NATIONAL LABORATORY OF THE ROCKIES

Frequency Control and Dynamics (Part 2)

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National Laboratory of the Rockies
March 2026

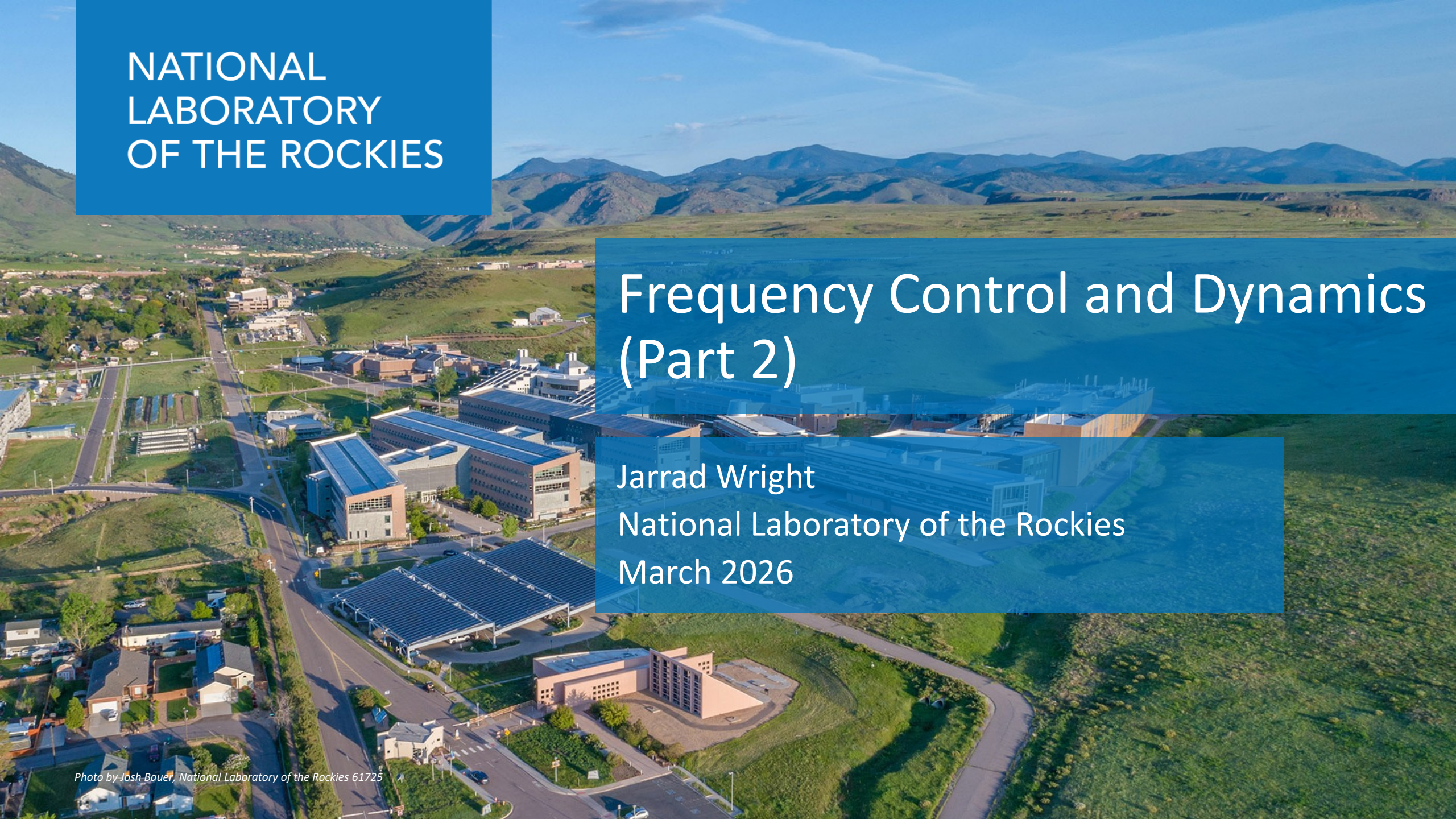


Photo by Josh Bauer, National Laboratory of the Rockies 61725

Refresher From Part 1

- What is frequency in a power system?
- Why do we need to control frequency?
- What is frequency stability, and are there different types?
- What is the swing equation?
- How do we control frequency in interconnected operations?
- What are the three tiers of frequency control?

