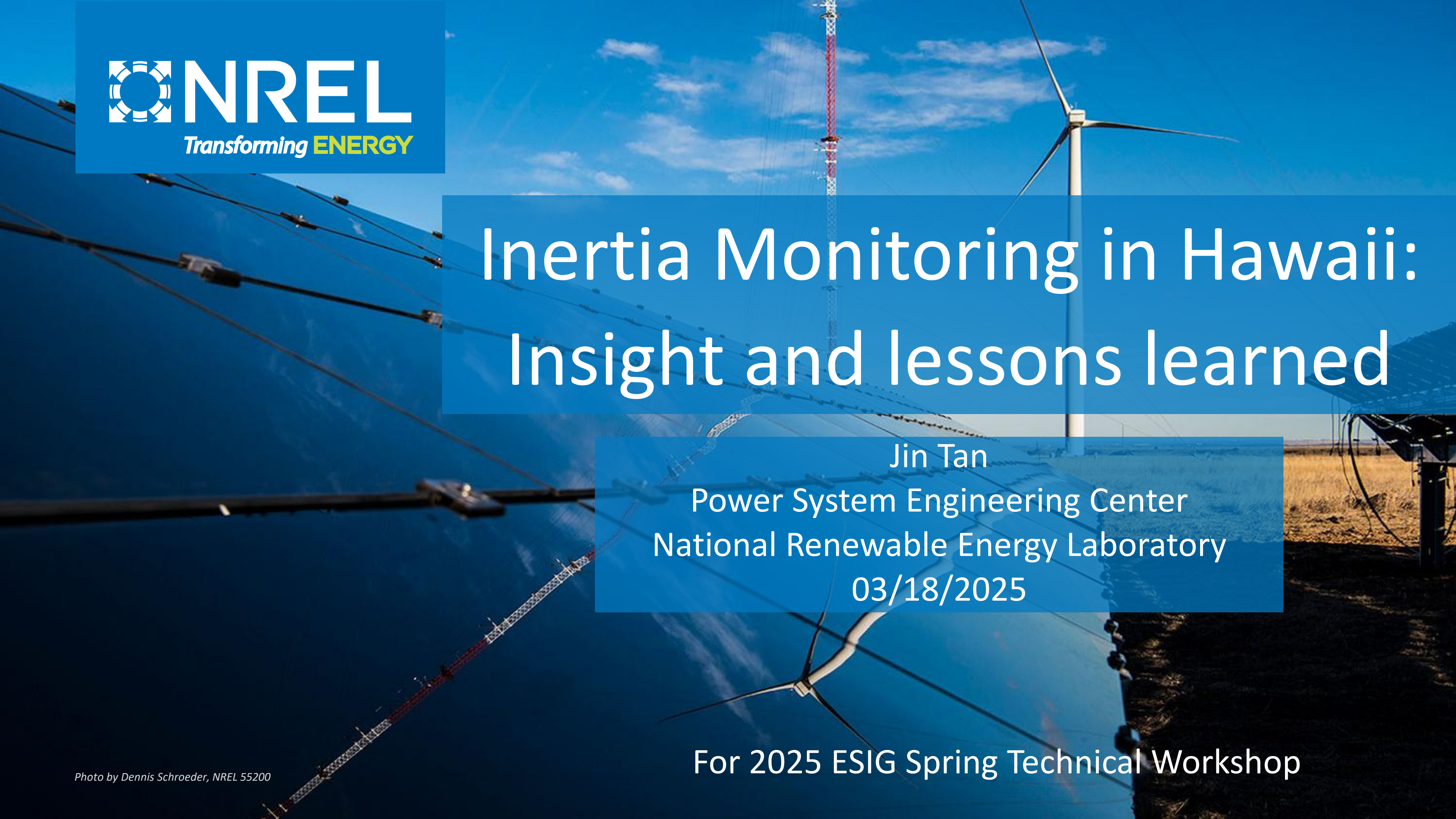

Inertia Monitoring in Hawaii: Insight and lessons learned

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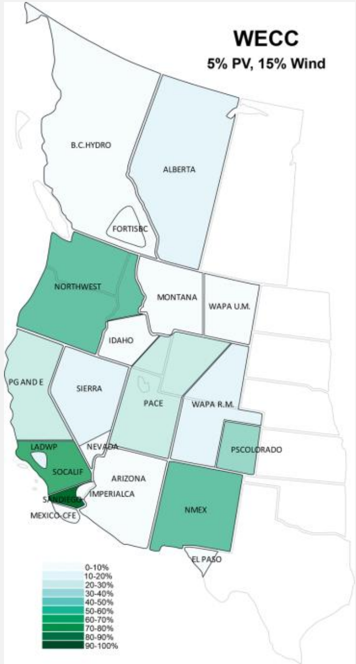
National Renewable Energy Laboratory
03/18/2025

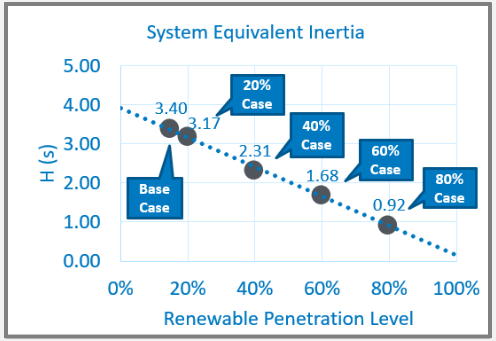
For 2025 ESIG Spring Technical Workshop

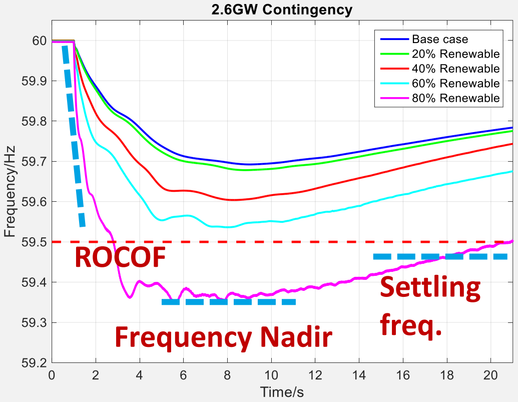
Photo by Dennis Schroeder, NREL 55200

