Utility and Grid Operator Resources for Future Power Systems Webinar Series

Inverter-Based Resources: Challenges and Potential Solutions for Grids With High Levels of Inverter-based Resources

Andy Hoke, Principal Engineer, NREL

Contributors: Shuan Dong, Jin Tan, Soham Chakraborty, Jing Wang

NREL Webinar Series
July 10, 2025

In this presentation

- Introduction: What is an inverter-based resource (IBR), and why do IBRs matter?
- Differences between synchronous machines and IBRs, and resulting challenges
- Some potential solutions for high IBR power systems:
    - Modeling needs, including Electromagnetic Transient (EMT)
    - IBR grid-support capabilities and standards
    - Grid-forming inverters
    - IBR-driven oscillation investigations
    - Protection solutions.
- Potential future challenges and opportunities.

Image Source: NREL

What is an IBR?

- The term IBR refers to **power electronic converter-interfaced generation and storage resources**.
- Most common IBRs are:
  - Solar PV plants
  - Wind (type 3 and type 4, i.e., all wind being deployed today)
  - Battery energy storage.
- STATCOMs and HVDC stations also interface with the grid through power electronics, so they share many qualities with IBRs.

IEEE 2800* definition:

inverter-based resource (IBR): Any source of electric power that is connected to the *transmission system (TS)* via power electronic interface, and that consists of one or more *IBR unit*(s) capable of exporting active power from a *primary energy source* or *energy storage system* to a TS. A *collector system* or a *supplemental IBR device* that is necessary for compliance with this standard is part of an IBR. *See also:* **IBR plant; IBR unit**.


Photo by Gregory Cooper / NREL 89865

**IEEE 2800 includes in its scope HVDC stations dedicated to interconnecting IBRs.*

PV: Photovoltaic.

STATCOM: Static Synchronous Compensator.

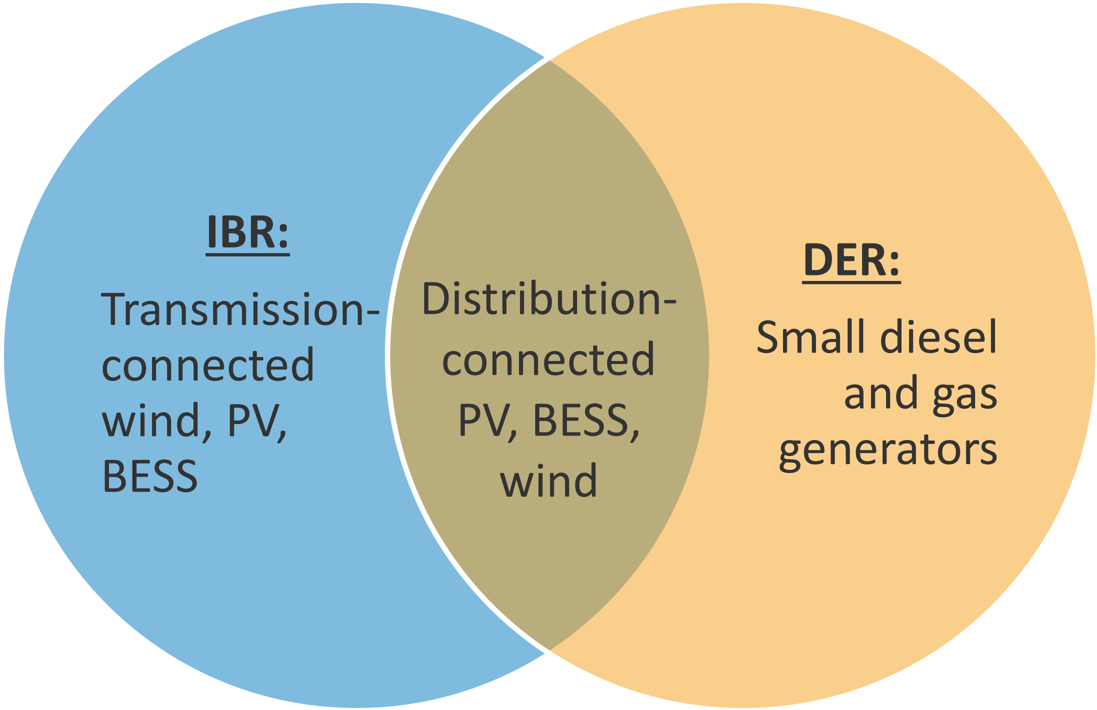
HVDC: High-Voltage Direct Current.

IBR versus DER: What's the difference?

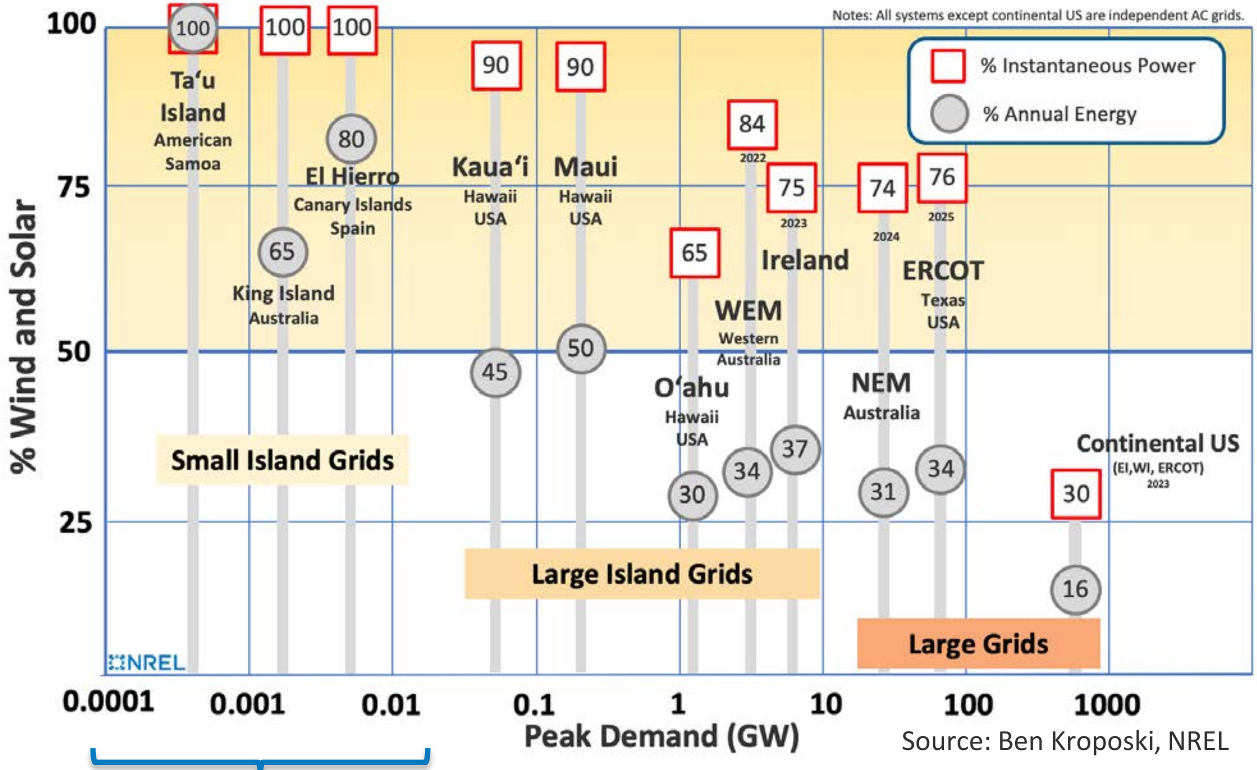
- An IBR can be connected to the bulk power system or a distribution system.
- DERs (as defined in IEEE 1547-2018) are specifically on the distribution system.
- Many DERs are IBRs, including the most common types: PV, battery.
- This presentation focuses on BPS-connected IBRs, but much of it also applies to distribution-connected IBRs.

