Island Power Systems With High Levels of Inverter-Based Resources: Stability and Reliability Challenges

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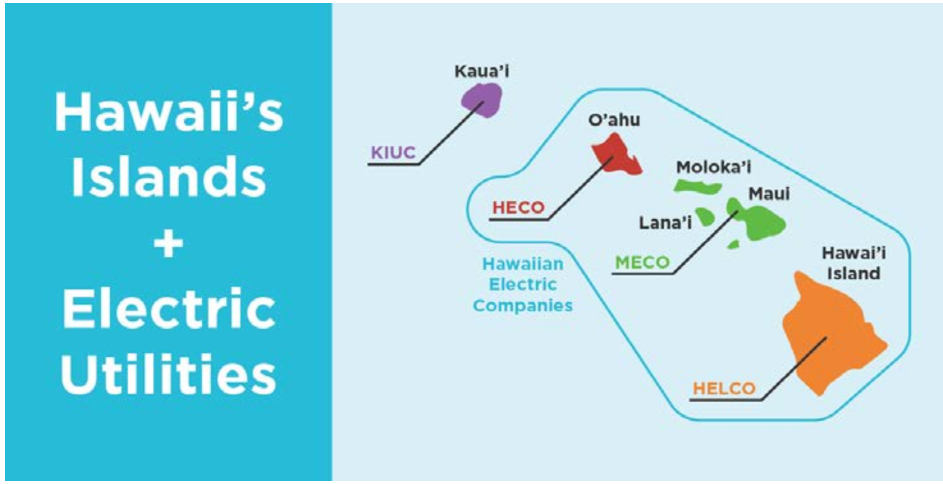
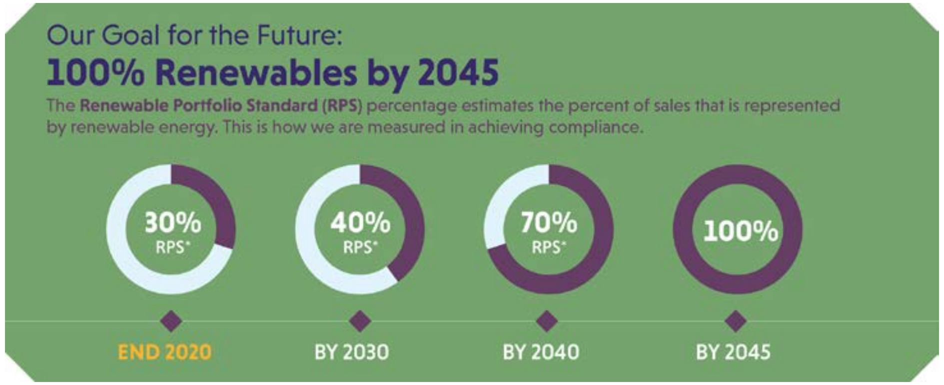
Content

- Why Island Power Systems?
- Stability and Reliability Challenges
- Example: 19.5-Hz Oscillation Event on Kauaʻi Island in 2021
- Path Forward—Ongoing Actions

Why Island Power Systems?