Part 2: Frequency Control of Battery Energy Storage Systems (BESS)

Integration of Inverter-Based Resources (IBRs)

IBRs Are Playing an Increasingly Large Role in Power Systems Around the World

- Power systems historically have been dominated by synchronous generators and alternating current (AC) transmission.
- Future power systems are expected to have large numbers of IBRs at various levels in power systems.
- **IBRs*** are power electronics interfaced devices converting direct current (DC) power from an energy source to alternating current (AC) power for use in an AC power systems (solar photovoltaics, modern wind plants, battery energy storage).

* Sometimes also referred to as converter-interfaced generation technologies (CIGs).

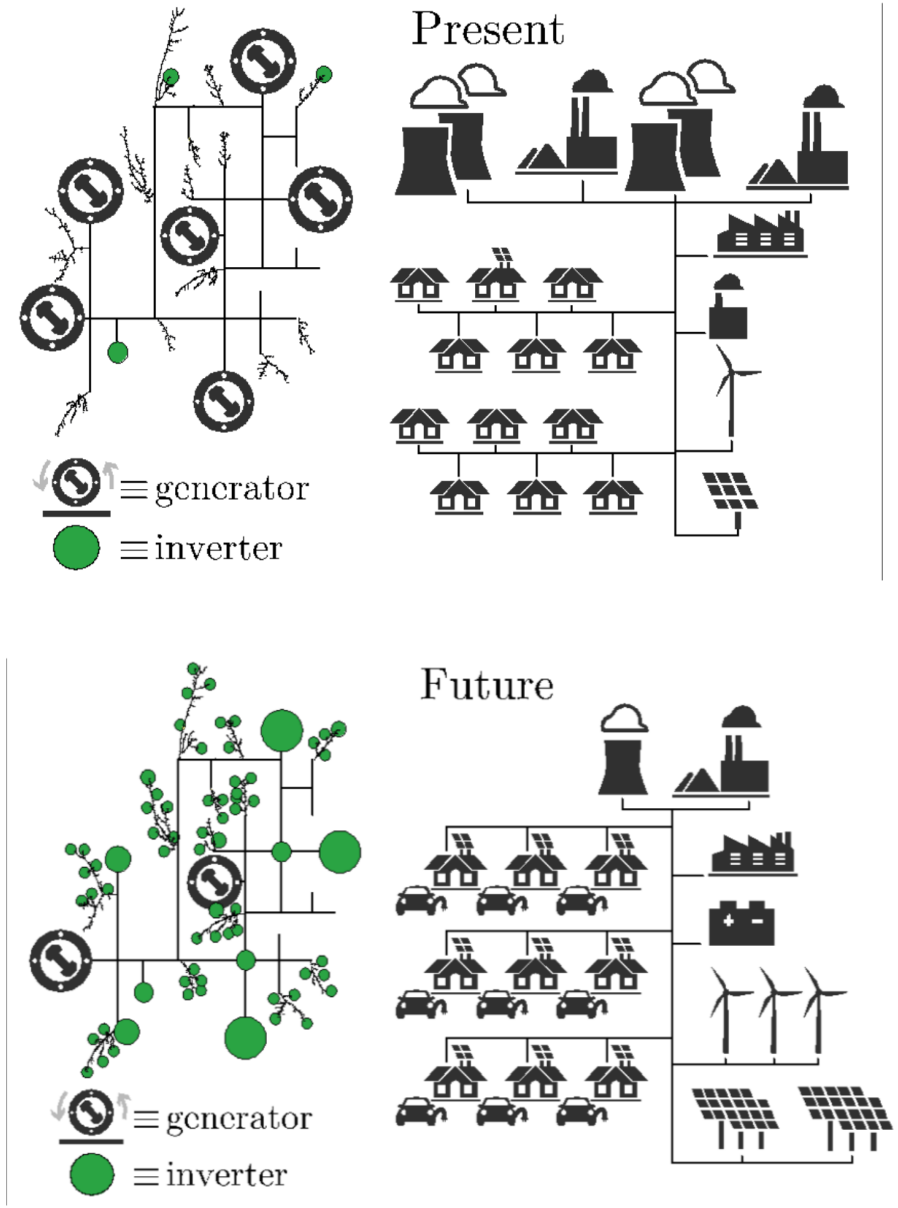


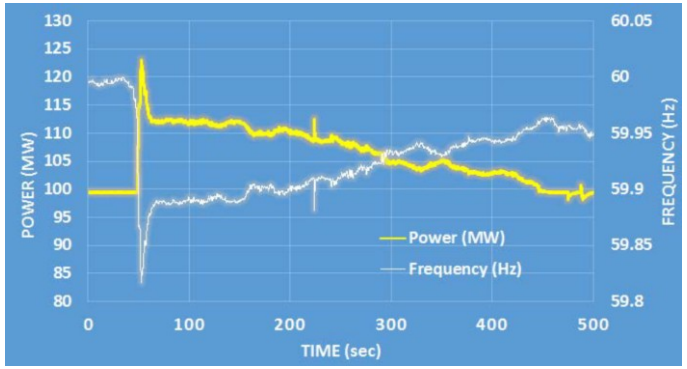
Image from Lin et al., Research Roadmap on Grid-Forming Inverters (NLR, 2020),

Source: UNIFI Consortium, UNIFI Specifications for Grid-Forming Inverter-Based Resources (NLR, 2024), https://docs.nrel.gov/docs/fy24osti/89269.pdf