DER: Distributed Energy Resource.
BPS: Bulk Power System.
PV: Photovoltaic
BESS: Battery Energy Storage System.

Examples of IBRs and DERs



IBRs in the power system today

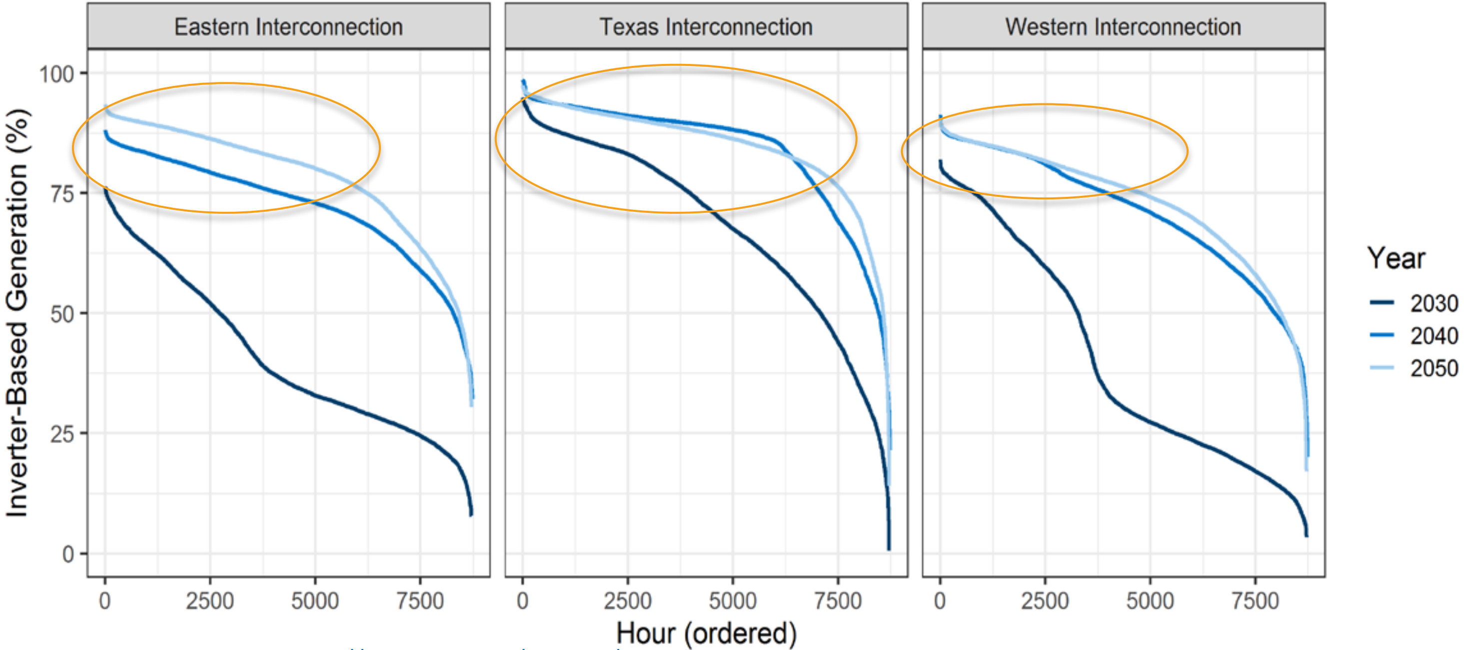


Source: Ben Kroposki, NREL

Small grids with no transmission system

IBRs in the power system tomorrow

All major U.S. interconnections are expected to reach **peak instantaneous IBR levels of 75%–98%** within the lifetime of IBRs being connected today:



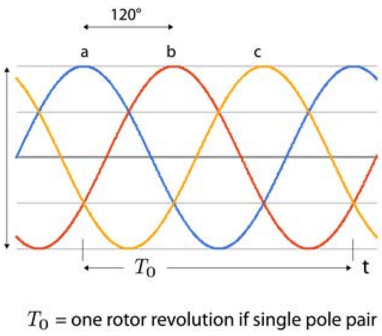
Data from 2021 DOE/NREL Solar Futures Study: https://www.nrel.gov/analysis/solar-futures.html.

In this presentation

- Introduction: What is an inverter-based resource, and why does it matter?
- Differences between synchronous machines and IBRs, and resulting challenges
- Some potential solutions for high IBR power systems:
    - Modeling needs, including EMT
    - IBR grid-support capabilities and standards
    - Grid-forming inverters
    - IBR-driven oscillation investigations
    - Protection solutions.
- Potential future challenges and opportunities.

Image Source: NREL

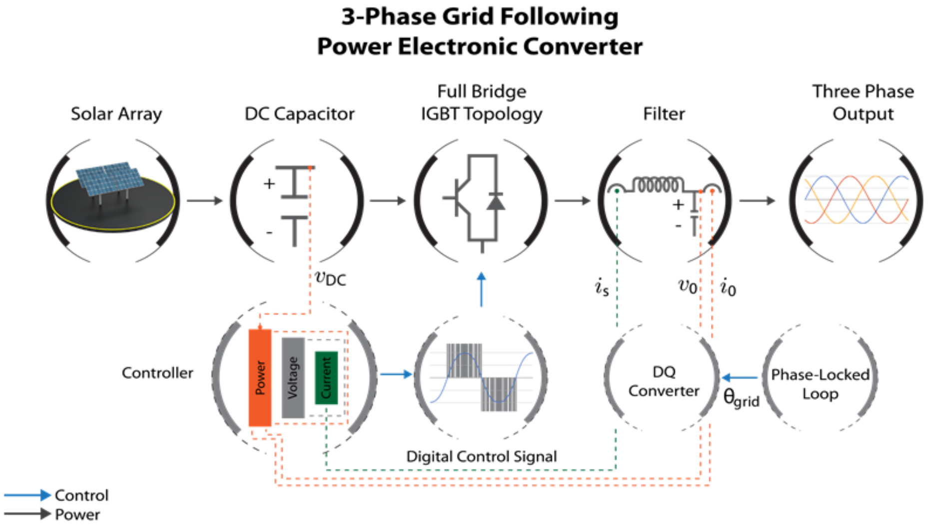
Synchronous generators



- Synchronous generator (SGs) naturally generate a sinusoidal output **voltage** waveform; they are ***grid-forming*** devices.
  - A de-facto voltage source on the power system
  - A large mass (the turbine/machine) is electromagnetically coupled to the AC power system
    - Embeds inertial characteristics.
- Governors, which change mechanical power, are relatively slow (>0.5 second)
  - Load perturbations initially met by inertial energy.
- Large, transient overcurrents in faulted conditions (4 to 7 times rated)
  - Basis for many protection systems.

“Stability and control of power systems with high penetrations of inverter-based resources,” R.W. Kenyon, et al., *Solar Energy*, 2020.

Grid-following (conventional) IBRs



- Inverter tracks the grid's existing, sinusoidal voltage waveform with a phase-locked loop and bases all control objectives on the assumed presence of this waveform
  - Hence, *grid-following ("GFL")*
  - Acts as a current source at fundamental frequency.
- A collection of cascaded dynamic control systems
  - Phase-locked loop
    - To determine phase of the power system.
  - Inner current loops
    - To regulate output current across filter inductor.
  - Power loops
    - To regulate power output to setpoints.
  - Auxiliary control
    - Grid support functionality, self-protection, fault behavior, and so on.
- Pulse width modulation control and associated power electronic switching
  - This happens fast enough not to significantly affect grid stability.
- As a result, grid-following IBRs rely heavily on advanced controls to ensure stable and reliable operation.