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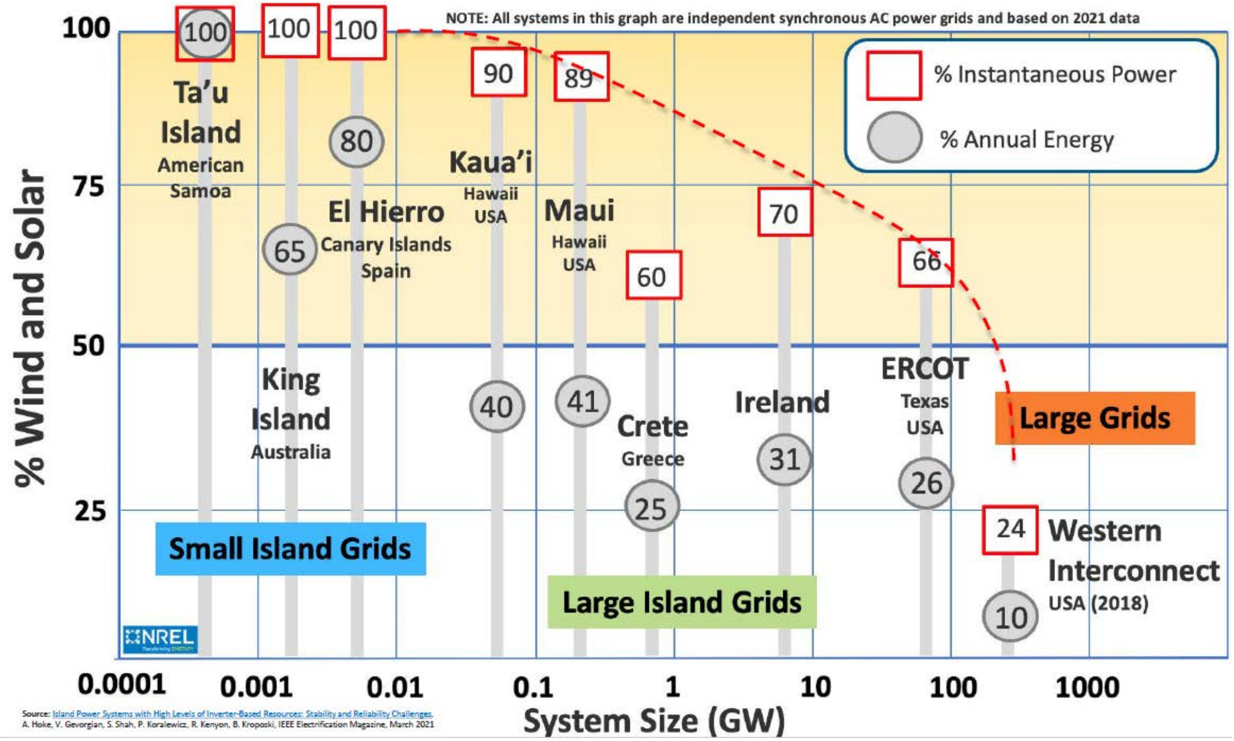


Credit: Benjamin Kroposki, NREL, 2021

The experience we cumulated from the island grids could forge a path of transforming a larger power grid into a highly renewable future.

Stability and Reliability Challenges

Operation

- Variability and uncertainty from renewables: Maintain the balance between production and consumption.
- Transient stability:
  - Frequency response: low inertia, high rate of change of frequency
  - Voltage stability issues
  - Oscillations caused by inverter-based resources (IBRs).
- Protection issues
- Frequency measurement issue
- Gaps between the scheduling and dynamics:
  - How do we ensure stability source adequacy at the planning and operation stage?

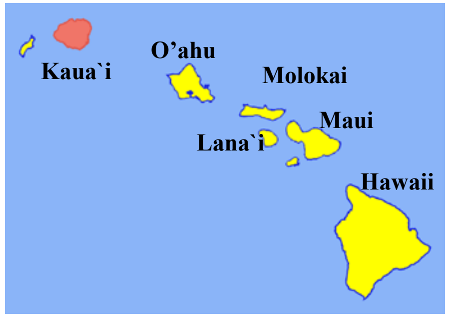
Planning

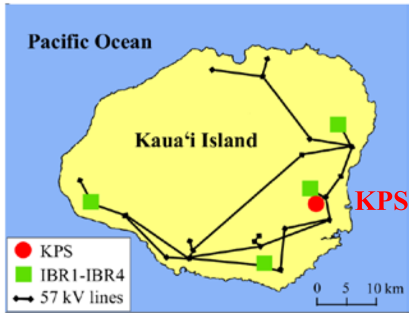
- Need for new technologies and controls:
  - Grid-forming (GFM) inverters, battery energy storage systems (BESS), etc.
  - Advanced controls from IBRs, such as fast frequency response (FFR), secondary frequency control, and black start
  - Coordination between IBRs and batteries.
- Dynamic simulation and analysis tools:
  - In the past: phasor-domain transient dynamics (PSS/E, PSLF, PowerWorld, etc.)
  - Today:
    - Full electromagnetic transient (EMT) simulation tools (PSCAD, RSCAD, etc.)
    - Co-simulation of phasor and EMT models.

19.5-Hz Oscillation Event on Kaua‘i Island in 2021

Kaua‘i Island Utility Cooperative (KIUC)