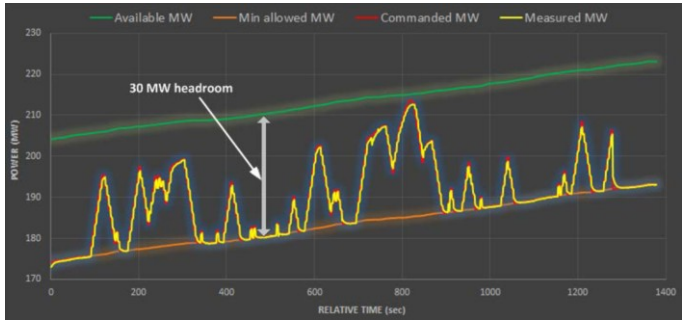
IBRs Can Provide Various System Services (including various forms of frequency control)

- 300-MW solar PV plant (CAISO)
- Partnership between First Solar, California ISO (CAISO), and National Laboratory of the Rockies
- Various services proven:
  - **Primary frequency response – Droop control**
    - 3%–5%, incl. deadband
    - 0.01%–0.21% control error.
  - **Secondary frequency control (AGC)**
    - 0.013% error (1-s)
    - 87%–94% (15-min) – typical accuracy from conventional units 40%–63% in CAISO.
  - **Voltage control**
    - Steady-state primary frequency control
    - Abnormal conditions (V-control).

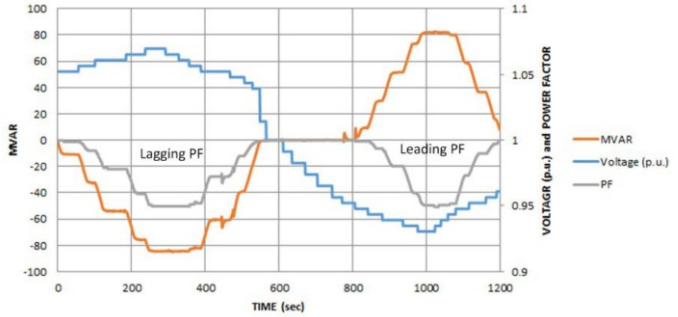
Primary frequency response (droop control)



AGC (regulating)



Primary frequency control demonstrating control mode switch when outside bounds (voltage control)



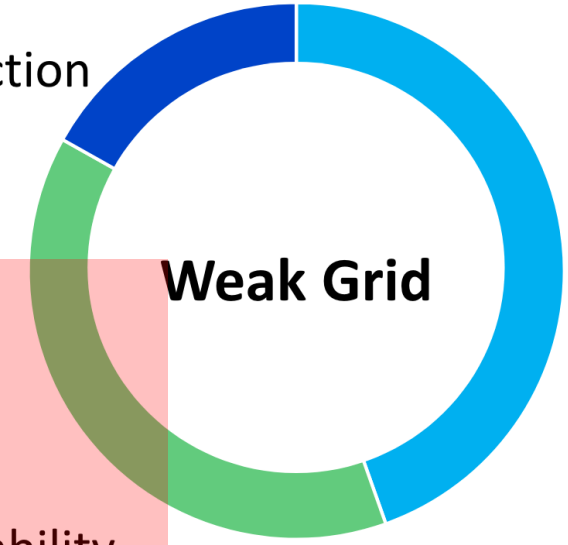
Source: Loutan et al., *Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant* (NLR), 2017), https://docs.nrel.gov/docs/fy17osti/67799.pdf

What Is a Weak Grid (or Weakening Grid)?

