Analysis of 19.5 Hz Oscillation on Kaua'i Island System

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Joint work with KIUC, AES and Purdue University

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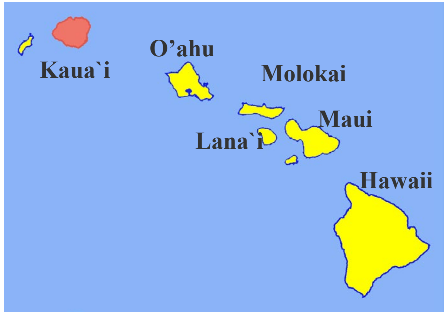
Agenda

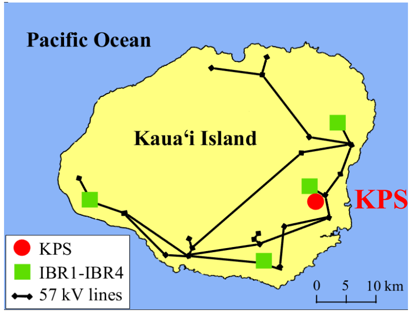
1. Background of KIUC oscillation event on Nov. 21, 2021
2. Measurement-based oscillation source identification
3. EMT model development and event replay
4. Dive in: Small signal analysis
5. Mitigation methods

19.5 Hz Oscillation Event on Kauai Island in 2021

Kaua'i Island Utility Cooperative (KIUC)

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

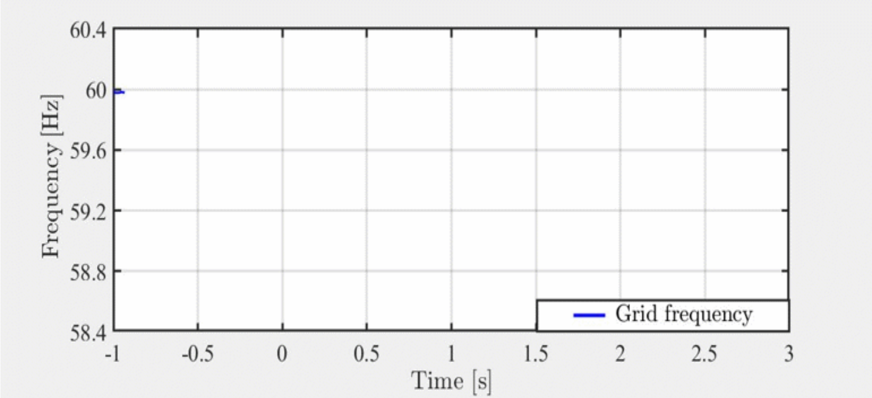




Remark:

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

Grid Frequency of Kauai Island Grid

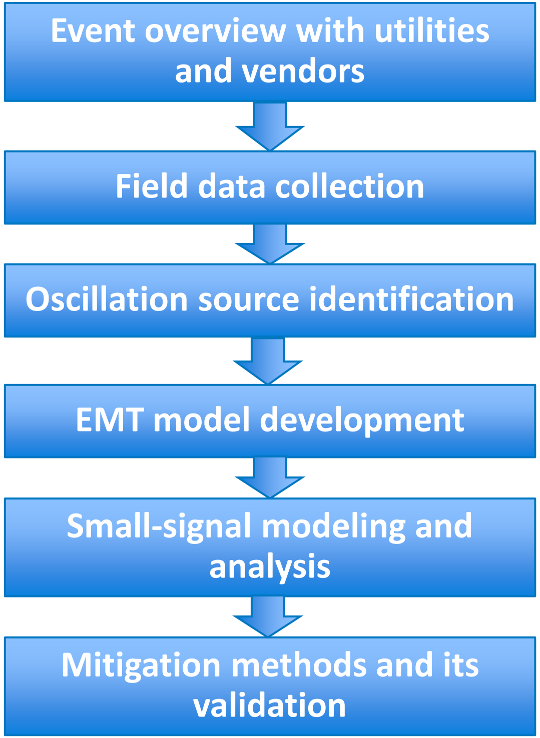


* S. Dong, B. Wang, J. Tan, C. J. Kruse, B.W. Rockwell, and A. Hoke, "Analysis of November 21, 2021, Kaua'i Power System 18-20 Hz Oscillations" (to be submitted).