Inertia: A Key Challenge for Grid Stability and Economic Operation



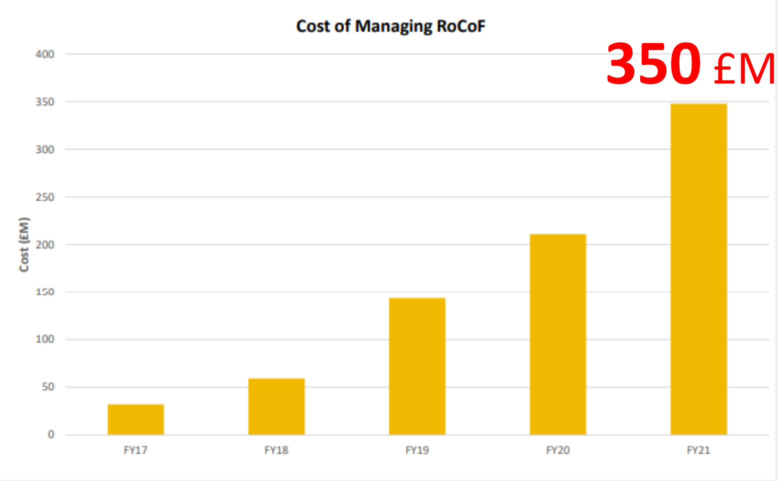
Renewable Penetration (20%, 40%, 60%, 80%)





Tan, Jin, Yingchen Zhang, Shutang You, Yong Liu, and Yilu Liu. "Frequency response study of US western interconnection under extra-high photovoltaic generation penetrations." In *2018 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1-5. IEEE, 2018.

