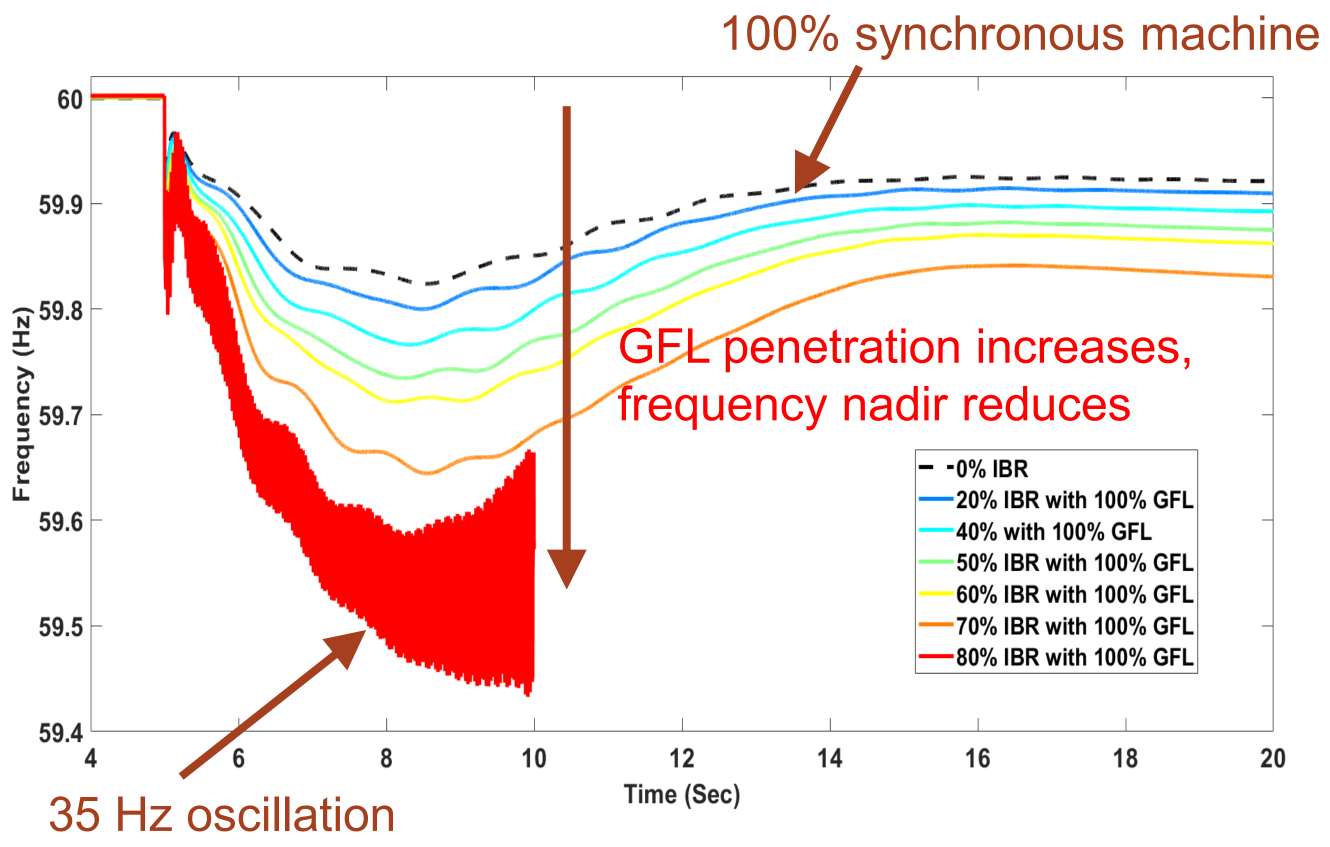



Response of gas generators, hydro generators, grid-forming and grid-following inverters near outage (*source: WECC report of the grid-forming inverter*)

