Stabilize High-IBR Power Systems with Grid-Forming Inverters

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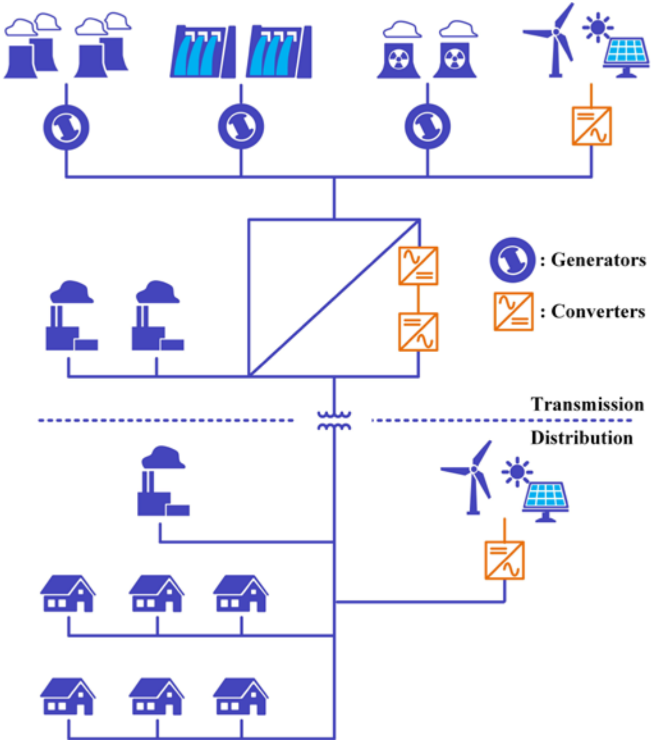
KIUC: Cameron J. Kruse, Brad W. Rockwell