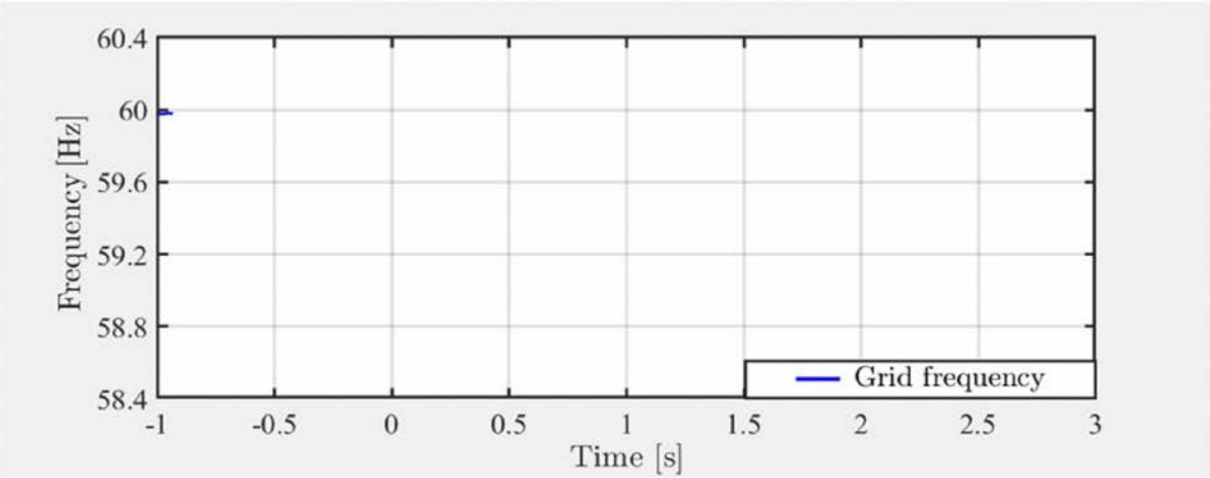
- System peak: 75.17 MW (in 2021)[1]
- **Time:** Nov. 21, 2021, at 05:30:47 a.m.
- **Event:** The largest generator (KPS) on Kaua‘i tripped. It had a 26.6-MW output, **60.6%** of power demand.





Remark:
- Fast frequency responses from four BESS avoided blackout.
- Significant **19.5-Hz oscillations** lasted for about 1 minute.

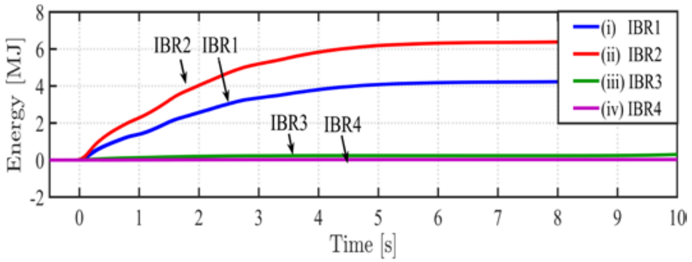
Grid Frequency of Kaua‘i Island Grid



* S. Dong, B. Wang, J. Tan, C. J. Kruse, B. W. Rockwell, K. Horowitz, and A. Hoke, “Analysis of November 21, 2021, Kaua‘i Power System 18- to 20-Hz Oscillations” (to be submitted).

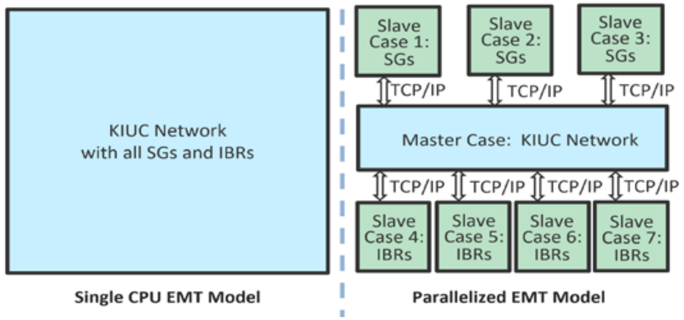
Oscillation Investigation (I)

Step 1: Oscillation Source Location



- Direct
- DEF[1,2]
- Sub/Super-Synchronous Power Flows Analysis [3]