# 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

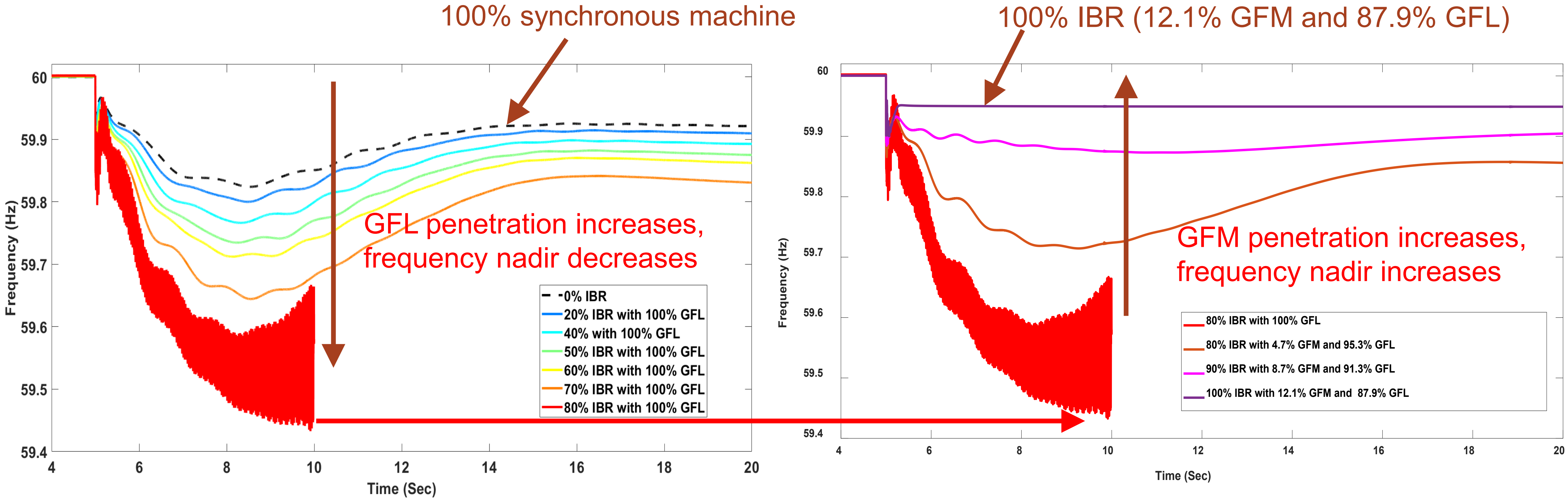



[1] Y. Liu, R. Huang, W Du*, *et al.*, "Highly-Scalable Transmission and Distribution Dynamic Co-Simulation with 10,000+ Grid-Following and Grid-Forming Inverters", IEEE Transactions on Power Delivery, 2023