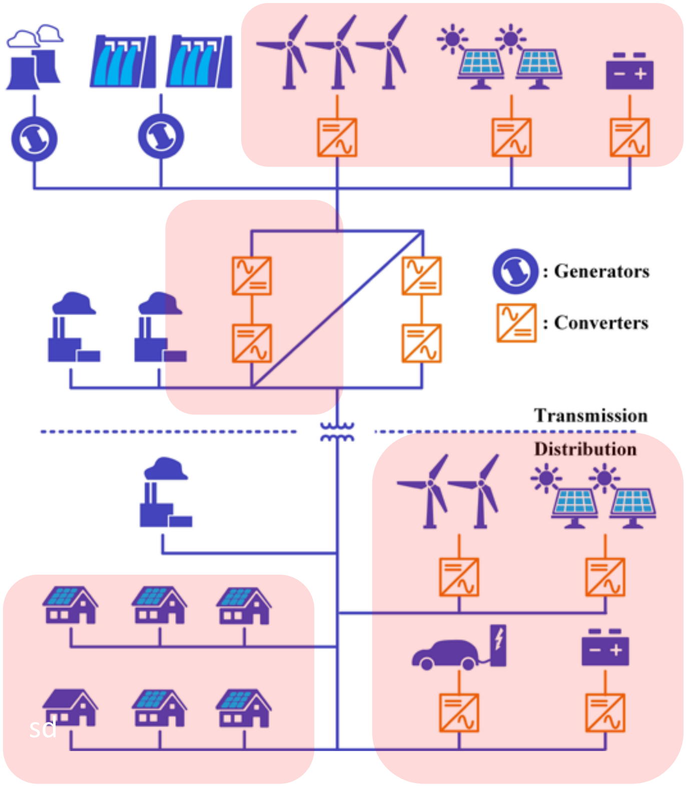
03/26/2024

Evolving Power Systems with Increasing Share of IBRs

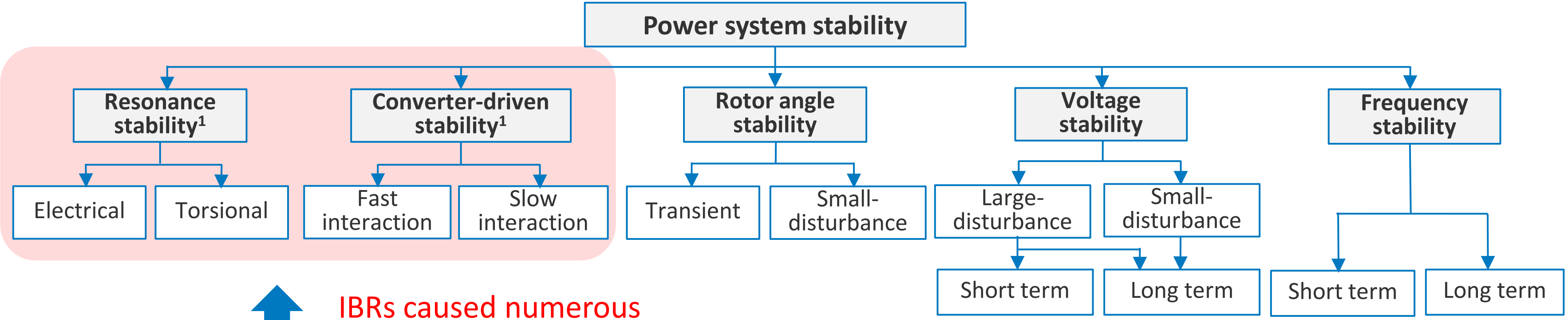
Conventional SG-dominated power systems



Future IBR-dominated power systems



Increasing Instability Concern With More IBRs

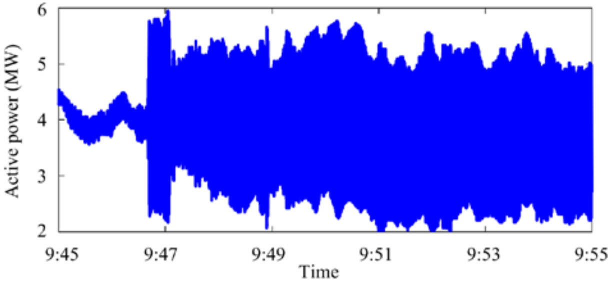


Power system stability

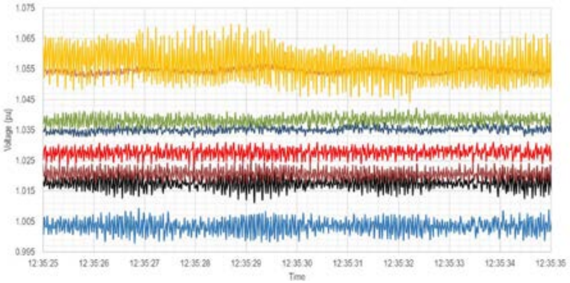
Resonance stability[1]
Converter-driven stability[1]
Rotor angle stability
Voltage stability
Frequency stability

Electrical
Torsional
Fast interaction
Slow interaction
Transient
Small-disturbance
Large-disturbance
Small-disturbance
Short term
Long term
Short term
Long term

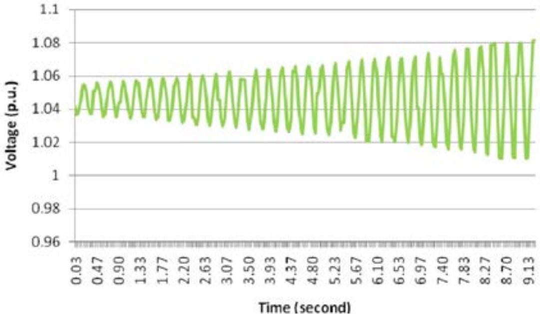
IBRs caused numerous oscillation events in the field



Hami 27-33 Hz oscillations[2] (2015)



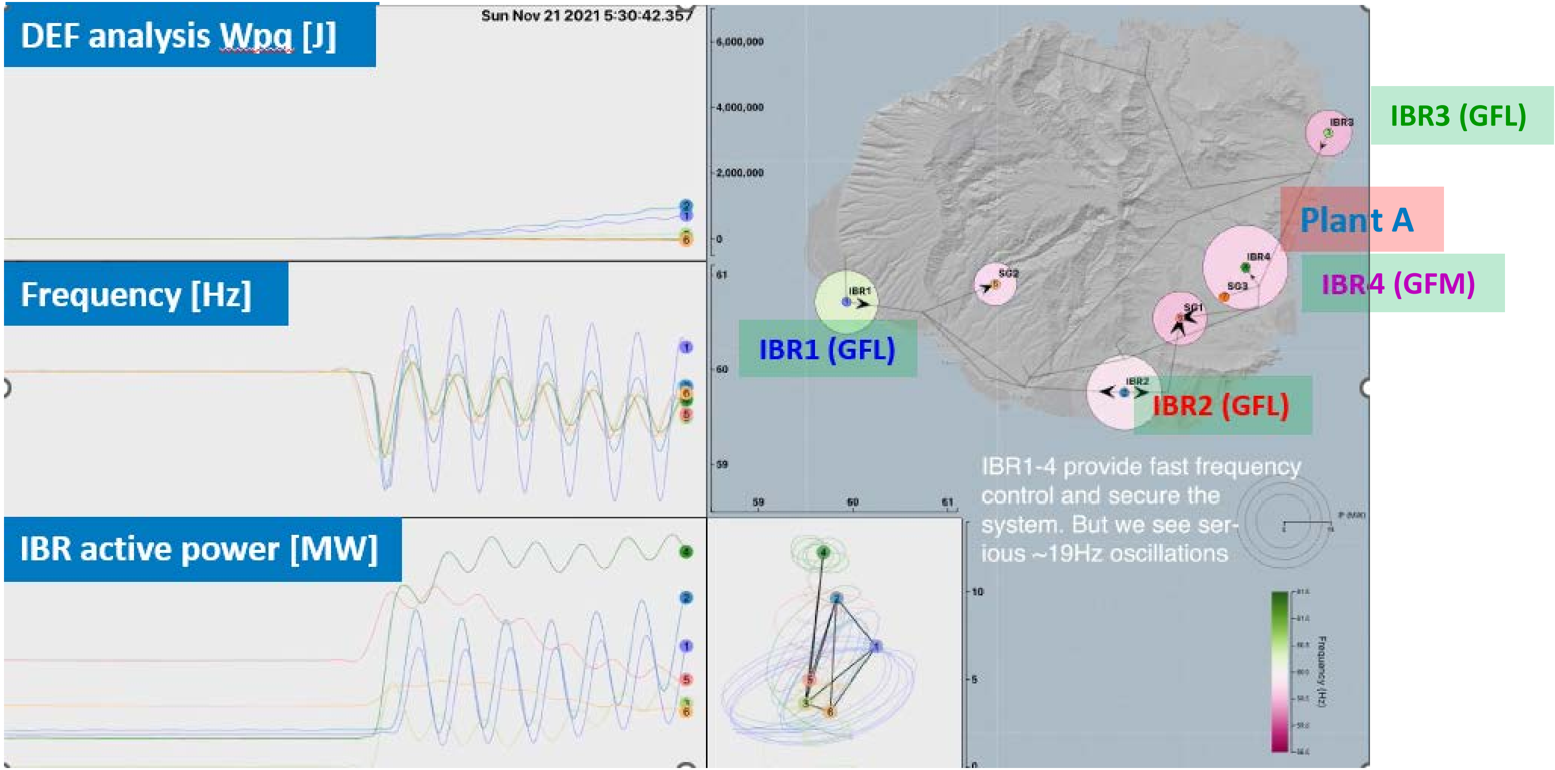
AEMO 19 Hz oscillations[3] (2020)



ERCOT 4 Hz oscillations[4] (2011)

1. N. Hatziargyriou *et al.*, "Definition and Classification of Power System Stability – Revisited & Extended," *IEEE Trans Power Syst.*, Jul. 2021.
2. H. Liu *et al.*, "Subsynchronous Interaction Between Direct-Drive PMSG Based Wind Farms and Weak AC Networks," *IEEE Trans Power Syst.*, Nov. 2017.
3. AEMO, "West Murray Zone Power System Oscillations 2020-2021", Feb. 2023.
4. S. -H. Huang, *et al.*, "Voltage control challenges on weak grids with high penetration of wind generation: ERCOT experience," IEEE PES GM, 2012.