Framework

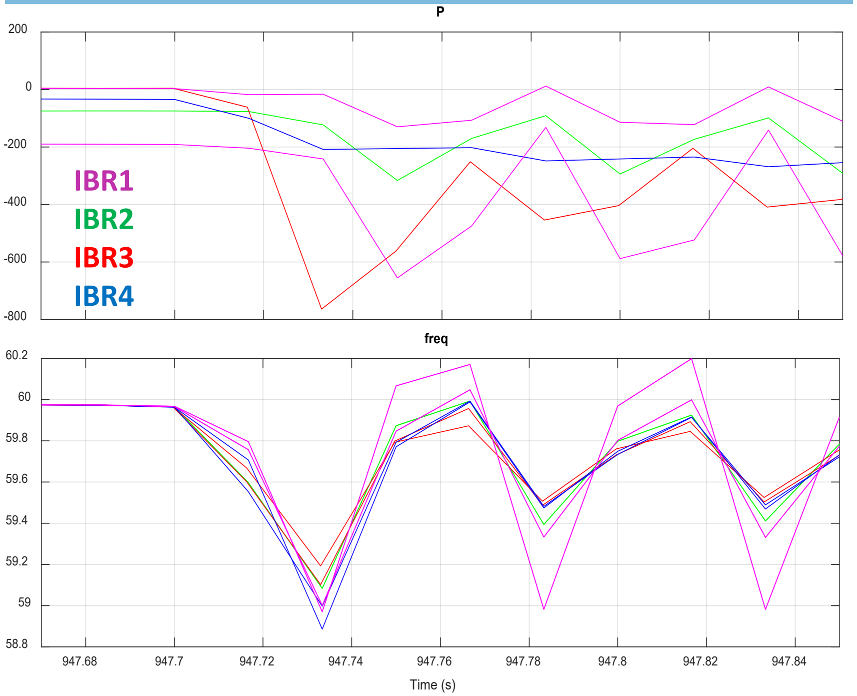
Propose a framework for investigating the real-world oscillation events

- **Step 1: Align the event and control actions with the frequency data, working with KIUC and AES.**
- **Step 2: Real data collection** (low-speed/high-speed DFR data from KIUC)
- **Step 3:** Oscillation source identification (Direct data analysis, DEF, **Sub/Super-Synchronous Power Flows analysis**)
- **Step 4:** Develop EMT model to replay the event.
- **Step 5:** Develop small signal model and apply the analysis to understand the root cause of these IBR-related oscillations.
- **Step 6:** Propose mitigation methods and validate them in the EMT model.
- **Step 7:** Test selected proposed mitigation methods in PHIL or in the field.

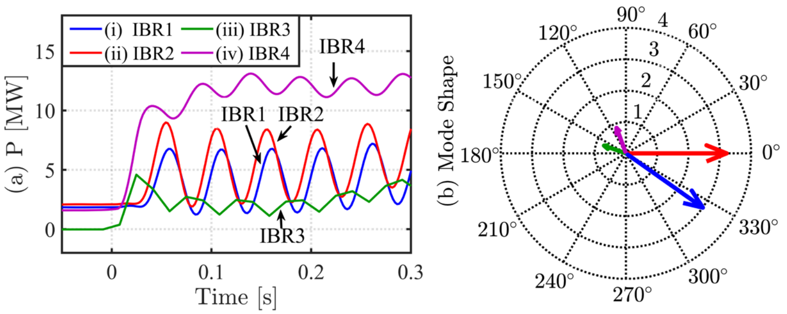


Oscillation Source Identification

Method 1: Direct data analysis method (KIUC, UTK, etc.)