"Stability and control of power systems with high penetrations of inverter-based resources," R.W. Kenyon, et al., *Solar Energy*, 2020

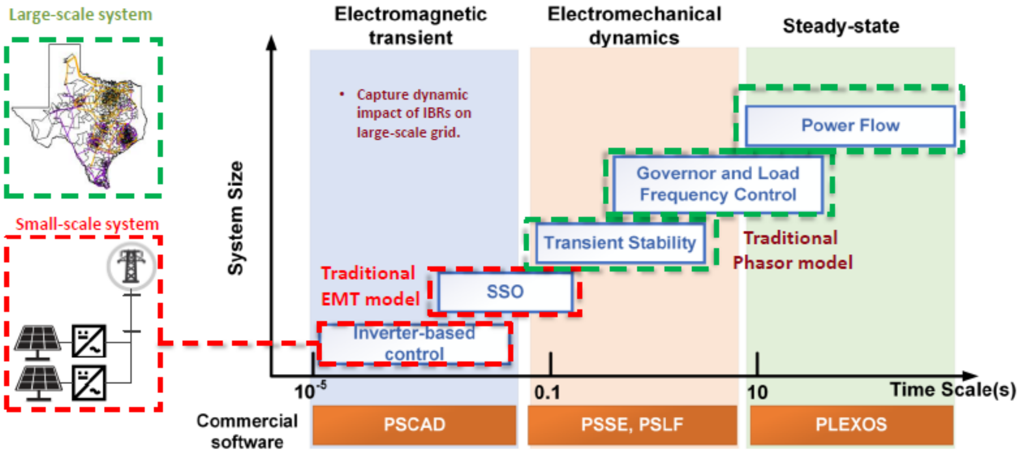
IBR controls

- **Inverter behavior is largely software/firmware driven.**
- Advantages
  - Flexible functionality
  - Adaptable response times
  - Behavior of equipment in field can often be improved without hardware change
  - Allows for innovation
  - Able to respond very quickly if needed.
- Disadvantages
  - Many control details are proprietary to each Original Equipment Manufacturer
  - Challenging for grid operators to handle diverse behaviors
  - Potential for bugs/unexpected behavior
  - Firmware maintenance brings cybersecurity concerns
  - Power system not historically designed for IBRs.


Photo by Werner Slocum / NREL

Challenges of operating grids with very high levels of IBRs

- Load-generation balance at various timescales
  - Sub-second (inertial timescale)
  - Seconds (primary frequency response timescale)
  - Minutes (secondary frequency regulation timescale)
  - Hourly and longer.
- Voltage and frequency transient stability
  - Small-signal stability; control interactions
  - Resilience to faults
  - Resilience to loss of generation/load
  - Resilience to loss of system strength.
- Black start
- Protection
- Fault ride-through.

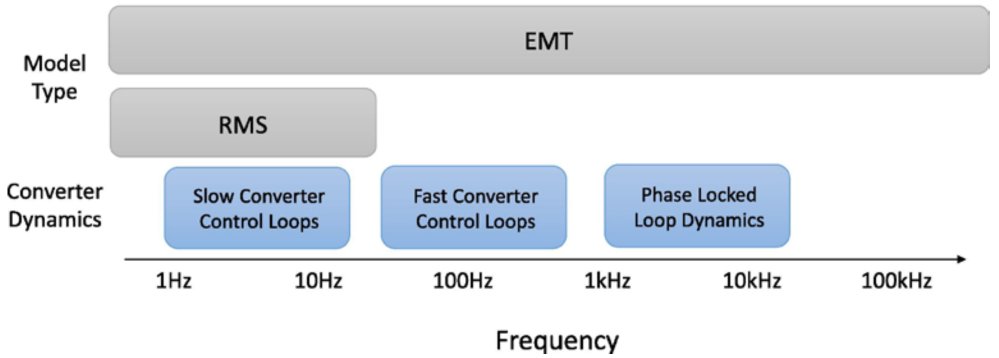


In this presentation

- Introduction: What is an inverter-based resource, and why do they matter?
- Differences between synchronous machines and IBRs, and resulting challenges
- Some potential solutions for high IBR power systems:
  - Modeling needs, including EMT
  - IBR grid-support capabilities and standards
  - Grid-forming inverters
  - IBR-driven oscillation investigations
  - Protection solutions.
- Potential future challenges and opportunities.

Image Source: NREL

Electromagnetic transient simulations



- Inverter controllers act on instantaneous AC voltages (point-on-wave) and can react in well under a line cycle.
- Traditional **positive sequence phasor domain simulation tools** (like PSSE, PSLF, and so on), operating on Root Mean Square (RMS) quantities, capture most conventional power system electromechanical modes well but do not model waveforms and **can miss dynamics faster than a few Hertz.**
- Electromagnetic transient (EMT) simulation tools (e.g., PSCAD, EMTP) can simulate AC waveforms on arbitrarily small timesteps, so can capture full IBR dynamics.
- Model runtimes are orders of magnitude slower.
- New IBRs should provide validated EMT models. EMT studies needed in some cases.

IBR performance needs

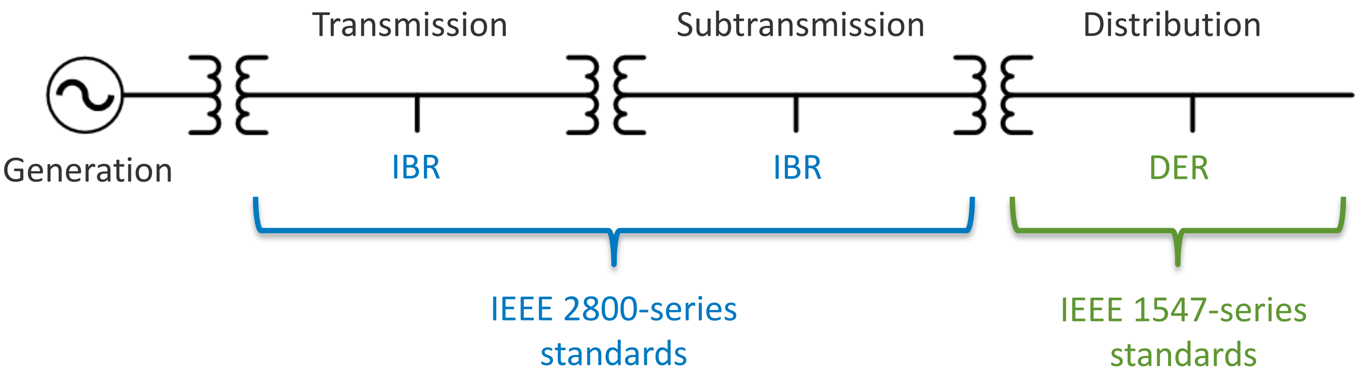
- Grid-supportive IBRs that (among other things):
  - Reliably **ride-through** transient events (low and high voltage, transient over voltage, low and high frequency, ROCOF, phase jumps, consecutive disturbances)
  - Provide configurable **voltage support** across range of operating conditions
  - **Inject current in response to balanced and unbalanced faults**
  - Provide configurable **frequency support** on various timescales.
- **Validated models** that accurately reflect IBR behavior
- **High fidelity data** to support performance monitoring, event analysis.

ROCOF: Rate of Change of Frequency.

IBR interconnection standards

- IEEE 1547 and IEEE 2800 are consensus-based standards developed by working groups open to all stakeholders and focused on North American applications.
- IEEE 1547 has formed the basis for reliable widespread deployment of DERs across all 50 states in the United States for the last 20 years.
- IEEE 2800-2022 is designed to achieve the same goal for BPS-connected IBRs.
  - It contains requirements to address all needs on previous slides.
  - Various entities are in the process of adopting it.

IBR interconnection standards



- Effective interconnection standards are needed from transmission down to distribution.
- Distribution needs differ from transmission needs, leading to two main standards families:
  - IEEE 2800 family: Applies to IBRs (only) on transmission and subtransmission.
  - IEEE 1547 family: Applies to DERs on distribution* including IBRs and synchronous generators.
    - Already widely adopted. Recently made publicly available by IEEE because it was mentioned in Federal Register.