Step 2: Full EMT Model Development for KIUC

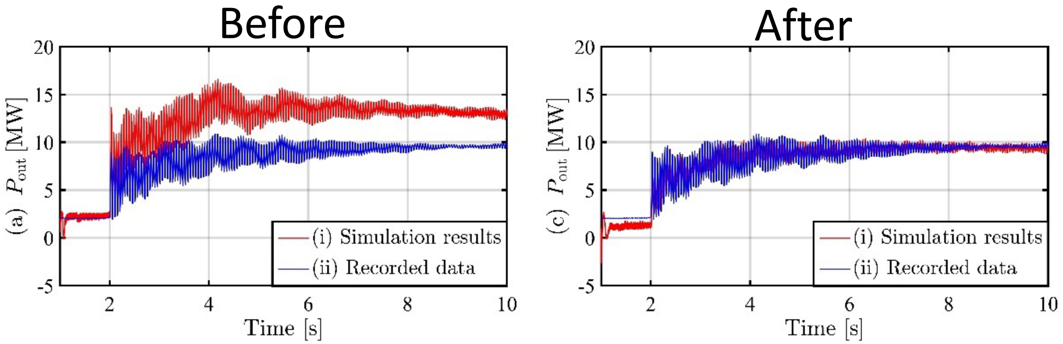


Simulating KIUC for 10s in PSCAD

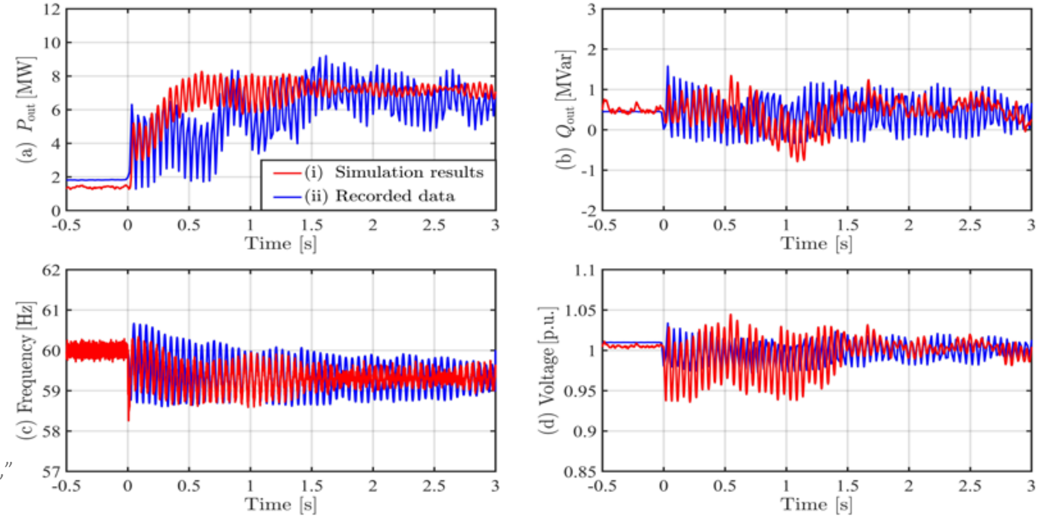
Before: **269 s***

After: **180 s**

Step 3: Tuning of Vendor-Provided IBR Models



Step 4: Event Replay Based on Full EMT Model



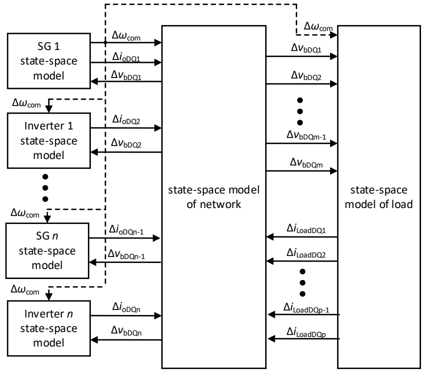
P, Q, Freq, and V response of IBR1.

1. L. Chen, Y. Min, and W. Hu. 2013, "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. Power Del.*, vol. 35, no. 5, pp. 2177–2185, 2020.

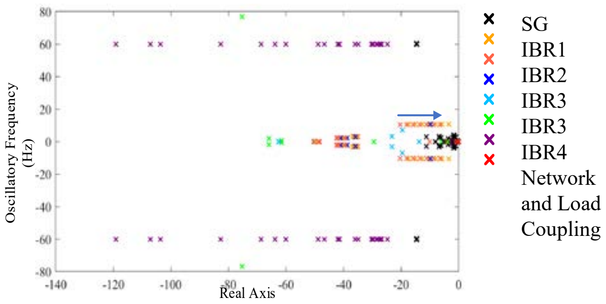
Oscillation Investigation (II)

Step 5: Develop an EMT-Oriented Small-Signal Analysis Model for KIUC

A modularized small-signal model of a large-scale grid based on the EMT model



Sensitivity study of control parameters (e.g., change Kp_{PLL} (PLL proportional gain) of IBR1 and IBR2 from 0.1 to 0.8)



Credit: Xiaonan Lu, Purdue University, 2022

Findings:

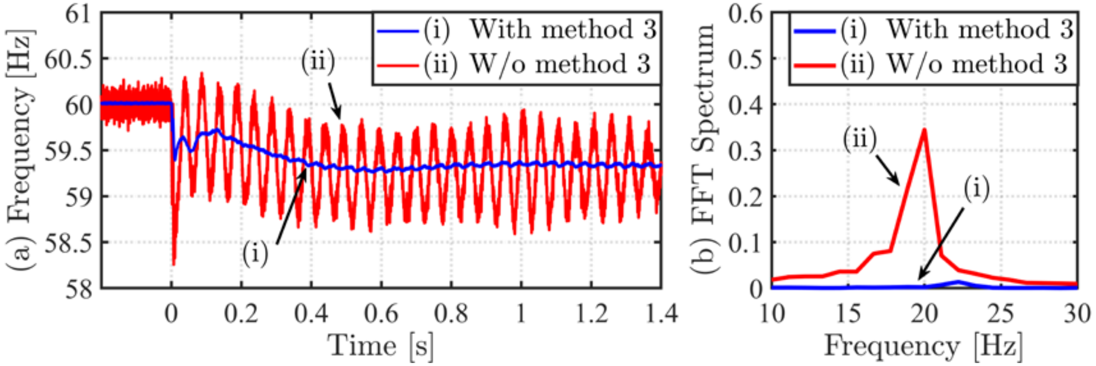
- Three grid-following (GFL) inverters could introduce some approx. 10- to 20-Hz oscillatory modes. They are well-damped before the event and move toward the imaginary axis (less damped) after the event.
- Properly tuning droop parameters, PLL could improve the damping for the 19.5-Hz oscillation modes.

Step 6: Mitigation Method and EMT Validation

Method 1: Make the P/f droop constant less aggressive.

Method 2: Reduce the PLL proportional gains.

Method 3: Convert existing GFL to GFM inverters.



Findings:

- The oscillation event is more related to **P and frequency** instead of Q and V.
- More than one mitigation method could be proposed. GFM is an effective one.

Path Forward—Ongoing Actions

From the planning and operation perspective:

- How to ensure stability resource adequacy at the scheduling stage → sufficient inertia, FFR, and active power reserve in IBRs
  - FFR quantification[1]
  - Add stability constraints to scheduling.[2]

From a control perspective:

- GFM control for HPP
- Black-start capability from IBRs and battery
- Advanced/coordinated controls of IBRs and battery.

From a simulation tool perspective:

- Needs for a fast EMT simulator for a large-scale power system (PSCAD, RSCAD, ParaEMT[3])
- Needs for co-simulation of phasor and EMT models (I PEP)
- Need multi-timescale tools to bridge the simulation gaps between the advanced ancillary service and advanced control of IBRs and to understand the trade-off among economics, stability, and reliability (FESTIV[4], MIDAS[5]).

From a stability analysis perspective:

- Needs for an EMT-oriented stability analysis tool to understand the root cause of this >10-Hz system-wide oscillation problem
- Measurement-based stability analysis tool (impedance scanning)
- Accurate frequency measurements and controls.

1. S. Dong, X. Fang, J. Tan, X. Cui, and A. Hoke, "Analytical Frequency Nadir Prediction Considering Inverter-Based Fast Frequency Response" arXiv preprint arXiv:2209.09413, 2022.
2. X. Liu et al., "Data-Driven Frequency Stability Constrained Unit Commitment: An Island System Study (submitted to *IEEE Trans. Sustainable Energy*).
3. B. Wang, J. Macck, D. Vaidhynathan, M. Reynolds, and J. Tan, "ParaEMT: Large-Scale Parallelizable Electromagnetic Transient (EMT) Dynamics Simulator," NREL, Golden, CA, Tech. Rep., forthcoming.
4. NREL, "Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV)."
5. H. Yuan and J. Tan, "Multi-Timescale Integrated Dynamics and Scheduling for Solar (MIDAS)," presented Feb. 18, 2020.

Path Forward—Open Questions

From the planning and operation perspective:

- What constraints and requirements are needed for IBRs to ensure the stability and reliability of a high-IBR dominated grid?

From a control perspective:

- How to identify the potential stability issues related to control in the planning stage?
- Standards and codes development.

From a simulation tool perspective:

- When do we need to transition to EMT simulations? And how?
- While we are developing GFL/GFM models in the phasor domain, what dynamics do we expect them to capture, and what might not?

From a stability analysis perspective:

- What are the driving factors for stability in the future grid?
- What should be the ratio of voltage-controlled resources (conventional generators, GFM inverters, and synchronous condensers) to current-controlled resources (GFL inverters) in a system for ensuring stability?

A. Hoke, V. Gevorgian, S. Sha, P. Koralewicz, R. Kenyon, and B. Kroposki, "Island Power Systems With High Levels of Inverter-Based Resources: Stability and Reliability Challenges," in *IEEE Electrification Magazine*, vol. 9, no. 1, pp. 74-91, March 2021, doi: 10.1109/MELE.2020.3047169.

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Thank you. Questions?

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