These Drive the Need for Re-imagining IBR Controls (grid forming (GFM) IBRs versus grid following (GFL) IBRs)

Low short circuit MVA

- Challenges system protection



High $\frac{\Delta V}{\Delta I}$

high sensitivity of IBR terminal voltage to its current injection

- Challenges stable operation of conventional IBR

High $\frac{\Delta f}{\Delta t}$

low system inertia

- Challenges frequency stability of power system

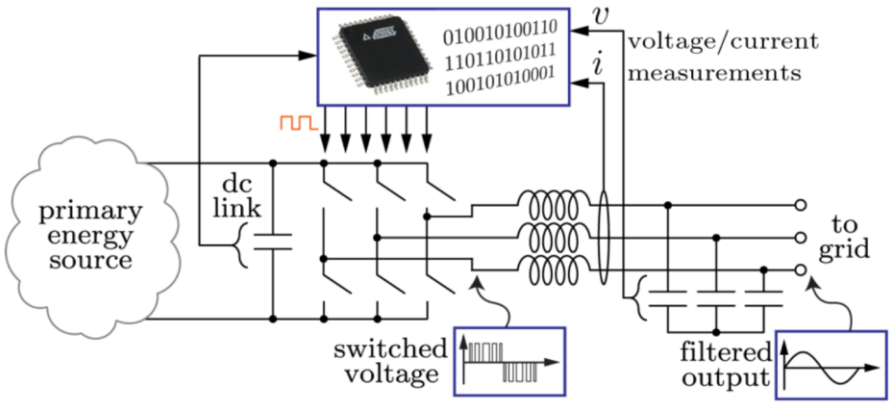
Source: Adjusted from Electric Power Research Institute (EPRI). 2023. "Grid Forming Inverters, EPRI Tutorial (2023)." https://www.epri.com/research/products/000000003002028090.

GFLs and GFMs – What's the Difference?

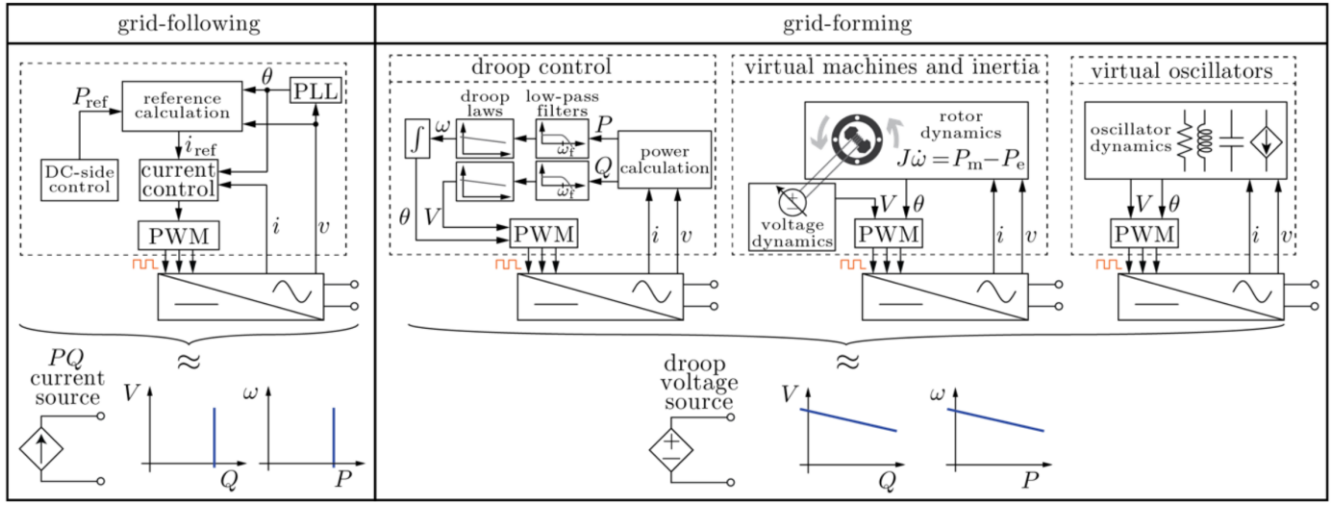
- **Many institutions have offered GFM definitions (2021–2023)**
  - ACER, AEMO, Fingrid, German TSOs, HECO, NGESO, NERC
  - There is no set definition (yet).

- **TLDR…**
  - **GFL** => Mimic current sources
  - **GFM** => Mimic voltage sources.