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



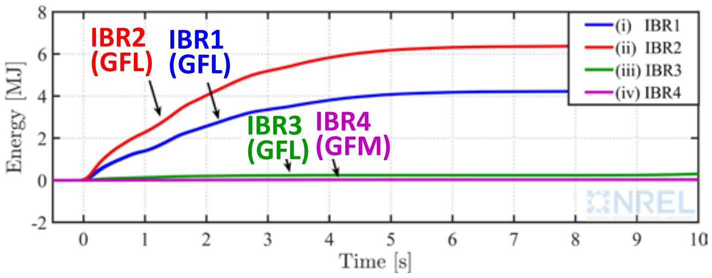
IBR1-4 provide fast frequency control and secure the system. But we see serious ~19Hz oscillations

Animation credit: NREL visualization team

- Sam Molnar, Kenny Gruchalla, Shuan Dong, and Jin Tan. "Visualization of the Oscillatory Dynamics of an Island Power System." In 2023 Workshop on Energy Data Visualization (EnergyVis), pp. 1-5. IEEE, 2023.)

Measurement-based Oscillation Source Identification

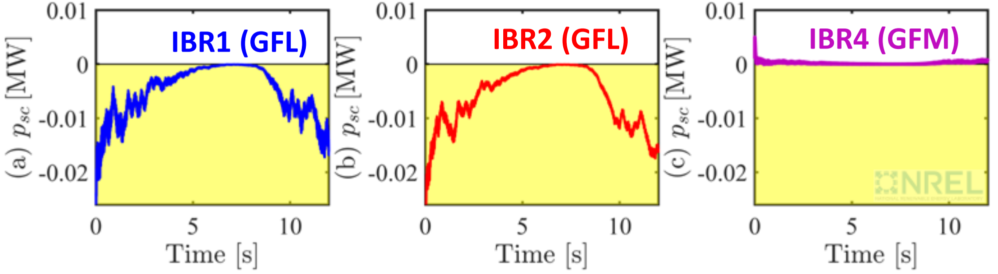
Dissipating Energy Flow (DEF) analysis[1,2]



Dissipating energy for each IBR with the phasor inputs P, Q, θ, and V:

$$W = \int \Delta P \mathrm{d}\Delta\theta + \Delta Q \mathrm{d}(\ln \Delta V).$$

Sub/Super-Synchronous Power Flows analysis[3]



Sub/super-synchronous power flow for each IBR with the 3-ph PoW data v_{abc} and i_{abc}:

$$p_{sc} = \mathrm{Re}\left\{\frac{\dot{U}_s}{\dot{I}_s}\right\} \cdot I_s^2 + \mathrm{Re}\left\{\frac{\dot{U}_c}{\dot{I}_c}\right\} \cdot I_c^2$$

Key Findings:

- IBR4 (GFM) was not source of the ~19.5 Hz oscillation, since it has $dW/dt \approx 0$ and $p_{sc} \approx 0$.
- IBR1 (GFL) and IBR2 (GFL) were oscillation sources, since they had $dW/dt > 0$ and $p_{sc} < 0$.

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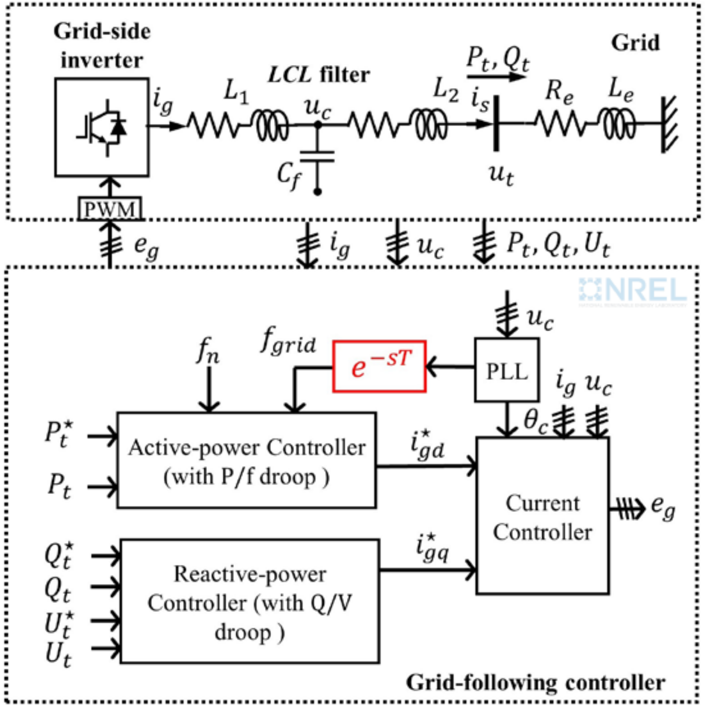
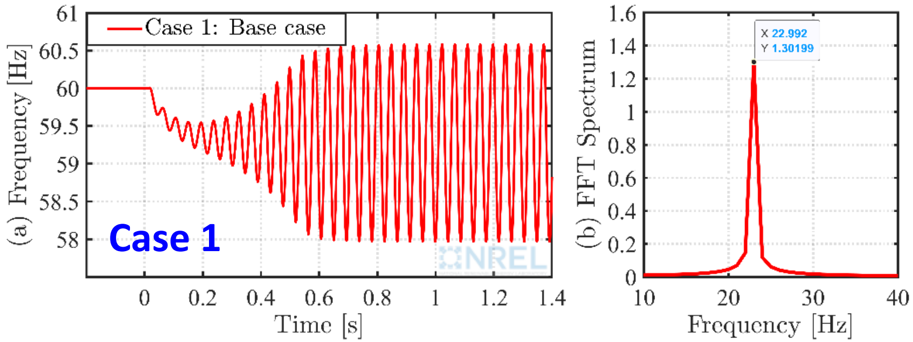
1. L. Chen, Y. Min, and W. Hu, "An energy-based method for location of power system oscillation source," *IEEE Trans. Power Syst.*, 2013.
2. S. Maslennikov, B. Wang, and E. Litvinov, "Dissipating energy flow method for locating the source of sustained oscillations," *Int. J. Electr. Power Energy Syst.*, 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.*, 2020.