Increased costs of managing Rate of Change of Frequency in Great Britain



https://www.naspi.org/sites/default/files/2021-06/20210630_naspi_webinar_system_inertia.pdf

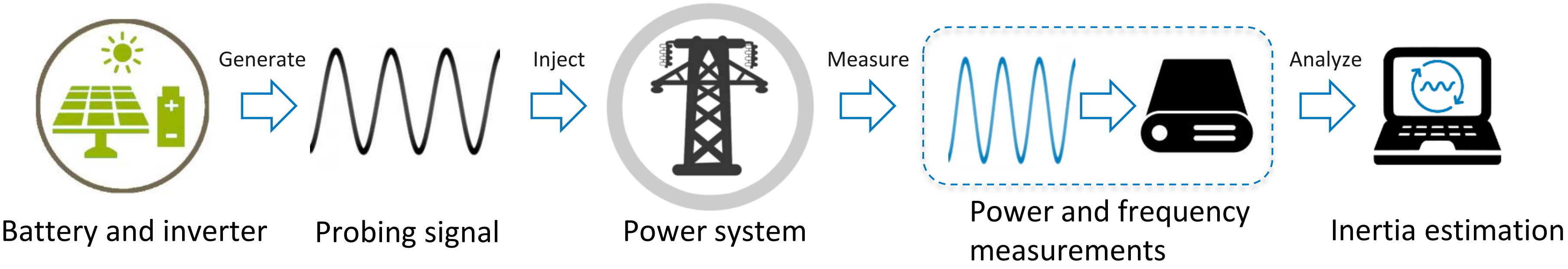
Our Approach

Key Innovations:

- Utilize a **battery and inverter** to inject active **power pulses** into the grid and

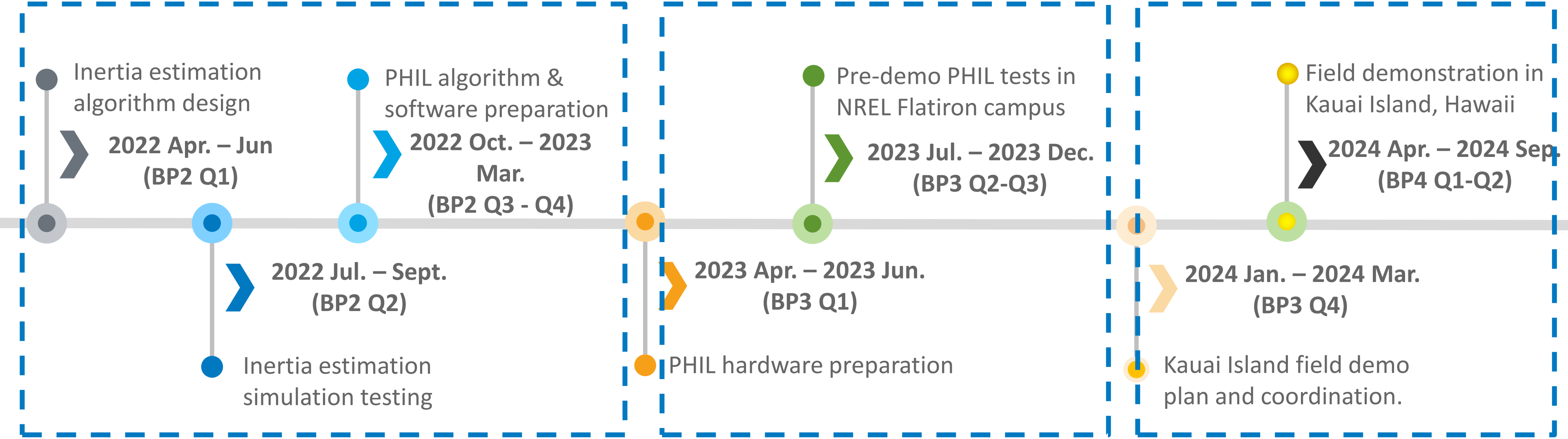
Benefit:

- No additional hardware cost by retrofitting the existing inverters to provide the grid situational awareness.
- More **consistent inertia estimation results** compared to conventional inertia estimation.