* 1547 can be applied on radial subtransmission as well.

IEEE 2800 adoption status

- Contains technical minimum interconnection requirements for large solar, wind, and storage plants, including offshore wind
- Developed by over ~175 working group participants from utilities, system operators, transmission planners, and OEMs
- Passed the IEEE SA ballot with 466 SA balloters with >94% approval, >90% response rate
- Currently being adopted by many Regional Transmission Organizations/Independent System Operators in North America
- The major IBR manufacturers have stated their equipment can meet IEEE 2800 going forward, but plant still needs to be designed and configured to meet 2800
  - Existing equipment in field may not meet all 2800 requirements, and retrofitting may be costly.

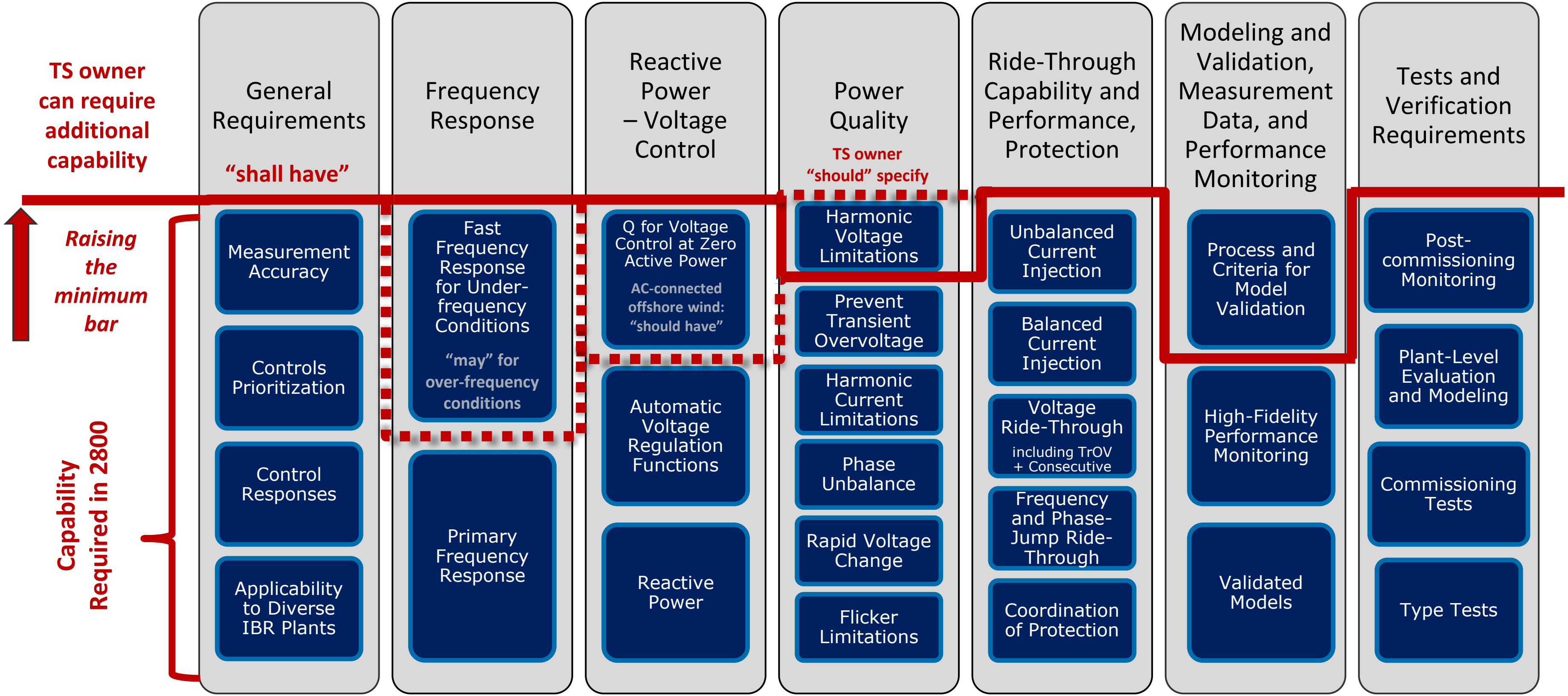
Entities understood to be **adopting** IEEE 2800:

ISO-NY, ISO-NE, MISO, ERCOT, SPP, Duke, SoCo, FPL, HECO, Ameren, AESO, HydroQuebec, SCE, PG&E, SDG&E, BPA, LIPA, TVA, GTC, GPA, and so on

Entities understood to be **considering adopting** IEEE 2800:

BPA, Ameren, Great River, Manitoba Hydro, SaskPower, IESO, PJM, SRP, and so on

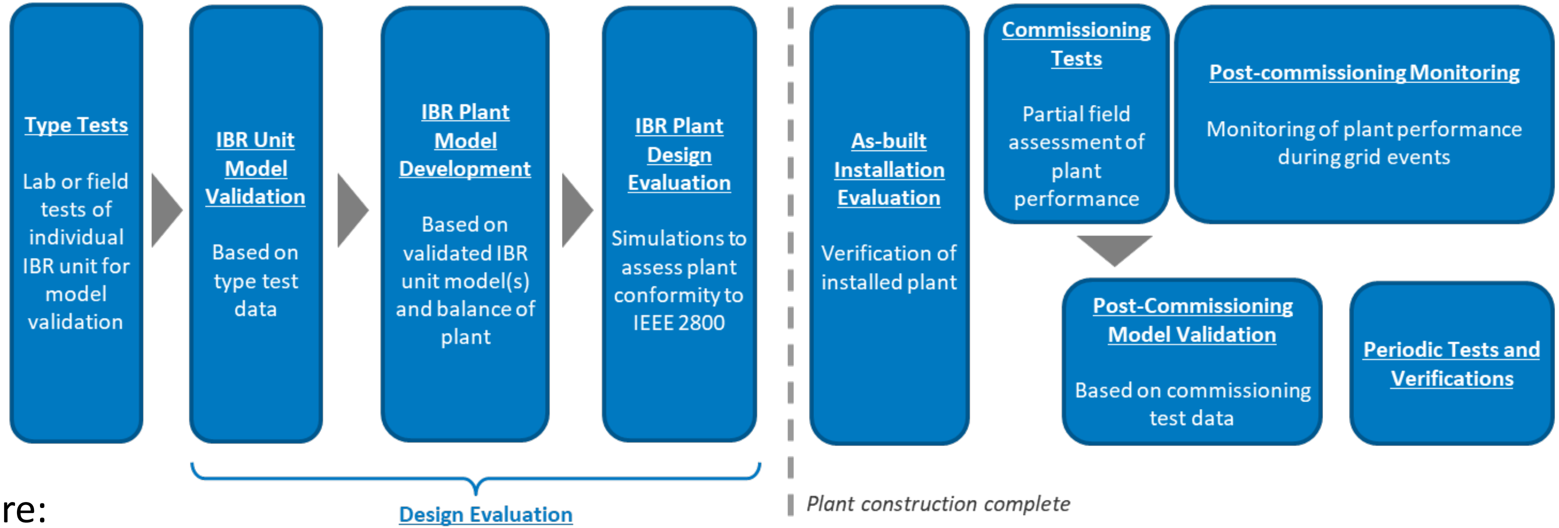
IEEE 2800-2022 technical minimum capability requirements



Source Jens Boemer, EPRI, available publicly at https://www.nerc.com/comm/RSTC/IRPS/IEEE_2800-2022_EPRI-NAGF-NATF-NERC_May_3-2022_Joint_Webinar.pdf