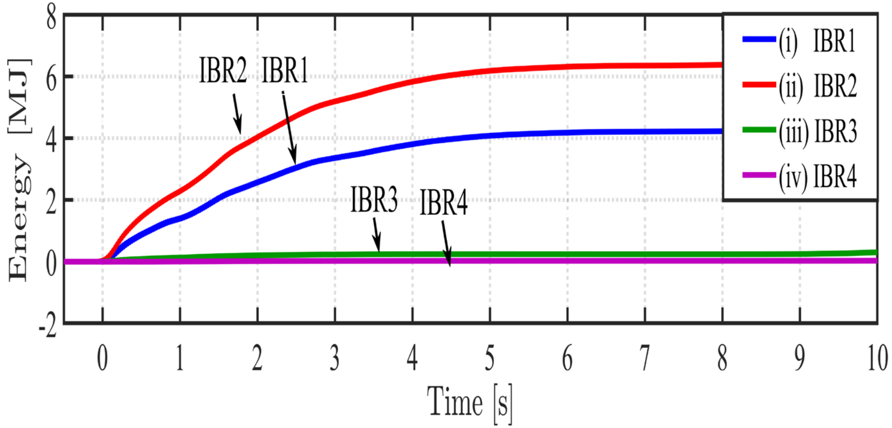


Method 2: Prony Analysis of Recorded IBR Active-power Responses

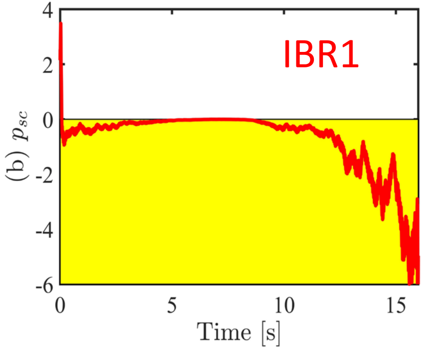


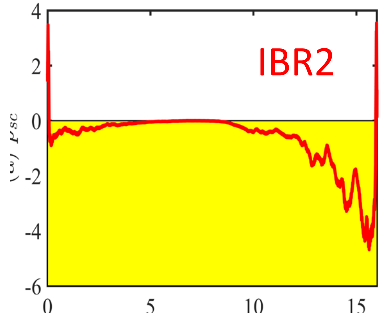
Oscillation Source Identification

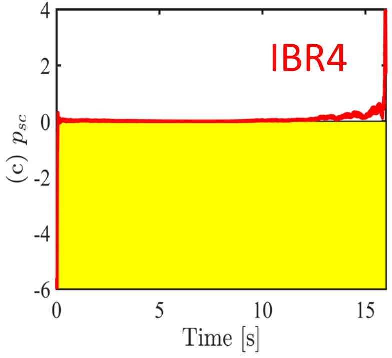
Method 3: DEF analysis method[1,2]



Method 4: Sub/Super-Synchronous Power Flows 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.

EMT Model Development

Purpose: Develop a full EMT model of Kaua`i to:

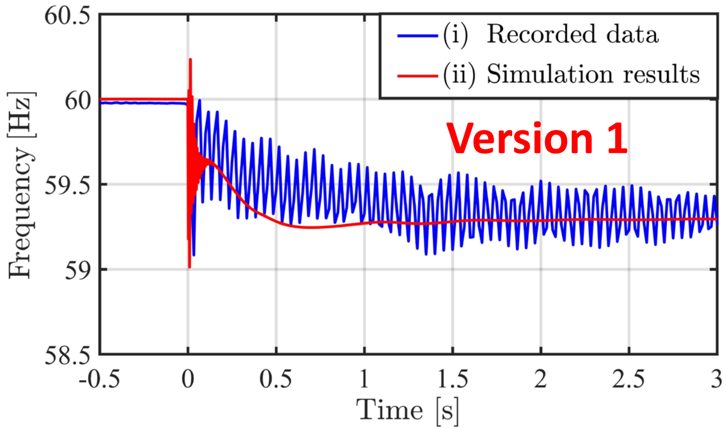
- Re-create and study the ~19 Hz oscillation event.
- Propose and test mitigation methods.