General structure of an inverter system with closed-loop control



Functional diagrams of grid-following and grid-forming inverters. Grid-following inverters mimic current sources at their output terminals, whereas grid-forming inverters act like voltage sources whose output abides by droop laws.



NREL 2020

Frequency Control With BESS

What Responses Do You Want From BESS?

- IBRs (incl. BESS) can provide classical **primary frequency response (PFR)**
  - Typically, a proportional response to speed.
- Most IBRs (incl. BESS) can provide equivalent inertial response as a **fast frequency response (FFR)**
  - Based on step-response (frequency(F) or rate of chang of frequency (RoCoF) trigger)
  - Based on the derivative of speed (RoCoF).
- **The amount of BESS response and the response's characteristics** depend on your system and how it is expected to evolve:
  - System inertia
  - Size of credible contingency
  - Speed of response
  - Magnitude of response.
- **For BESS,** PFR and FFR will be limited by state of charge (other IBRs potentially constrained by prime mover).

Three main types of FFR provided by IBRs:
(a) grid frequency, f , (b) step response, P_{ffr1}, (c) proportional response, P_{ffr2}, (d) derivative response, P_{ffr3}

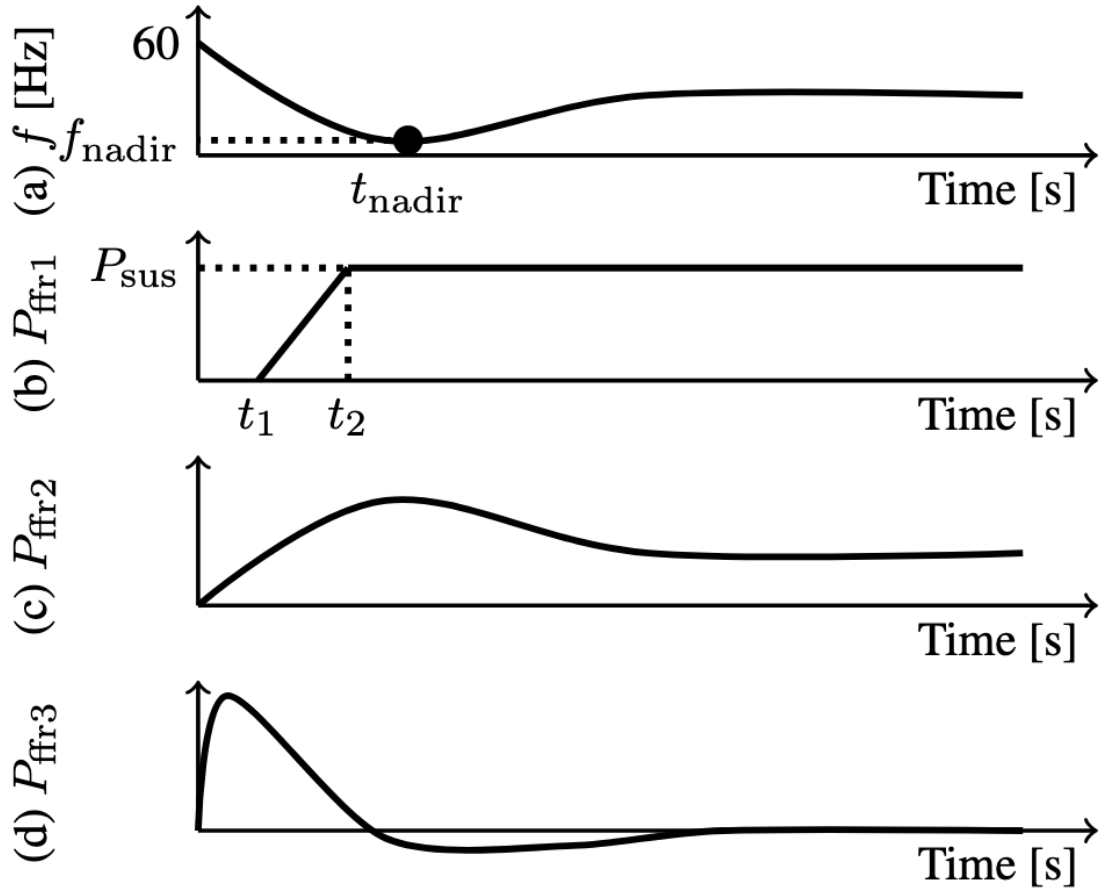
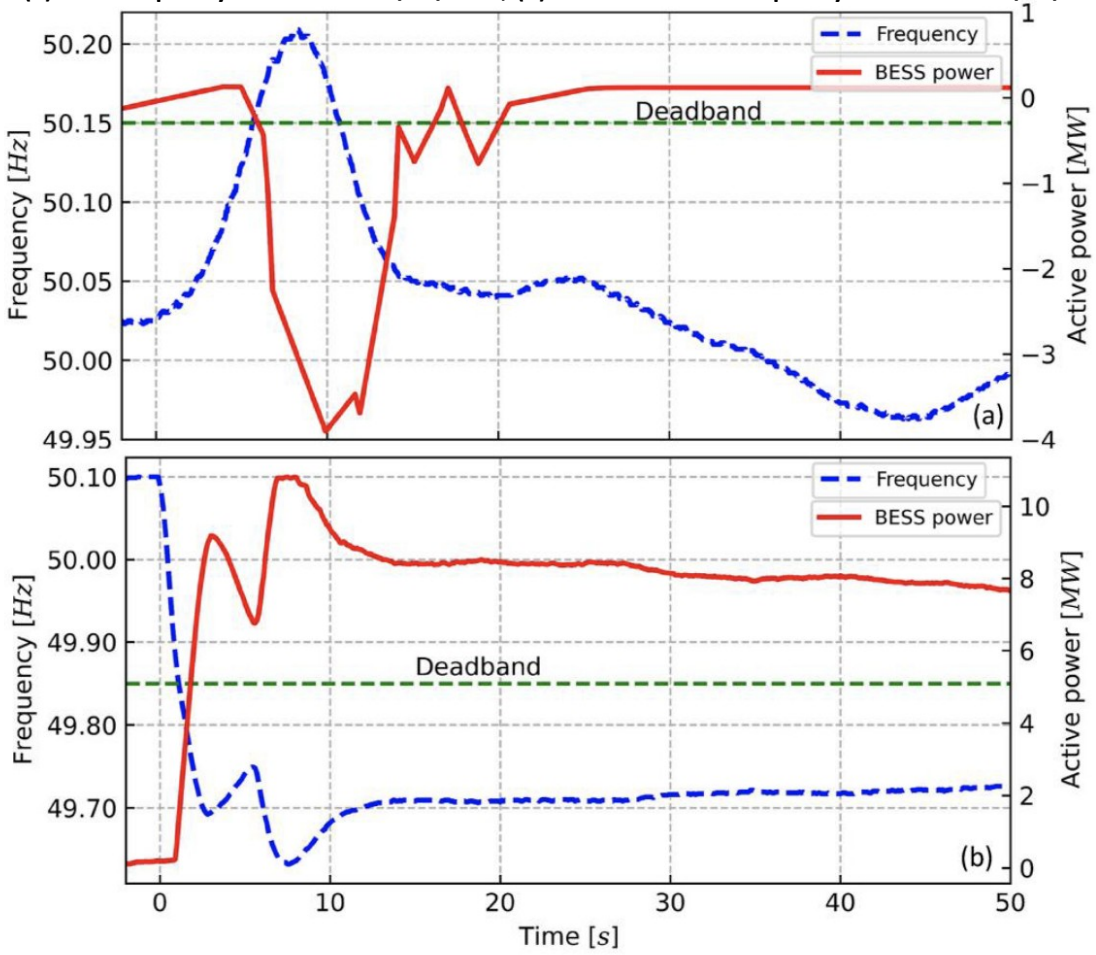