From Lab Testing to the Field Demonstration

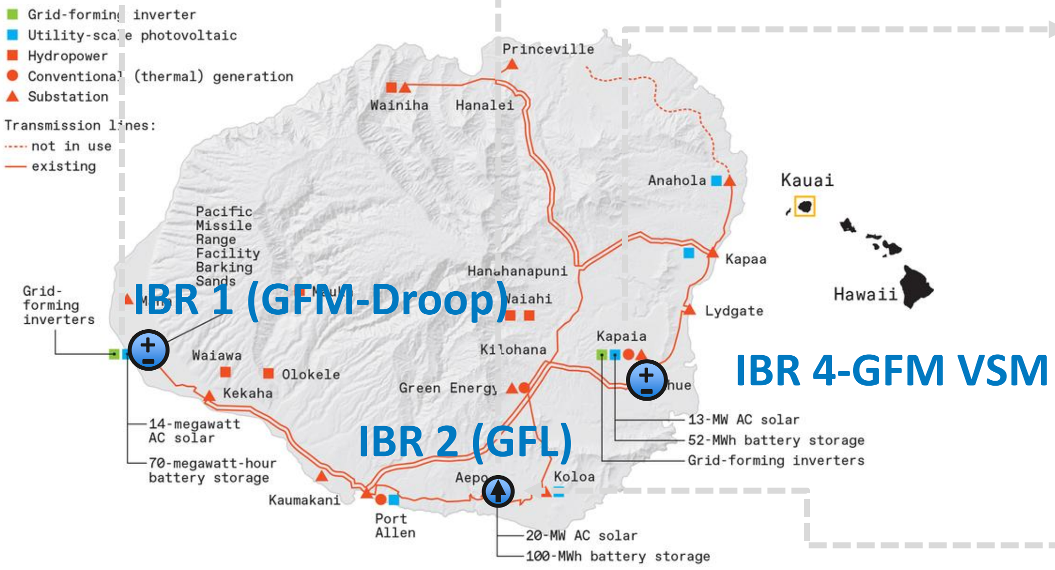
Goal: Demonstrate the capabilities and benefits of using a hybrid PV power plant (HPP) to provide **situational awareness** of real-time power system **inertia** and quantify the IBRs' contribution to effective inertia.



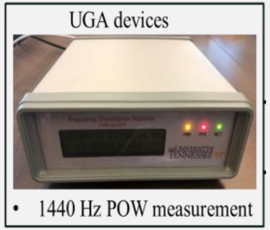
- Design probing-signal based **inertia estimation algorithms**.
- **Pre-demo PHIL tests** at NREL
- **Field demonstration** in Kaua`i Island.

Field Testing on Kaua`i Island

The field testing leverages the **hybrid PV power plant (IBR 2)** to inject probing pulses to the KIUC power grid for inertia estimation.