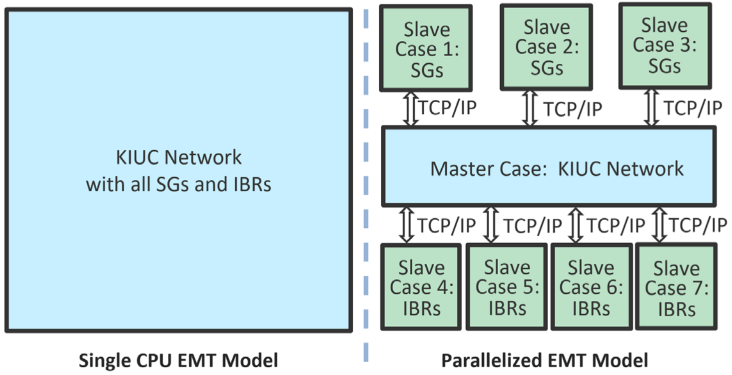
Challenges

- Accuracy of the IBR models.

Achievements:

- Develop two versions of the EMT model with different IBR models.
  - **Version 1**: model IBRs with generic GFL and GFM models
  - **Version 2**: Vendor-provided IBR models (where available)
- Steady-state power flows of the EMT model have been **validated** by using SCADA data.
- Used E-TRAN Plus to achieve **parallel simulation** of KIUC model by splitting the model into eight parts.
- Dynamics of Version 1
  - Match settling frequency.
  - **No ~19 Hz oscillation!**





Before: **269 s***

After: **180 s**

*** Simulating KIUC for 10s in PSCAD**

Tuning of Vendor-provided IBR Models for V2

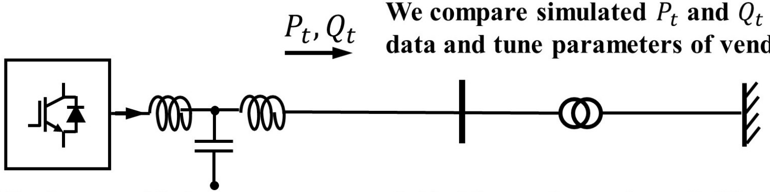
Challenges

- The vendor-provided models (red trace) don't reflect the dynamic performance of IBRs in the field (blue trace).

Solution

- Retune the control parameters of vendor-provided models in an infinite-bus test system by replaying DFR data.
- Key parameters have been adjusted: P/f droop constant, plant-level controllers, etc.

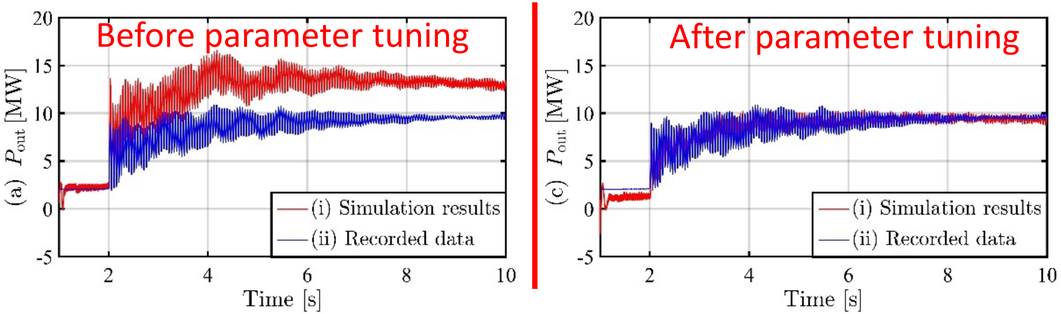
We compare simulated P_t and Q_t with the field data and tune parameters of vendor's model