IEEE 2800 next steps

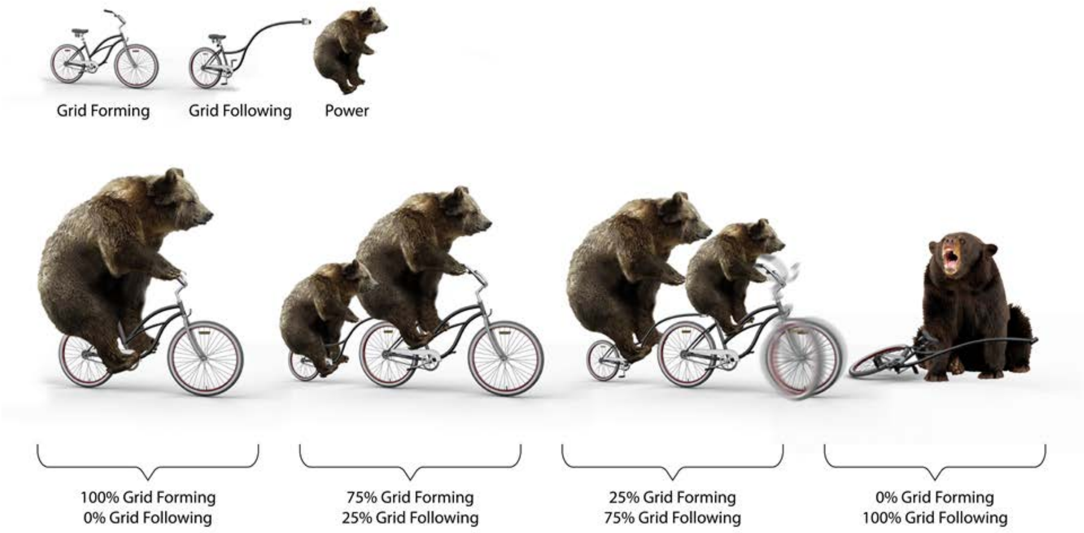
- Ongoing: **Adoption by industry.** Urgent, given high expected IBR deployment
- Ongoing: **Completion of IEEE P2800.2—recommended practice for 2800 conformity assessment** (e.g., tests, modeling, commissioning, monitoring). ***Join us!***



- Future:
  - Update 2800 to reflect lessons learned from adoption*
  - Perhaps an IEEE standard defining grid-forming IBR performance?

*Standards will always be evolving. Don't let that slow adoption.

What happens with fewer synchronous machines?

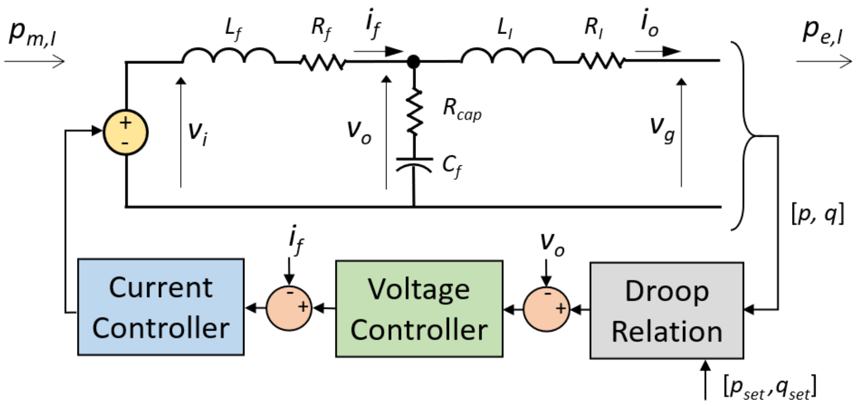


Here, *grid-forming* is a broad term including synchronous machines.

- With fewer grid-forming assets online, the *stiffness* of the AC voltage is reduced.
  - Metrics such as short circuit ratio/system strength attempt to capture this.
- This impacts the stability of assets that require a voltage waveform to operate—i.e., grid-following inverters.
- Not necessarily a low-inertia problem, although there is a relation if the only grid-forming assets involved are synchronous generators.

"Stability and control of power systems with high penetrations of inverter-based resources," R.W. Kenyon, et al., *Solar Energy*, 2020.

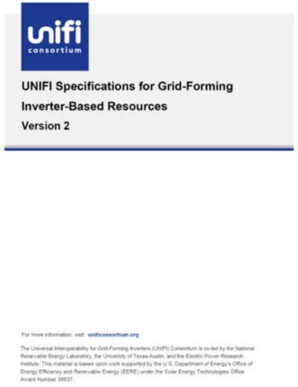
Grid-forming (GFM) inverters



"Stability and control of power systems with high penetrations of inverter-based resources," R.W. Kenyon, et al., *Solar Energy*, 2020.
Grid Forming Technology: Bulk Power System Reliability Considerations, NERC, Dec 2021.
"Research Roadmap on Grid-Forming Inverters," Y. Lin et al., NREL/TP-5D00-73476, Nov 2020.

- Whereas grid-following inverters track an existing AC voltage waveform, a *grid-forming* inverter **generates an AC voltage waveform** at its output terminals
  - Acts as a voltage source
  - Does not depend on external source for stability
  - Inherently resists changes in grid conditions.
- Grid-forming inverters have been used for decades in off-grid/islanded applications
- **Emerging application: grid-connected *GFM inverters in parallel with the rest of the power system***
  - Synchronize with other voltage sources via droop control (or similar).
- Control schemes are designed to accomplish objectives such as
  - Load sharing
  - Voltage control.
- Some limitations compared to grid-forming synchronous machines, such as over-current capabilities
  - Control can be very fast. (Good? Bad?)

Grid-forming (GFM) inverters—state of the art



"Massive Integration of Power Electronic Devices (MIGRATE)," 2017-2020, https://www.h2020-migrate.eu/ .
"Research Roadmap on Grid-Forming Inverters," Y. Lin et al., NREL/TP-5D00-73476, Nov 2020.
"UNIFI Specifications for Grid-forming Inverter-based Resources – Version 2," UNIFI Consortium, April 3, 2024. https://unificonsortium.org/resources/#toc_Specifications_v2.

- Key to operation of power systems at/near 100% instantaneous inverter-based resources
- GFM battery inverters for use in parallel with large power systems are recently available from many manufacturers
    - GFM PV and wind are in R&D stage
- The term "grid-forming" is becoming a buzzword
- NERC Inverter-based Resource Performance Working Group (IRPWG) definition:
    - ~ *"An inverter that maintains a constant voltage phasor in the transient and sub-transient time frames"*
- Positive field experience is emerging
- Performance is not standardized
- Required/incentivized in some recent RFPs.

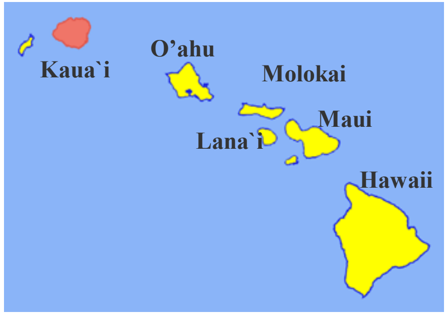
RFP = request for proposal.