# 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.

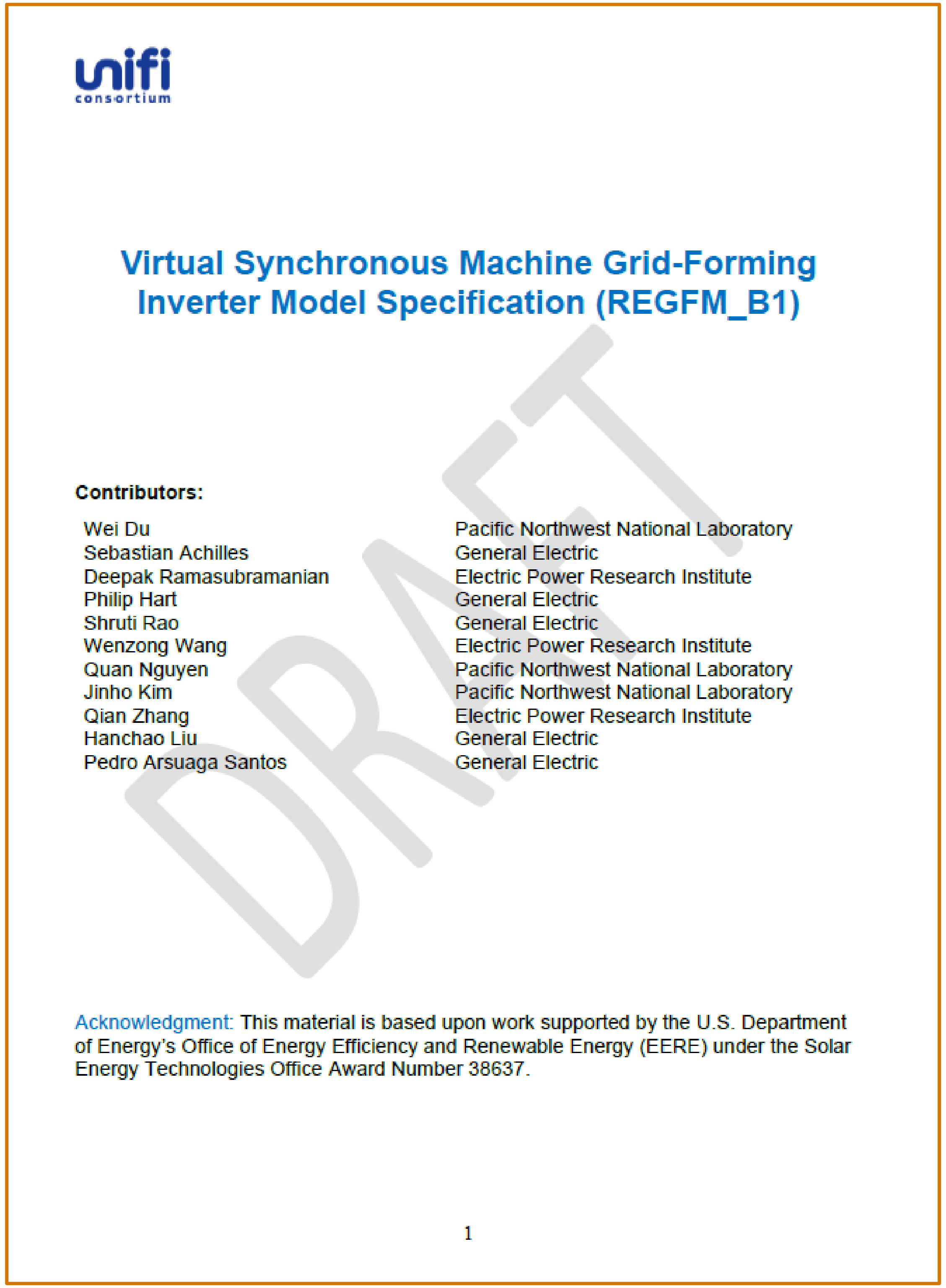



[1] Y. Liu, R. Huang, W Du*, *et al.*, "Highly-Scalable Transmission and Distribution Dynamic Co-Simulation with 10,000+ Grid-Following and Grid-Forming Inverters", IEEE Transactions on Power Delivery, 2023

# 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


**Contributors:**

| | |
|---|---|
| Wei Du | Pacific Northwest National Laboratory |
| Sebastian Achilles | General Electric |
| Deepak Ramasubramanian | Electric Power Research Institute |
| Philip Hart | General Electric |
| Shruti Rao | General Electric |
| Wenzong Wang | Electric Power Research Institute |
| Quan Nguyen | Pacific Northwest National Laboratory |
| Jinho Kim | Pacific Northwest National Laboratory |
| Qian Zhang | Electric Power Research Institute |
| Hanchao Liu | General Electric |
| Pedro Arsuaga Santos | General Electric |



Acknowledgment: This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 38637.