Replay KIUC 19.5 Hz Oscillation Event with Infinite-Bus System



Single GFL infinite bus system

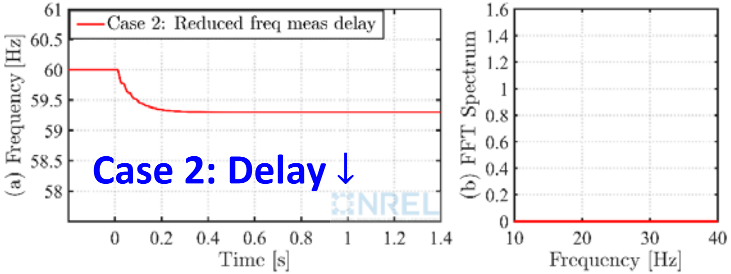


Case 1 (base case) recreates a ~20 Hz oscillation following the grid frequency drop and SCR reduction from 3.4 to 2.6 at t = 0 s.

- We recreate the ~20 Hz oscillation by properly tuning the single GFL infinite bus system with freq. measurement delay e^{-sT}.

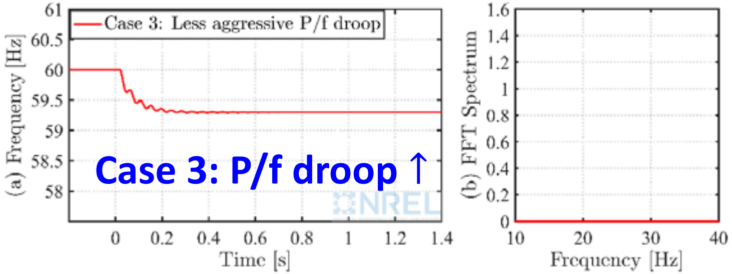
1. Shuan Dong, Andy Hoke, Bin Wang, Lizhi Ding, Xiaonan Lu, Cameron J. Kruse, Brad W. Rockwell, and Jin Tan, "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems With Case Study for Kaua'i System," *IEEE Transactions on Circuit and Systems I: Regular Paper*, 2025.

Root Cause of 19.5 Hz Oscillation Event



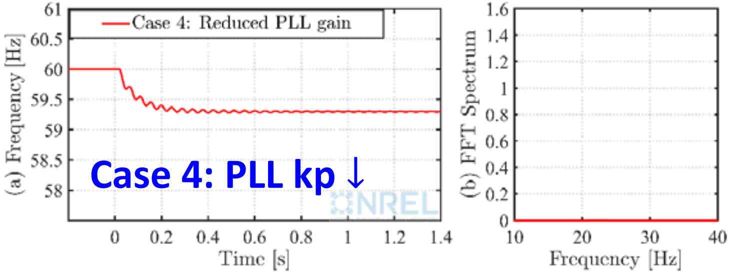
Case 2: Delay ↓

Case 2 with smaller freq. measurement delay 8 ms.



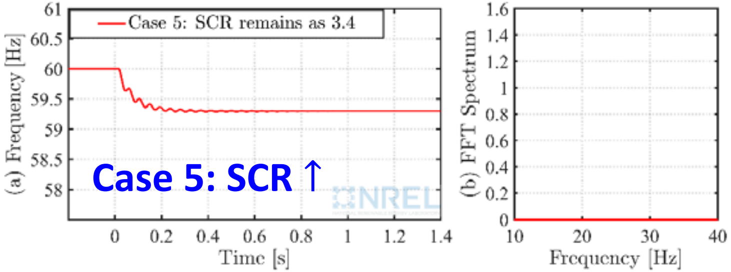
Case 3: P/f droop ↑

Case 3 with less aggressive P/f droop constant (4%).



Case 4: PLL kp ↓

Case 4 with smaller PLL proportional gain (50 -> 40).



Case 5: SCR ↑

Case 5 with stronger grid connection (SCR = 3.4).

- Case 1-5 validates the **root cause of Kaua`i Island 19.5 Hz oscillation event**:
  ``GFLs with larger frequency measurement-delays and non-optimal parameterization operating under weak grid conditions.''