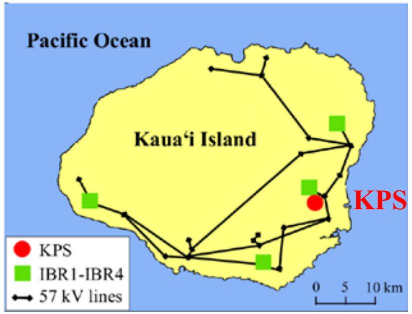
Example NREL study of high-IBR operations

with Kaua'i Island Utility Cooperative, KIUC

19.5 Hz Oscillation Event on Kauai

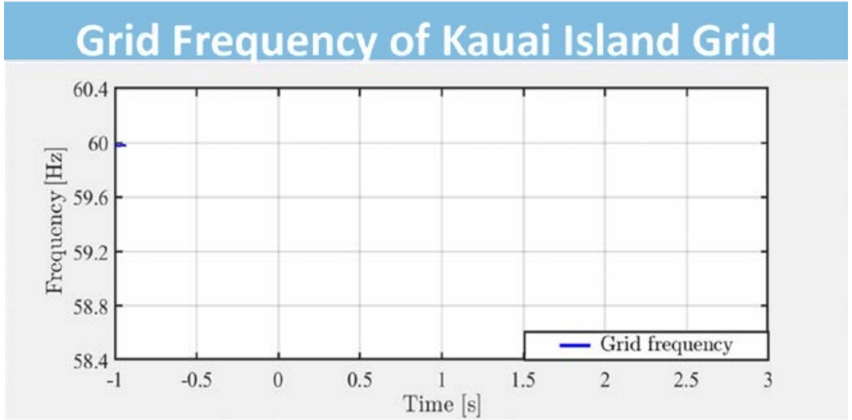
- System peak: 75.17 MW (in 2021)
- **Time:** Nov. 21, 2021, at 05:30:47
  Event: The largest generator (Plant A) on Kauai tripped. It had a 26.6 MW output, **60.6%** of power demand.





Remark:

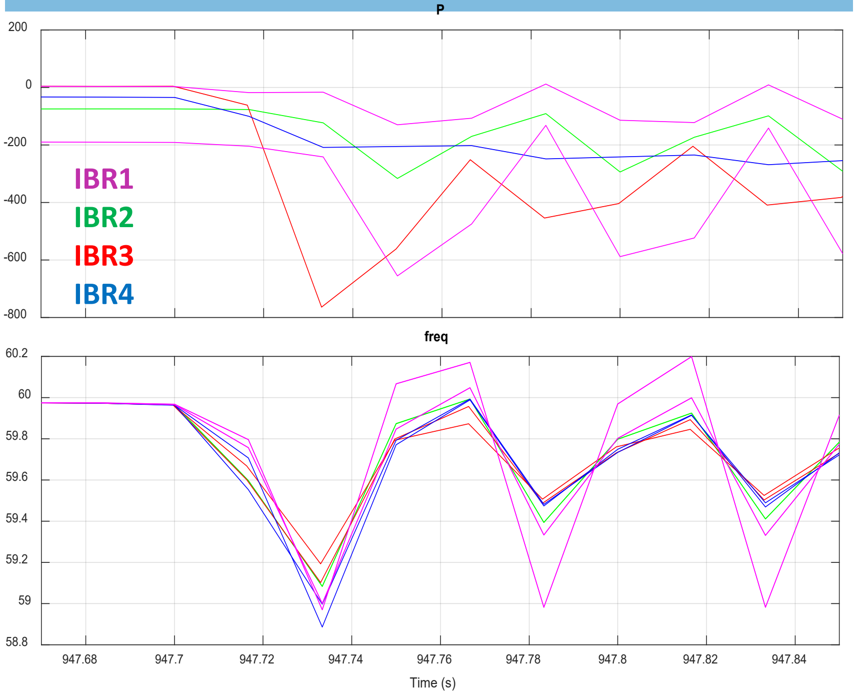
- Fast power response from 4 BESSs avoided significant load shedding and possible blackout.
- Significant **19.5 Hz oscillations** lasted for about 1 minute.



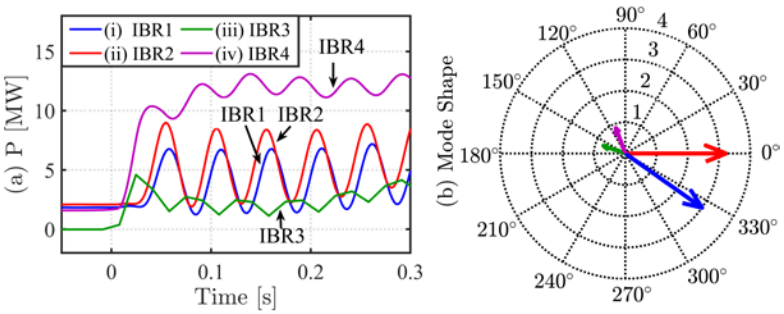
S. Dong, B. Wang, J. Tan, C. J. Kruse, B.W. Rockwell, and A. Hoke, "Analysis of November 21, 2021, Kaua'i Power System 18-20 Hz Oscillations" (https://arxiv.org/pdf/2301.05781).

Oscillation source identification

Method 1: Direct data analysis method (Phasor measurement unit and Digital Fault Recorder (DFR) data)



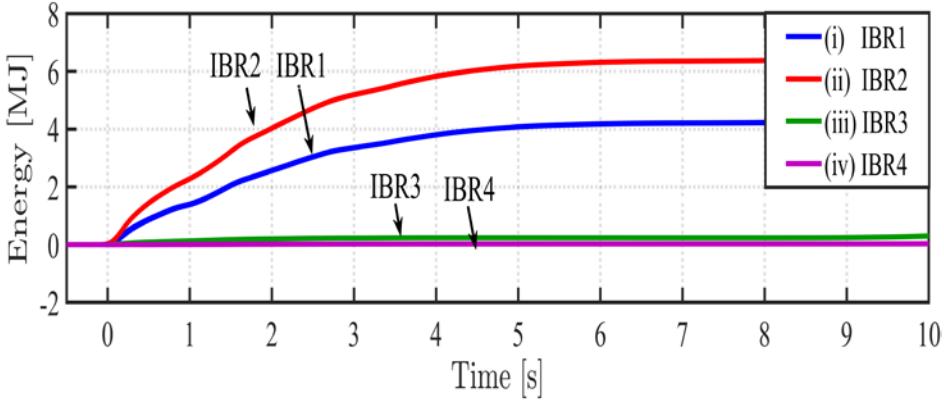
Method 2: Prony analysis of recorded IBR active-power responses



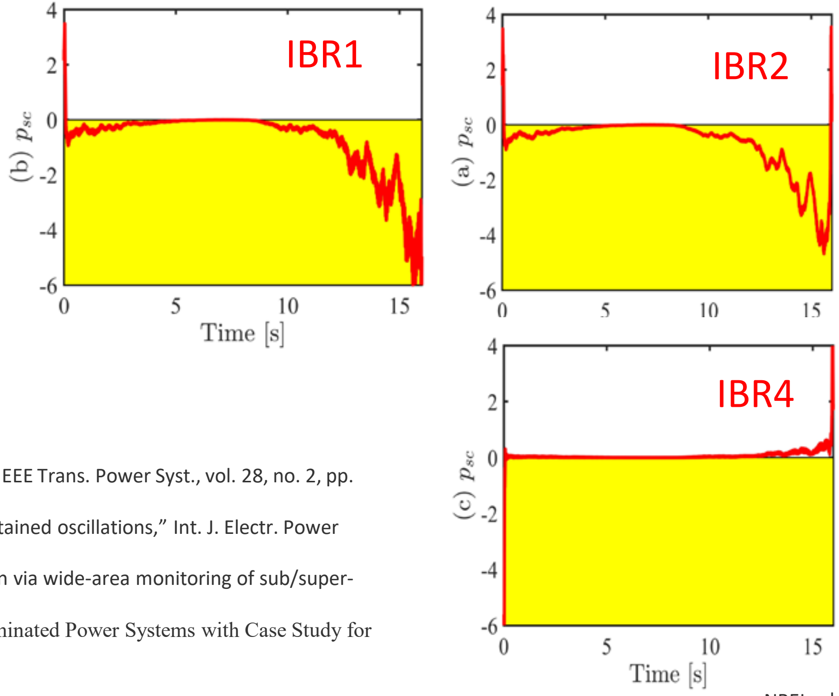
S. Dong, et al., "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems with Case Study for Kaua'i System," *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2025.