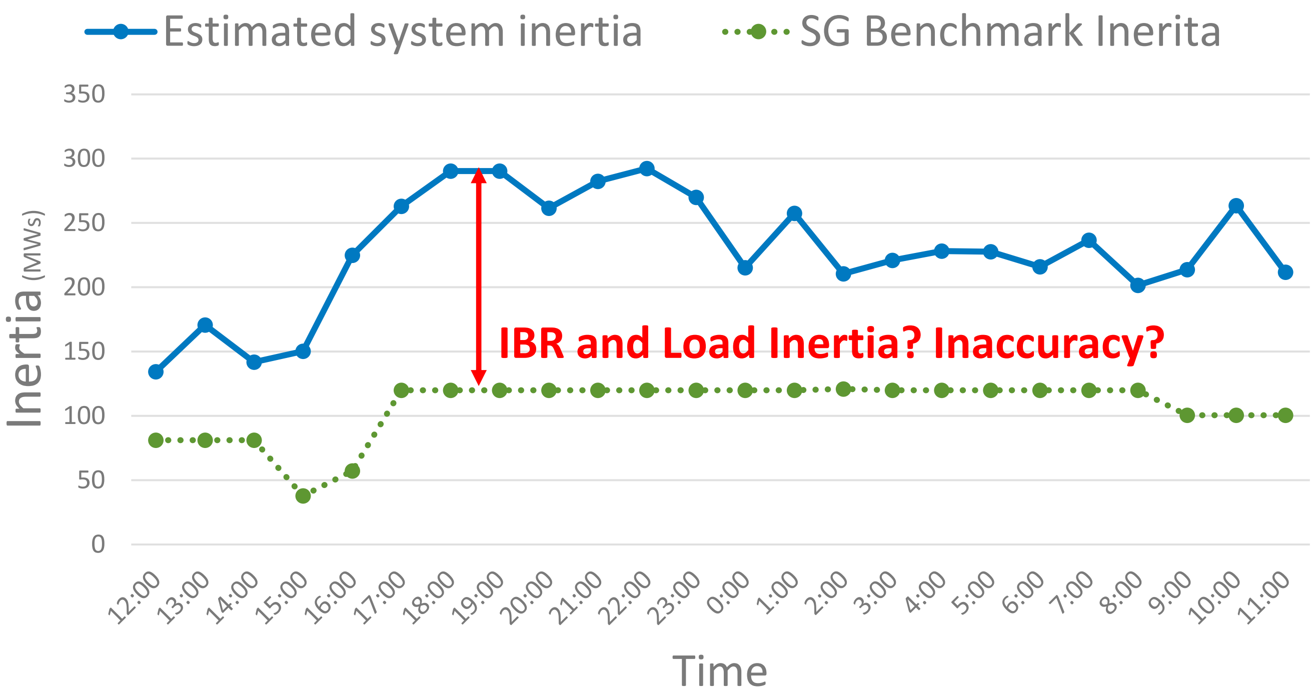
High-speed data from UGA and DFR



Probing pulse injection from the Hybrid PV plant

B. Kroposki and A. Hoke, "A Path to 100 Percent Renewable Energy: Grid-Forming Inverters will Give Us the Grid We Need Now," in IEEE Spectrum, vol. 61, no. 5, pp. 50-57, May 2024, doi: 10.1109/MSPEC.2024.10523014.

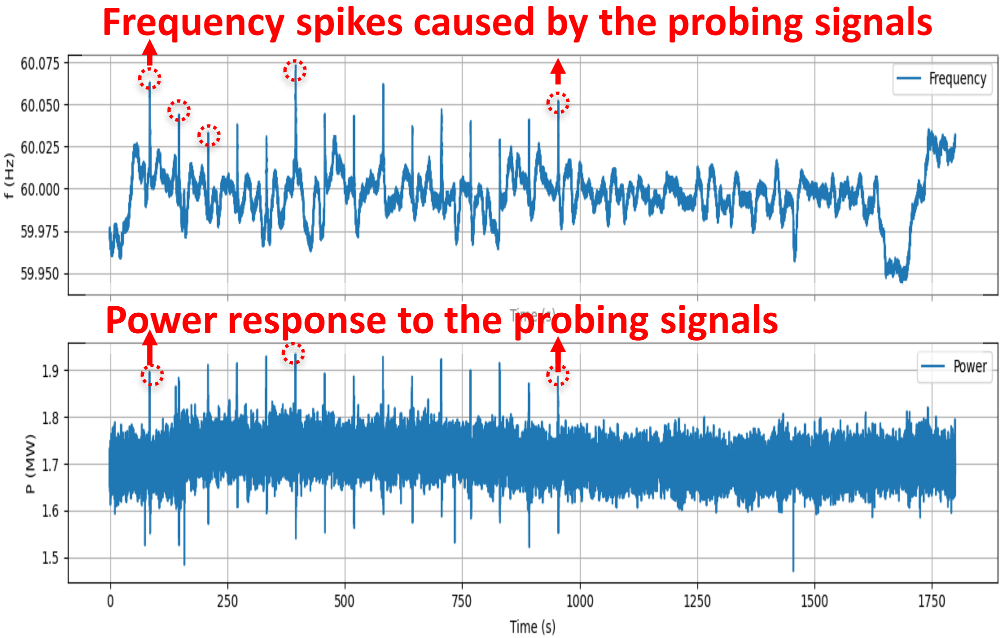
24-hour Inertia Estimation Indicates Highly Variable Inertia



Need in-depth analysis to understand the variable inertia for a grid !