Vendor-provided black box model

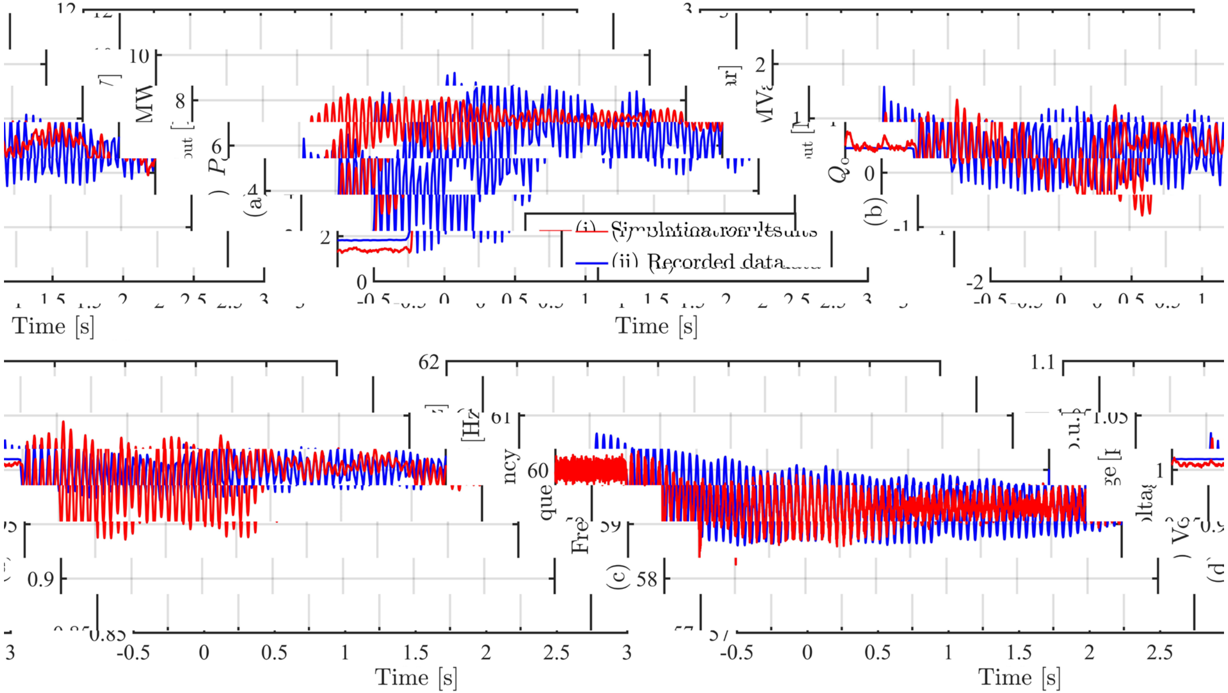
Grid: We use three-phase PoW voltage data u_{abc} as inputs

P response of vendor models before and after parameter tuning in infinite-bus test system

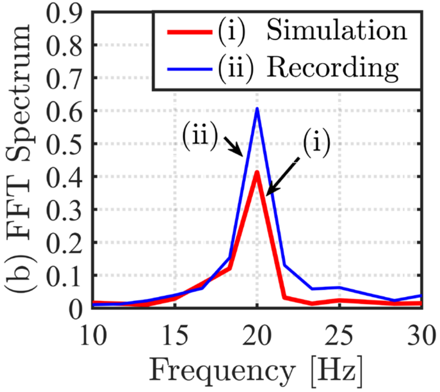


The simulated response (red trace) is closer to the field data (blue trace).