Oscillation source identification

Method 3: DEF (dissipating energy flow) analysis method[1,2,4]



Method 4: Sub/Super-synchronous power flow analysis[3]

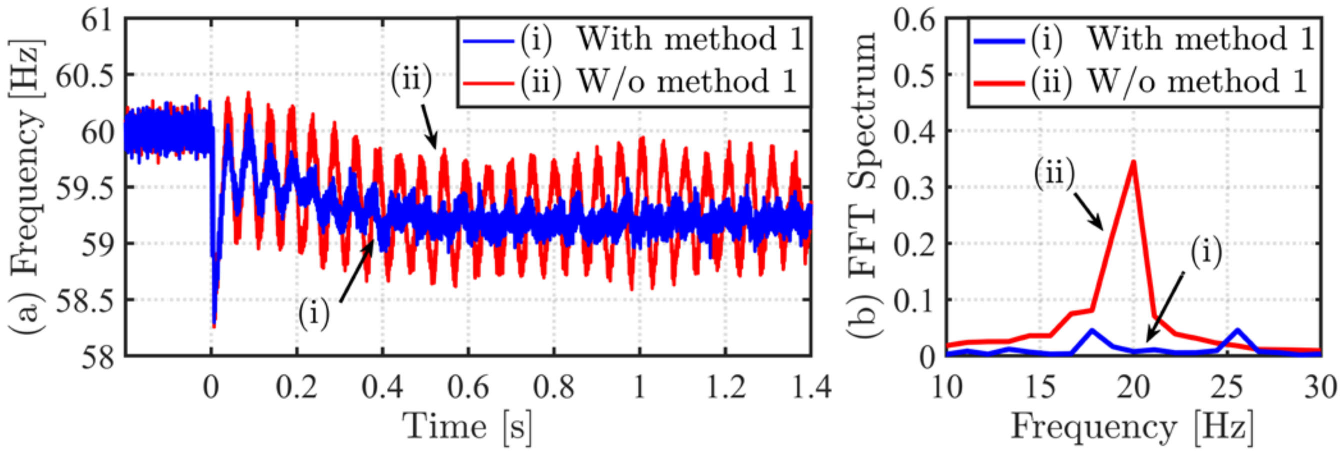


1. L. Chen, Y. Min, and W. Hu, "An energy-based method for location of power system oscillation source," IEEE Trans. Power Syst., vol. 28, no. 2, pp. 828–836, 2013.
2. S. Maslennikov, B. Wang, and E. Litvinov, "Dissipating energy flow method for locating the source of sustained oscillations," Int. J. Electr. Power Energy Syst., vol. 88, pp. 55–62, 2017.
3. X. Xie, Y. Zhan, J. Shair, Z. Ka, and X. Chang, "Identifying the source of subsynchronous control interaction via wide-area monitoring of sub/super-synchronous power flows," IEEE Trans. Pow-er Del., vol. 35, no. 5, pp. 2177–2185, 2020.
4. S. Dong, et al., "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems with Case Study for Kaua'i System," *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2025.

Mitigation method 1: Adjust P/f droop

Method 1: Make the P/f (power/frequency) droop constant less aggressive.

- Test Method 1 in the KIUC EMT model by changing IBR1's and IBR2's inverter-level P/f droop constant from 3% to 4%.
- The simulation results show that it can reduce the ~19 Hz oscillation magnitude and remove the peak in the FFT spectrum.



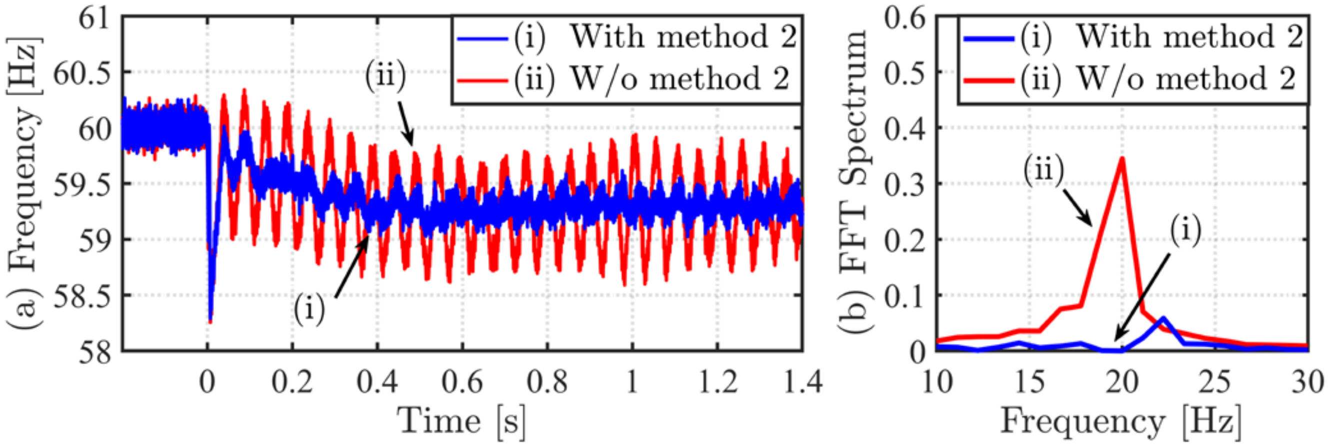
Source: S. Dong, et al., "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems with Case Study for Kaua'i System," *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2025.

FFT = fast Fourier transform.

Mitigation method 2: Adjust PLL parameter

Method 2: Reduce PLL proportional gains.

- Test Method 2 in the KIUC EMT model by reducing IBR1's and IBR2's PLL proportional gains (Kppll) from 0.15 to 0.10.
- The simulation results show that it can the ~19 Hz oscillation magnitude and remove the peak in FFT spectrum.



Source: S. Dong, et al., "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems with Case Study for Kaua'i System," *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2025.

PLL = phase-locked loop.

Mitigation method 3: Upgrading to GFM

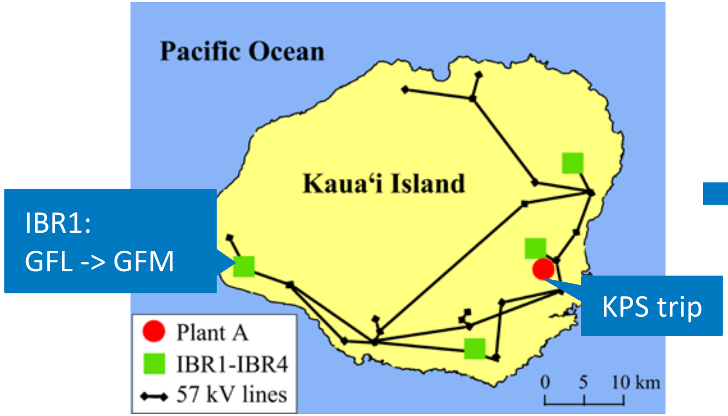
- Event overview with utilities and vendors
- Field data collection
- Oscillation source identification
- EMT model development
- Small-signal modeling and analysis
- **Mitigation methods and their validation**