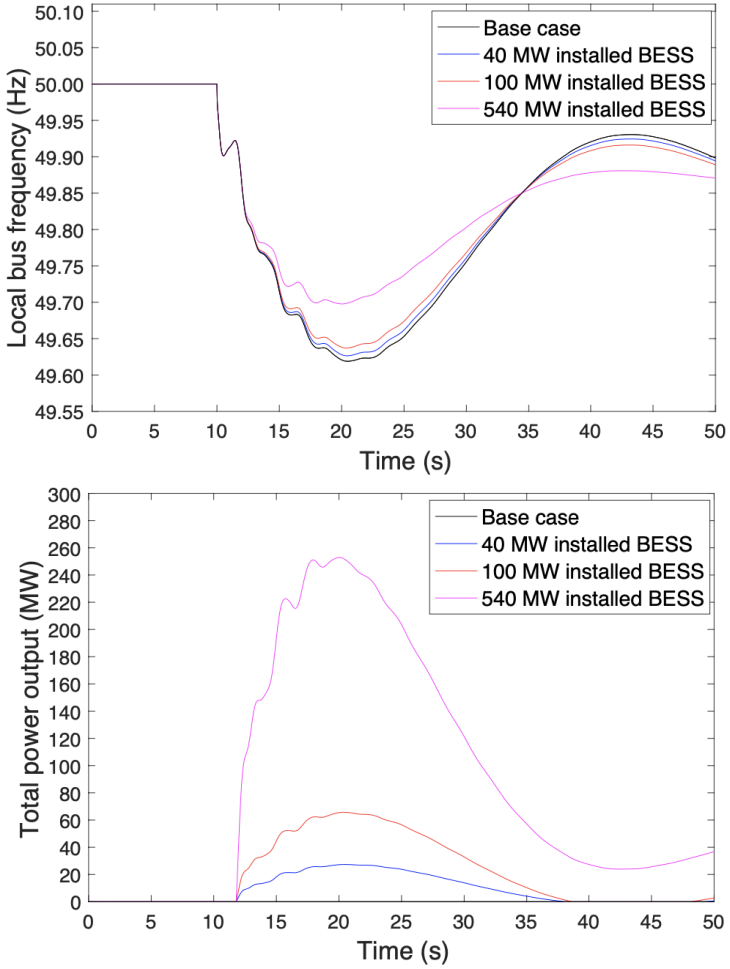
Image from Shuan Dong, Xin Fang, Jin Tan, Ningchao Gao, Xiaofan Cui, and Anderson Hoke. 2023. "A Unified Analytical Method To Quantify Three Types of Fast Frequency Response From Inverter-Based Resources." Presented at the 22nd Wind & Solar Integration Workshop, Copenhagen.

Example of BESS Primary Frequency Response (PFR)

Example of battery energy storage systems (BESS) active power response to frequency disturbances at Kilroot power station (a) over-frequency occurred on 04/03/2016, (b) cascaded under-frequency occurred on 22/11/2021.



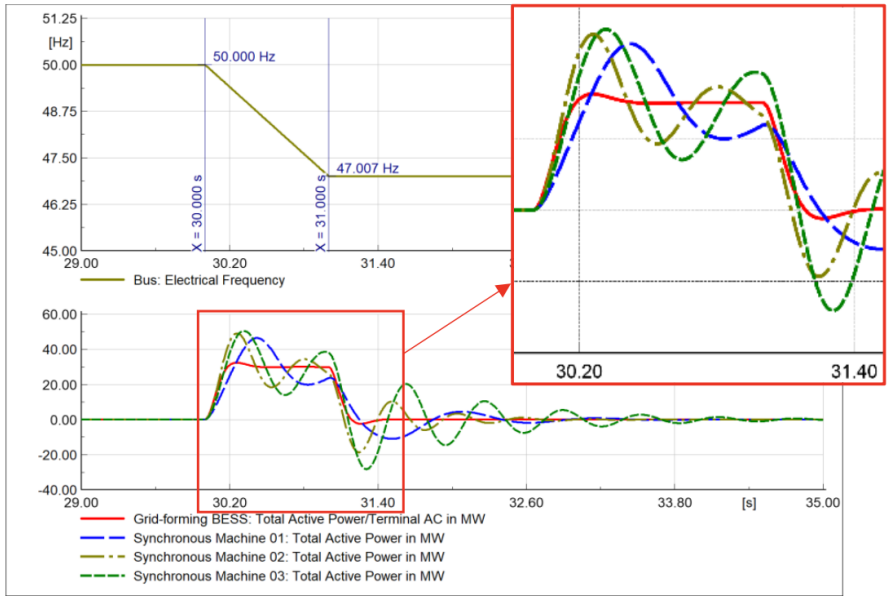
Bus frequency (top) and total electrical power (bottom) for a simulated system response following large generator contingency with varying levels of installed BESS



Images from Al Kez, D., A. M. Foley, F. Ahmed, and D. J. Morrow. 2023. "Overview of Frequency Control Techniques in Power Systems With High Inverter-Based Resources: Challenges and Mitigation Measures." IET Smart Grid 6 (5): 447–469. doi: 10.1049/stg2.12117.