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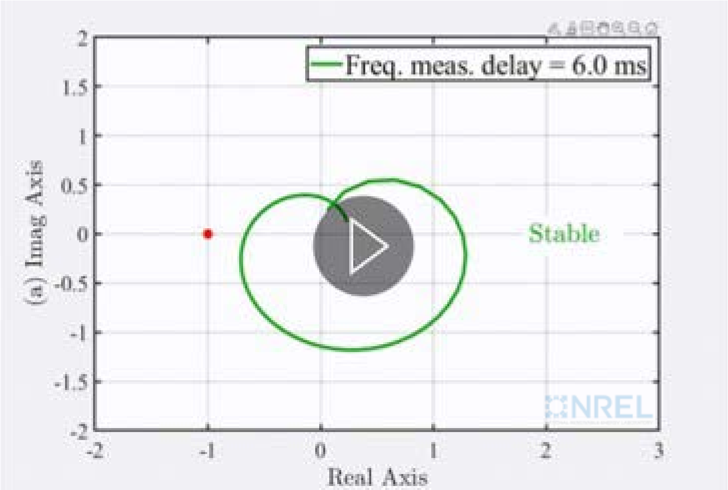
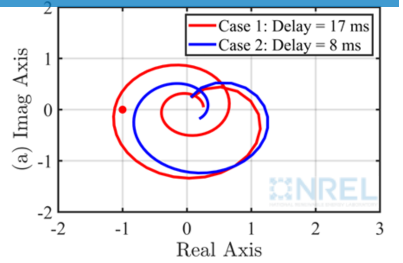
1. Shuan Dong, Andy Hoke, Bin Wang, Lizhi Ding, Xiaonan Lu, Cameron J. Kruse, Brad W. Rockwell, and Jin Tan, "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems With Case Study for Kaua'i System," *IEEE Transactions on Circuit and Systems I: Regular Paper*, 2025.

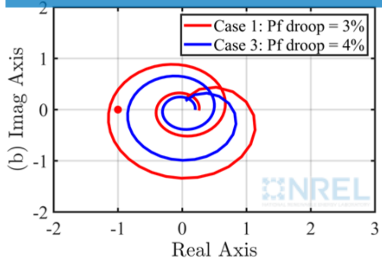
Root Cause of 19.5 Hz Oscillation Event



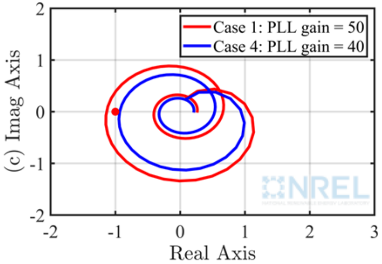
Impacts of freq. meas. delay



Impacts of P/f droop constant



Impacts of PLL gain



Impacts of SCR

- Case 1-5 validates the **root cause of Kaua`i Island 19-20 Hz oscillation event**: *``GFLs with larger frequency measurement-delays and non-optimal parameterization operating under weak grid conditions.''*

1. Shuan Dong, Andy Hoke, Bin Wang, Lizhi Ding, Xiaonan Lu, Cameron J. Kruse, Brad W. Rockwell, and Jin Tan, "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 Circuit and Systems I: Regular Paper*, 2025.

Mitigation Methods 1&2: Tuning GFL Parameters

Mitigation Methods 1&2: GFL Parameter Tuning

Event root causes

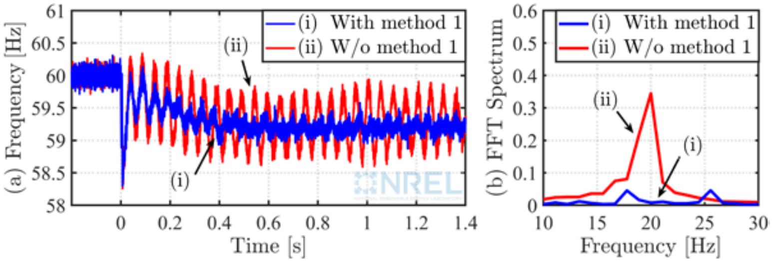
GFL

Freq. meas. delay

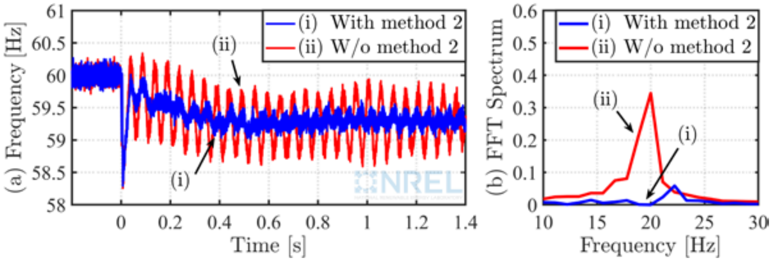
Aggressive P/f droop

Large PLL kp

Small SCR



- **Method 1:** Revise IBR1 (GFL) and IBR2 (GFL) inverter-level P/f droop constant from 3% to 4%
- We reduce the ~19.5 Hz oscillation magnitude and remove the peak in FFT spectrum.



- **Method 2:** Reduce IBR1 (GFL) and IBR2 (GFL) PLL proportional gains from 0.15 to 0.10.
- We reduce the ~19.5 Hz oscillation magnitude and remove the peak in FFT spectrum.

1. Shuan Dong, Andy Hoke, Bin Wang, Lizhi Ding, Xiaonan Lu, Cameron J. Kruse, Brad W. Rockwell, and Jin Tan, “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 Circuit and Systems I: Regular Paper*, 2025.

Mitigation Method 3: Add SGs/SCs

Mitigation Method 3: Adding SGs (Simulation Validation)

Event root causes
GFL
Freq. meas. delay
Aggressive P/f droop
Large PLL kp
Small SCR

Base case

Add SGs

	IBR1 (x MW)	IBR2 (x MW)	IBR3 (x MW)	IBR4 (x MW)	SG 1 (x MW)	SG 2 (x MW)	SG 3 (x MW)	SG 4 (x MW)	Results
Case 1	🟩	🟩	🟩	🟩	🟪	🟪	🟪	🟪	~19 Hz oscillation
Case 2	🟩	🟩	🟩	🟩	🟩	🟪	🟪	🟪	~19 Hz oscillation
Case 3	🟩	🟩	🟩	🟩	🟩	🟩	🟪	🟪	~19 Hz oscillation
Case 4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟪	Stable
Case 5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	Stable

🟩: Generator is online 🟪: Generation is offline

- **Method 3:** Adding more SGs, we reduce the ~19.5 Hz oscillation magnitude.