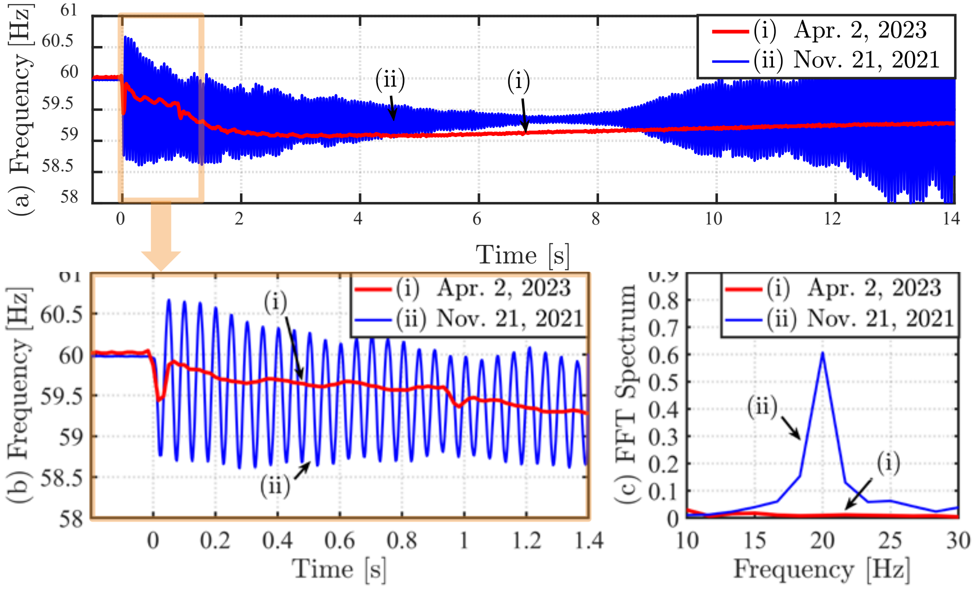
Mitigation Method 3: Upgrading to GFM (Simulation Validation)

		IBR1 (14 MW)	IBR2 (20 MW)	IBR3 (6 MW)	IBR4 (13 MW)	Results
Base case	Case 1 (Base)	GFL	GFL	GFL	VSM	~19.5 Hz oscillation
Upgrade one GFL to droop-based GFM	Case 2(a)	Droop GFM	GFL	GFL	VSM	Stable
	Case 2(b)	GFL	Droop GFM	GFL	VSM	Stable
	Case 2(c)	GFL	GFL	Droop	VSM	Stable
Upgrade one GFL to VSM	Case 3(a)	VSM	GFL	GFL	VSM	Stable
	Case 3(b)	GFL	VSM	GFL	VSM	Stable
	Case 3(c)	GFL	GFL	VSM	VSM	Stable
Upgrade all GFLs to droop-GFM or VSM	Case 4	Droop GFM	Droop GFM	Droop GFM	Droop GFM	Stable
	Case 5	VSM	VSM	VSM	VSM	Stable

GFL = grid following.
VSM = virtual synchronous machine.

April 2, 2023, event: GFM removes oscillations





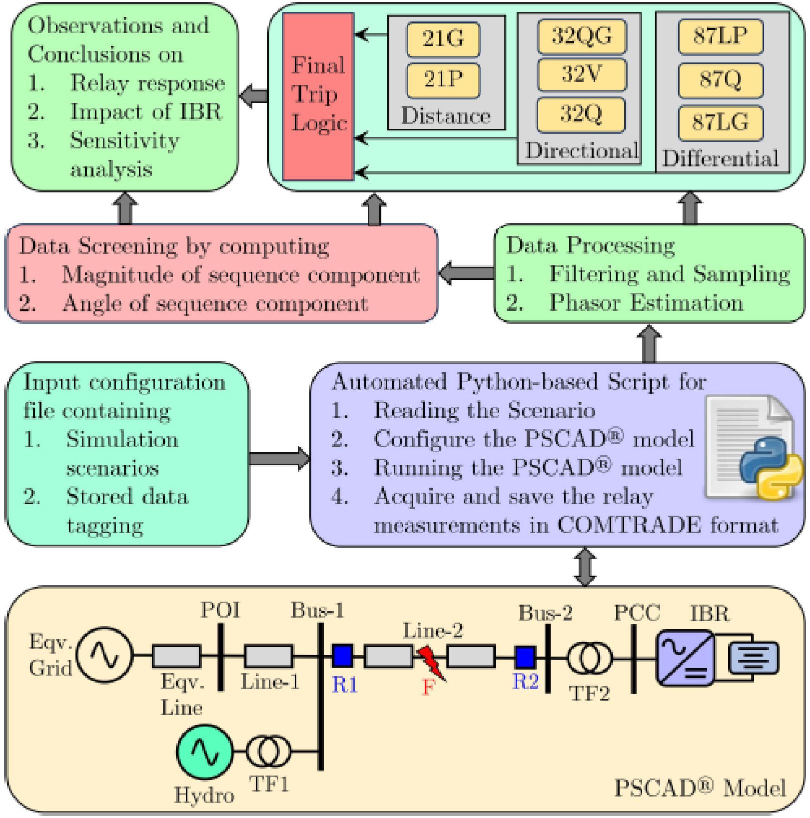
- **Event:** On April 2, 2023, Plant A was tripped again with output power ~25 MW. But IBR1 had been upgraded to GFM, and IBR3's BESS had been decommissioned.
- **Observation:** No ~19.5-Hz oscillation (see red traces) following trip on April 2, 2023. So, adopting GFM effectively mitigates the ~19.5-Hz oscillation and improves the system stability.
- **Question:** The frequency nadir is low (~59.1 Hz). Adopt more aggressive P/f droop at IBR1?

KIUC study conclusions

Conclusions:

- PSSE model does not capture fast IBR-driven oscillation.
- PV-BESS plants can provide extremely fast response to frequency events.
  - GFM plants are faster and more stable.
- Two PV-BESS plants from different vendors have been operating stably on Kauai for 2 years.
  - One uses droop-based GFM; the other uses virtual synchronous machine-based GFM.
- KIUC's power system operates with up to 90% inverter-based resources and 100% renewable many days.
  - KIUC plans to add two more GFM BESS and one smaller synchronous condenser.
- As with any plant, it is important to verify that GFM inverters will ride through system events.

Protection for high-IBR grids (ongoing)



Preliminary results:

- Differential protection is typically reliable at moderate IBR levels but may need adjustment for very high IBR levels.
- Backup protection is still needed, unless differential has redundant high-speed communications.
- Distance protection works if IBRs meet IEEE 2800 fault current injection requirements.

Paulo Pinheiro et al., "Benefits and Recommendations for Using Classic Protection Functions in Transmission Lines Interfacing IBRs Compliant to IEEE 2800," CIGRE Grid of the Future Symposium, November 2024.

Conclusions

- IBRs (solar, wind, batteries) are becoming widely adopted power sources.
- Operating high-IBR power systems bring challenges that are not present with lower levels of IBRs.
  - Needs advanced planning and implementation of appropriate standards/grid support.
  - IBRs will need ride-through, voltage and frequency support, accurate models, and so on.
  - IEEE 2800 addresses these topics, and many entities are already adopting it.
- Because it can be logistically challenging and expensive to retrofit IBRs with new capabilities, it is important that IBRs being installed today have the functionalities needed for high-IBR conditions.
  - Adopt latest standards (and continue to update them).
- For very high IBR conditions, some IBRs will need to be grid-forming.
  - Grid-forming battery inverters are available for BPS applications and add little cost relative to conventional battery inverters.

Future challenges and opportunities

Challenges:

- The response of IBRs to faults on the transmission system differs greatly from that of synchronous machines. At current IBR levels, this is a manageable problem. Better solutions may be needed in the future for very high IBR levels.
- Getting the generation to the load centers. **We need to proactively build transmission.** (Not an IBR-specific problem… it just happens that PV and wind are often far from load and benefit from geographical diversity.) See https://www.nrel.gov/grid/national-transmission-planning-study.html.
- We will need firm generation and/or long-duration storage for days/weeks of low solar and wind output.

Opportunities:

- Because grid-forming inverters dampen fast dynamics, it *may* be possible to reduce the need for EMT modeling once we have confidence in GFM performance. This can speed interconnection.
- IBR vendors can provide validated dynamic models (phasor and EMT).

Thank You

www.nrel.gov

Contact: Andy.Hoke@nrel.gov

NREL/PR-5D00-92325

This work was authored by NREL for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding for the technical work provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. Funding for the webinar preparation provided by the U.S. Department of Energy Office of Policy. 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.

NREL