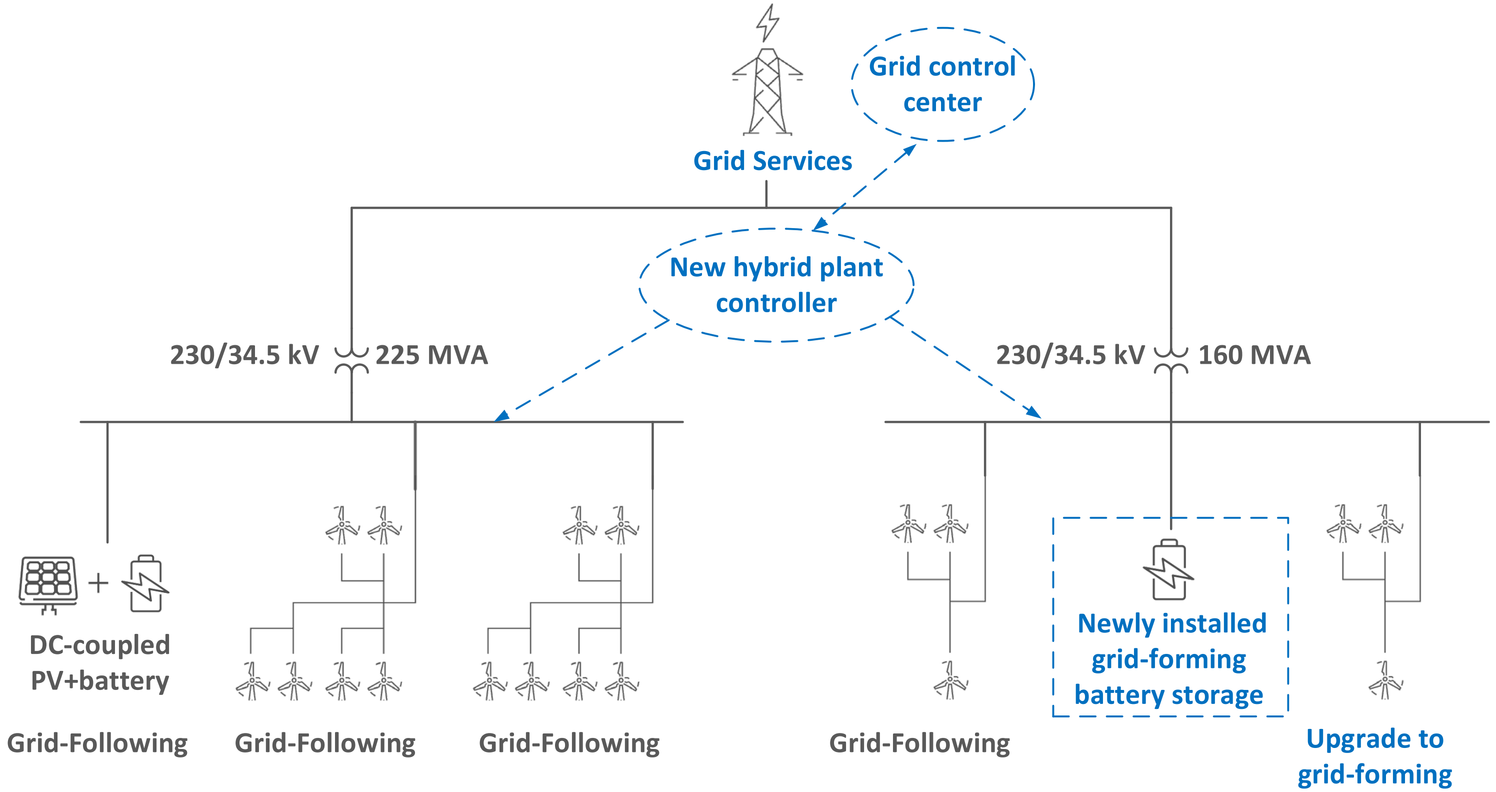

1

# 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

- 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 in the coming years

# Thank you

**Wei Du**
Wei.du@pnnl.gov