Mitigation Method 4: Convert GFL to GFM

Event root causes
GFL
Freq. meas. delay
Aggressive P/f droop
Large PLL kp
Small SCR

Mitigation Method 4: Upgrading to GFM (Simulation Validation)

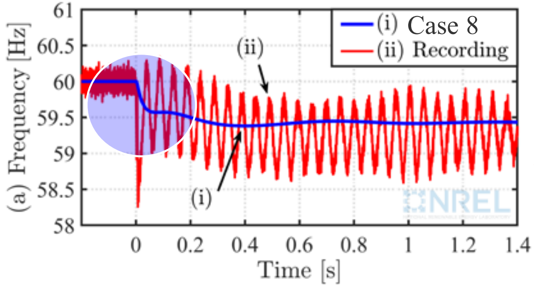
		IBR1 (x MW)	IBR2 (x MW)	IBR3 (x MW)	IBR4 (x MW)	Results
Base case	**Case 1 (Base)**	GFL	GFL	GFL	VSM	**~19 Hz oscillation**
Upgrade one GFL to Droop	**Case 6(a)**	Droop	GFL	GFL	VSM	**Stable**
	Case 6(b)	GFL	Droop	GFL	VSM	**Stable**
	Case 6(c)	GFL	GFL	Droop	VSM	**Stable**
Upgrade one GFL to VSM	**Case 7(a)**	VSM	GFL	GFL	VSM	**Stable**
	Case 7(b)	GFL	VSM	GFL	VSM	**Stable**
	Case 7(c)	GFL	GFL	VSM	VSM	**Stable**
Upgrade all GFLs to Droop or VSM	**Case 8**	Droop	Droop	Droop	Droop	**Stable**
	Case 9	VSM	VSM	VSM	VSM	**Stable**

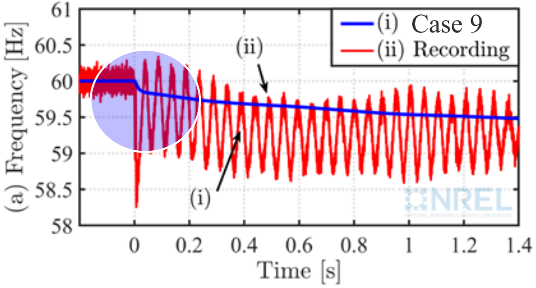
- **Method 4:** Converting any one GFL to Droop- or VSM-based GFM, we can remove the ~19.5 Hz oscillations.

Adopting VSM Further Reduces RoCoF

Compare Case 8 and Case 9:

- Adopting VSM-based GFM results in smaller RoCoF than adopting Droop-based GFM due to its provided virtual inertia.





Mitigation Method 4: Upgrading to GFM (Simulation Validation)

	IBR1 (x MW)	IBR2 (x MW)	IBR3 (x MW)	IBR4 (x MW)	Results
Case 1 (Base)	GFL	GFL	GFL	VSM	~19 Hz oscillation
Case 6(a)	Droop	GFL	GFL	VSM	Stable
Case 6(b)	GFL	Droop	GFL	VSM	Stable
Case 6(c)	GFL	GFL	Droop	VSM	Stable
Case 7(a)	VSM	GFL	GFL	VSM	Stable
Case 7(b)	GFL	VSM	GFL	VSM	Stable
Case 7(c)	GFL	GFL	VSM	VSM	Stable
Case 8	Droop	Droop	Droop	Droop	**Stable**
Case 9	VSM	VSM	VSM	VSM	**Stable**

- **Method 4:** Converting any one GFL to Droop- or VSM-based GFM, we can remove the ~19.5 Hz oscillations.

Mitigation Method 4: Convert GFL to GFM (Field Validation)

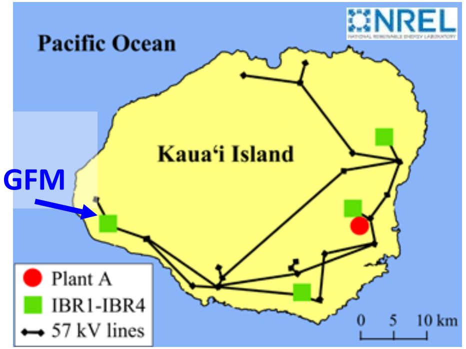
Mitigation Method 4: Upgrading to GFM (Field Validation)

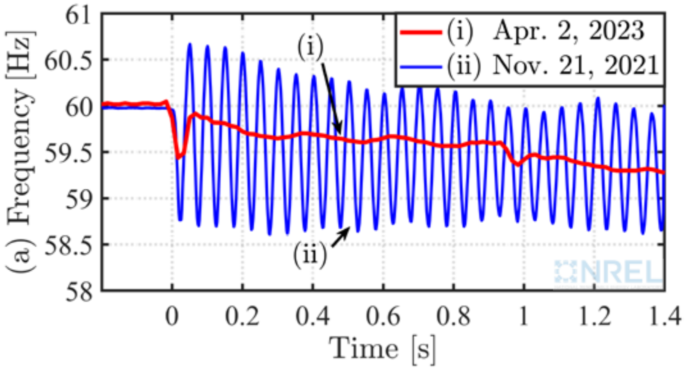
	IBR1 (x MW)	IBR2 (x MW)	IBR3 (x MW)	IBR4 (x MW)	Results
Case 6(a)	Droop	GFL	GFL	VSM	**Stable**