KIUC EMT Model to Replay ~19 Hz Oscillation



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



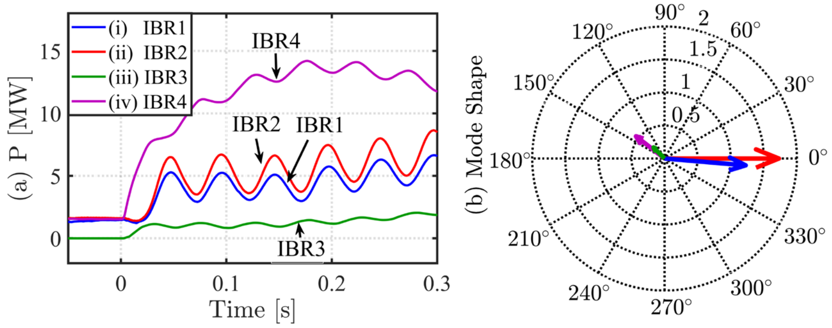
Achievement

- **A full EMT model of Kaua`i Island that can recreate ~19 Hz oscillations** by retuning and connecting vendor-provided models.

1. 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” (to be submitted).

Validation of KIUC EMT Model: Mode Shape Analysis

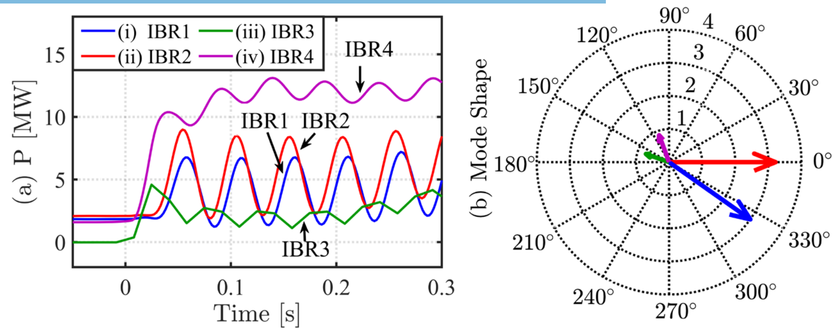
Simulation of EMT model



Prony analysis of **simulated** IBR active-power responses:

- IBR1 and IBR2 had larger oscillation magnitude.
- IBR1 and IBR2 oscillated against IBR3 and IBR4.

Analysis of measurement data



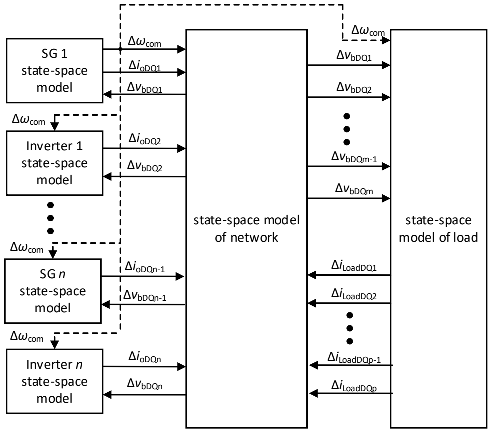
Prony analysis of **recorded** IBR active-power responses:

- IBR1 and IBR2 had larger oscillation magnitude.
- IBR1 and IBR2 oscillated against IBR3 and IBR4.

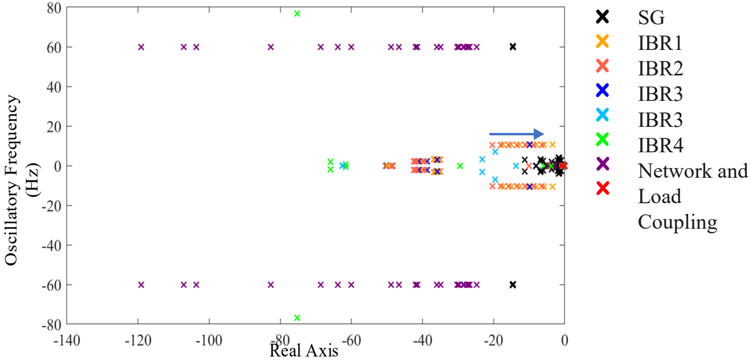
This comparison further validates the accuracy of our EMT model.