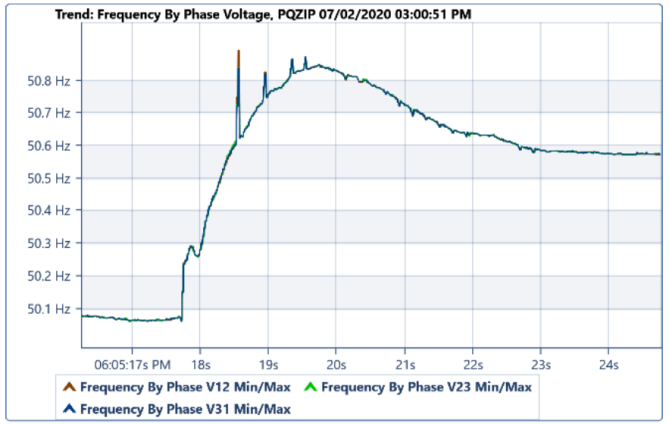
Example of Fast Frequency Response (FFR) From BESS

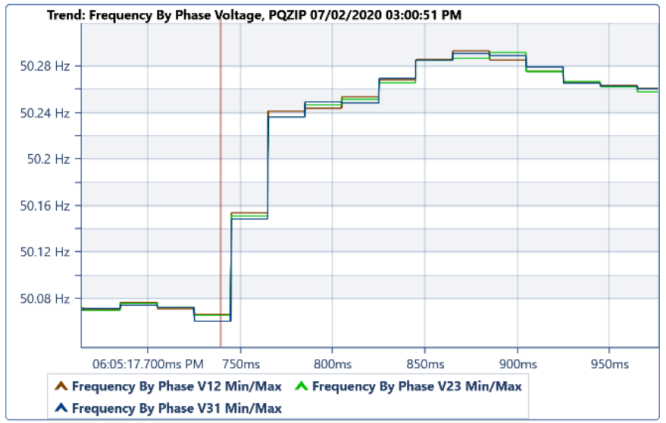
Simulated

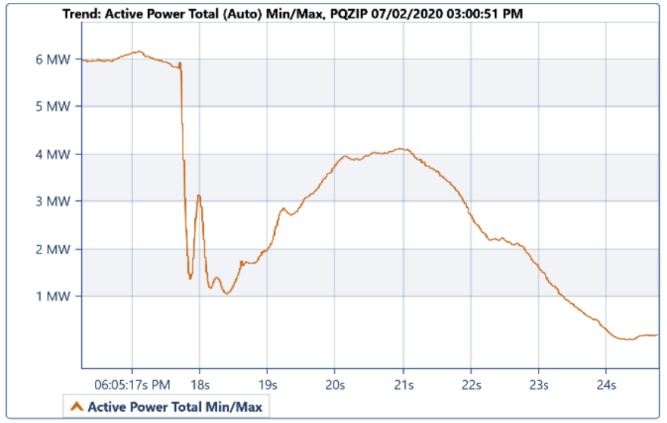


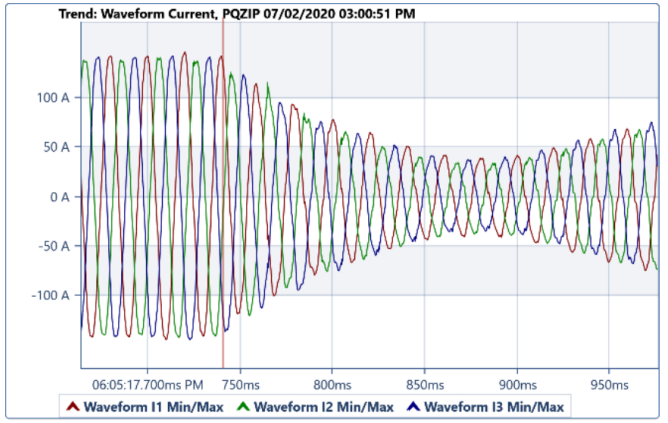
Dalrymple Battery Energy Storage System (BESS), 30 MVA / 8 MWh Grid Forming BESS

Measured









Source: Cherevatskiy, S., S. Sproul, S. Zabihi, R. Korte, H. Klingenberg, B. Buchholz, A. Oudalov. 2020. "Grid Forming Energy Storage System Addresses Challenges of Grids With High Penetration of Renewables (A Case Study)," CIGRE Paris Session.

This presentation was created for electricity sector institutions in Malawi as part of the efforts to establish the Southern Africa Battery Energy Storage Center of Excellence (SABESS CoE), which is supported by the Global Energy Alliance for People and the Planet (The Alliance). For more information about the SABESS CoE, please contact: sabesscoe@mzuni.ac.mw.

Thank You

NLR/PR-2A00-99878

This work was authored by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by Global Energy Alliance for People and the Planet (The Alliance). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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