Event root causes

- GFL
- Freq. meas. delay
- Aggressive P/f droop
- Large PLL kp
- Small SCR

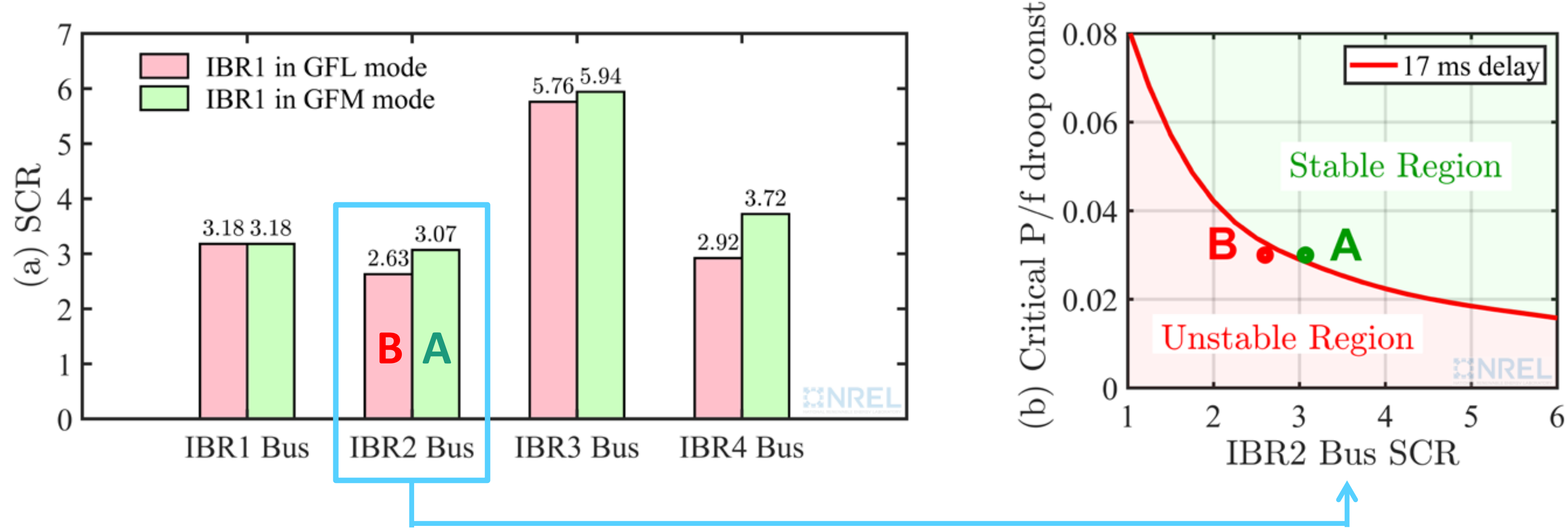
IBR1:
GFL -> GFM





- **Event:** On Apr. 2nd, 2023, Plant A with output power ~26 MW was tripped again. But IBR1 has been upgraded to Droop-based GFM.
- **Observation:** No ~19.5 Hz oscillation (see red traces) following Plant A trip on Apr. 2nd, 2023.
- **Conclusion:** Adopting GFM can effectively mitigate the ~19.5 Hz oscillation.

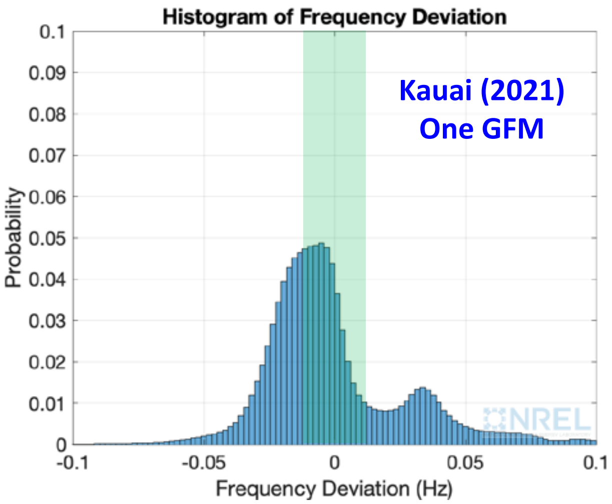
Stability Region Visualization With 2nd GFM



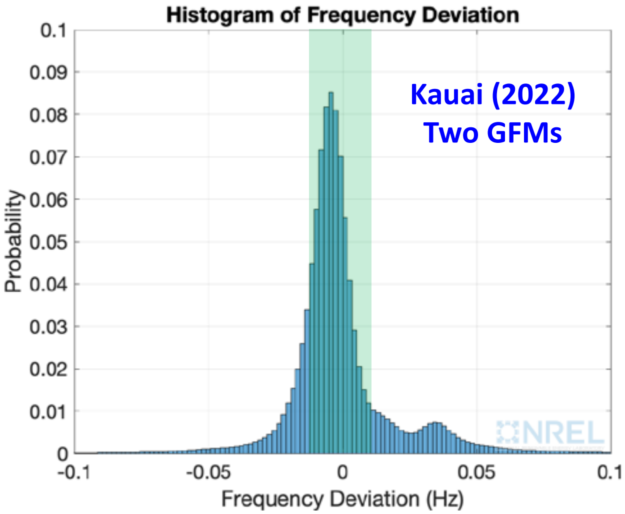
If converting IBR1 from GFL to droop-based GFM mode, we increase the grid strength at the PCC of other IBRs and mitigate the oscillations (see green bars in Fig. (a) and operating point A in Fig. (b)).