Develop an EMT-oriented Small Signal Analysis Model

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



Sensitivity study of control parameters(e.g., Change K_{PLL}) of IBR1 and IBR2



Credit: Xiaonan Lu, Purdue University, 2022

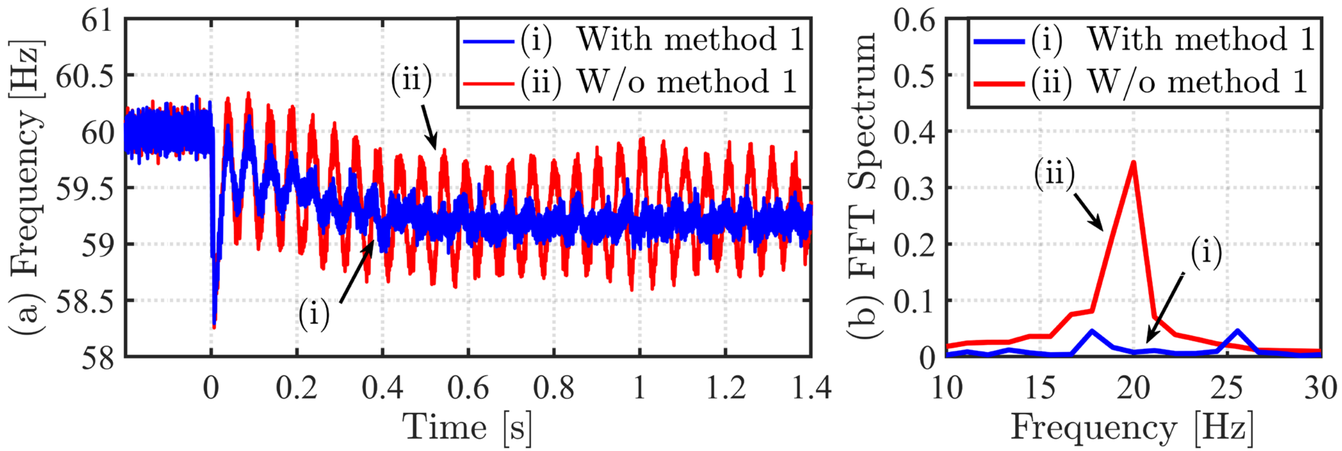
Findings:

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

Mitigation Method 1: Adjust P/f Droop

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

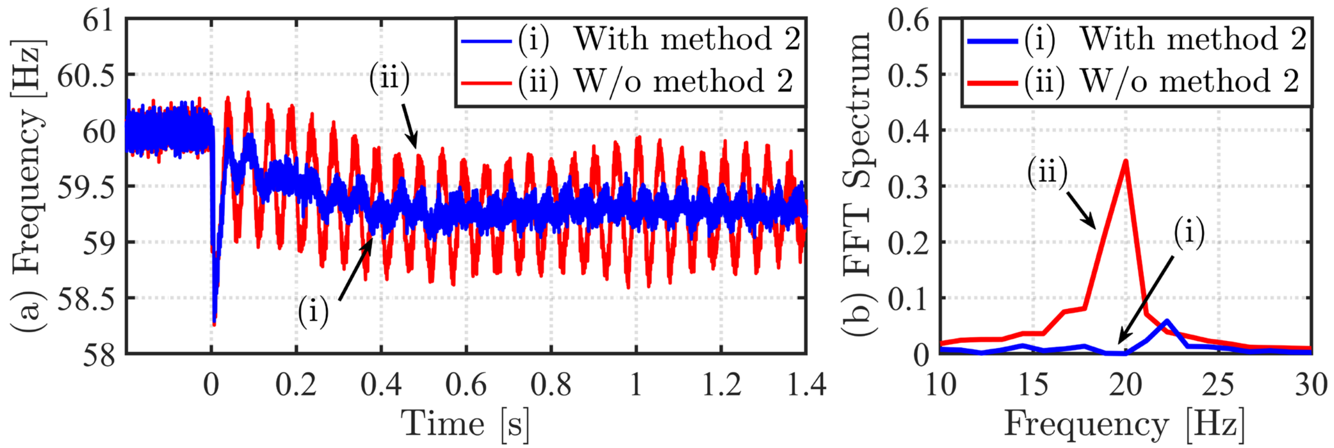
- Test Method 1 in the KIUC EMT model by changing IBR1 and IBR2’s inverter-level P/f droop constant from 3% to 4 %.
- The simulation results show that it can reduce the ~19 Hz oscillation magnitude and remove the peak in the FFT spectrum.