1. Shuan Dong, Andy Hoke, Bin Wang, Lizhi Ding, Xiaonan Lu, Cameron J. Kruse, Brad W. Rockwell, and Jin Tan, “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 Circuit and Systems I: Regular Paper*, 2025.

Also, 2nd GFM Improves Kaua`i Frequency Dynamics



2021 Kaua`i system with one GFM
[-0.01Hz, 0.01Hz] Probability = 34.19%

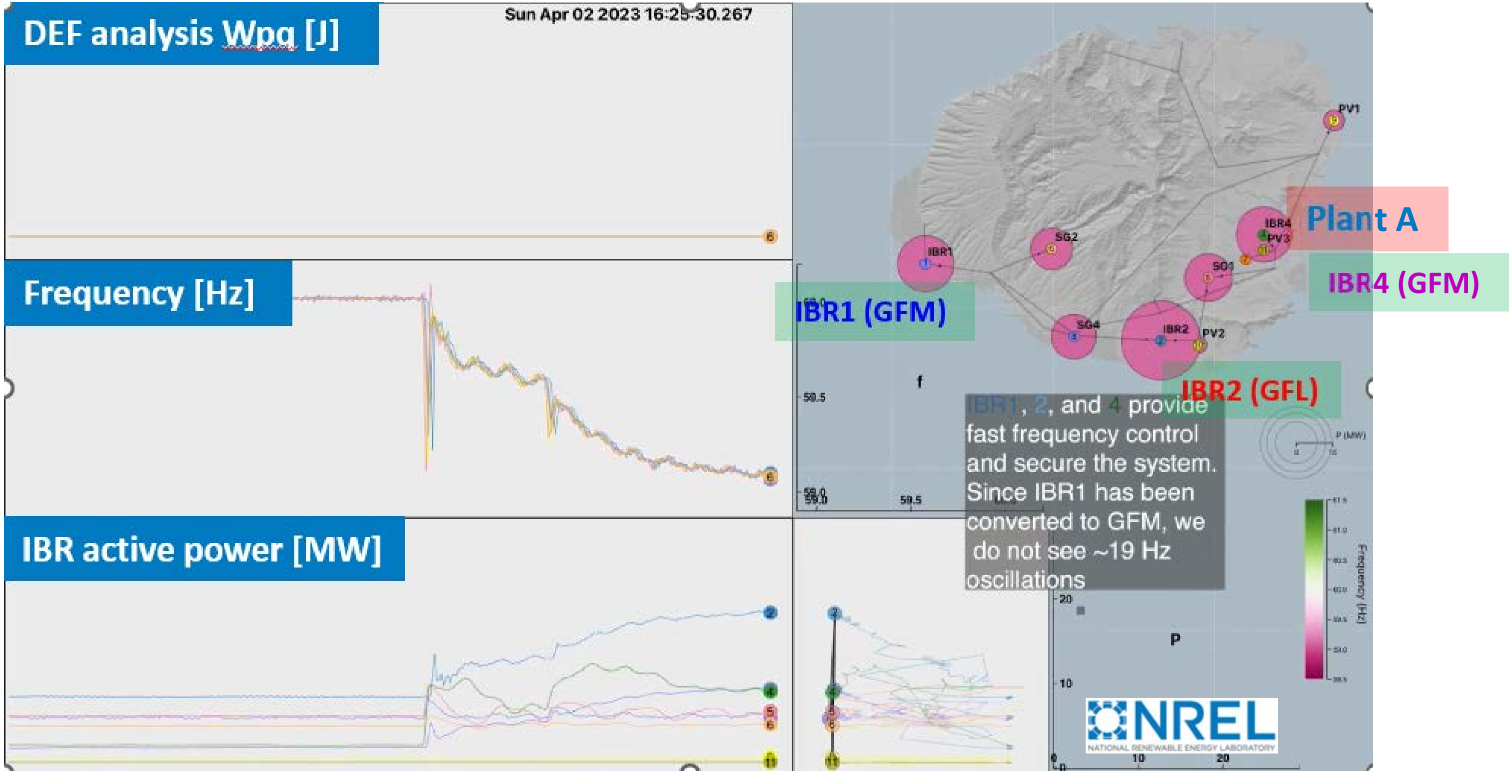


2022 Kaua`i system with two GFMs
[-0.01Hz, 0.01Hz] Probability = 60.05%

After converting IBR1 from GFL to droop-based GFM mode, we improve the frequency dynamics by reducing the frequency deviation (thanks to GFM's fast frequency responses).

- Figure credit: Our NREL colleague Hongfei

April 2nd Event on Kaua‘i Island in 2023 (With 2nd GFM)



IBR1, 2, and 4 provide fast frequency control and secure the system. Since IBR1 has been converted to GFM, we do not see ~19 Hz oscillations

Animation credit: NREL visualization team

- Sam Molnar, Kenny Gruchalla, Shuan Dong, and Jin Tan. "Visualization of the Oscillatory Dynamics of an Island Power System." In 2023 Workshop on Energy Data Visualization (EnergyVis), pp. 1-5. IEEE, 2023.)

Concluding Remarks

- The increasing penetration of IBRs challenges the stable operation of power systems.
- GFM can strengthen the grid, reducing GFL-related oscillation risks.
- GFM can improve frequency dynamics by providing fast frequency response. Specially, VSM further improves the frequency nadir by providing virtual inertia.
- Be aware… GFM can possibly introduce other challenges and is not necessarily silver bullet, but well-designed GFMs can help stabilize future high-IBR-penetration power systems.

1. Shuan Dong, Andy Hoke, Bin Wang, Lizhi Ding, Xiaonan Lu, Cameron J. Kruse, Brad W. Rockwell, and Jin Tan, "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 Circuit and Systems I: Regular Paper*, 2025.

Thank you!

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National Renewable Energy Laboratory

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