Mitigation Method 2: Adjust PLL Parameter

Method 2: reduce PLL proportional gains

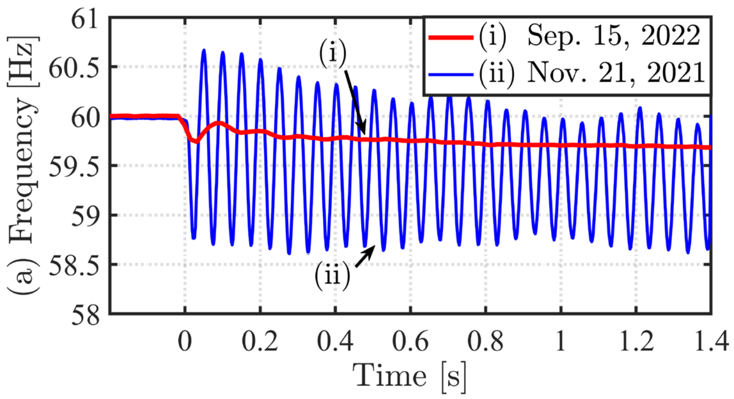
- Test Method 2 in the KIUC EMT model by reducing IBR1 and IBR2's PLL proportional gains (Kppll) from 0.15 to 0.10
- The simulation results show that it can the ~19 Hz oscillation magnitude and remove the peak in FFT spectrum.

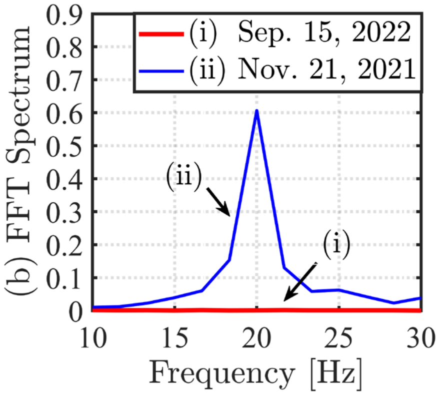


Mitigation Method 3: Upgrading to GFM

Method 3: Convert existing GFL to GFM inverters

- On Sep. 15th, 2022, Plant A with an output 8.6 MW was tripped again. But IBR1 has been upgraded to grid-forming (GFM) controllers in the field.
- There is no ~19 Hz oscillation (see red traces) following the Plant A trip on Sep. 15th, 2022.
- After KIUC converted IBR1 from GFL to GFM, it can effectively mitigate the ~19 Hz oscillations.





Conclusions and Future Work

Conclusions:

- We locate the source of oscillation with both the DEF method and sub/super-synchronous power flows.
- We have built the KIUC EMT model with the vendor-provided model, fine-tune the IBR parameters based on field data, and replay the ~19 Hz oscillation on Nov. 21, 2021.
- We identify four pairs of parameters that affect the simulated ~19 Hz oscillation.
- We propose three methods that mitigate the simulated ~19 Hz oscillation.

Future work:

- Perform detailed small-signal analysis of Kaua`i Island power systems.
- Perform impedance scanning on our KIUC EMT model.
- Validate our mitigation methods with power hardware-in-the-loop (PHIL) tests.

Team

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Thank you!

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