Algorithm Accuracy Validated on Single SG: Shows < **6%** Estimation Error

- **Data:** high-resolution Digital Fault Recorder
- 3 tests conducted as SGs are in SC modes

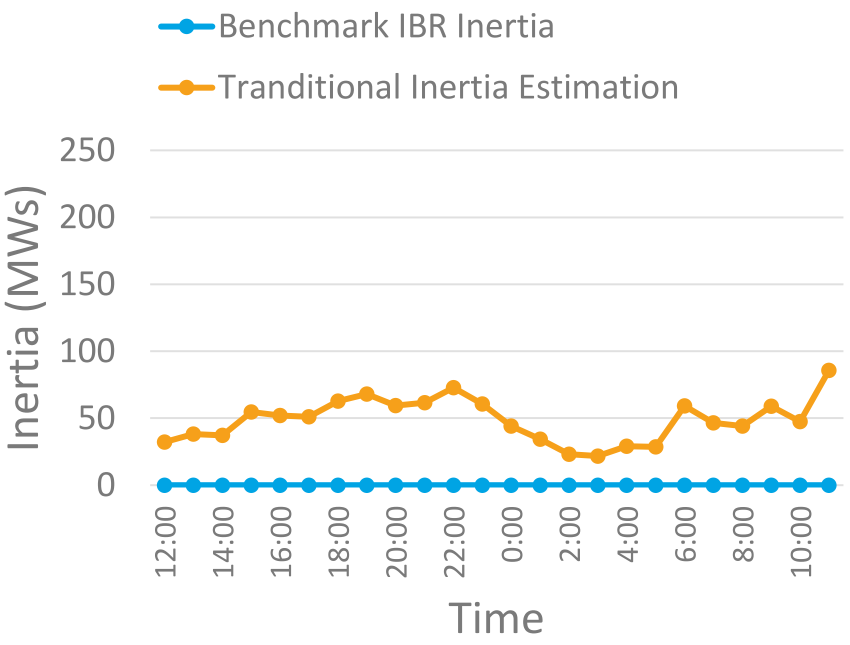


Synchronous Generator: Estimated vs. Actual Inertia

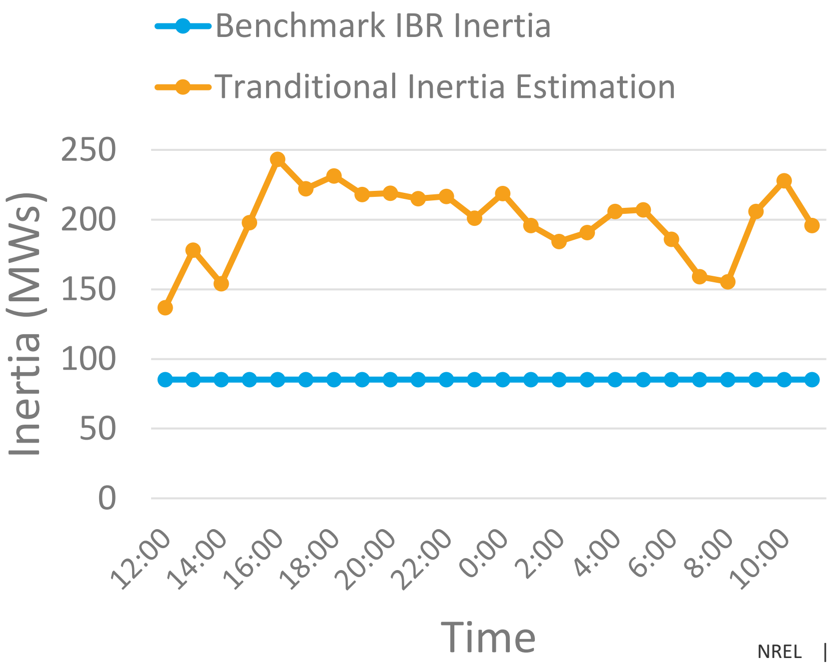
Tests	Estimated Inertia (MWs)	Nameplate Inertia (MWs)	Error (%)
1	57.07		-2.67%
2	55.48	58.63	-5.37%
3	59.04		0.70%

Traditional Inertia Estimation Method Generates **Time-Varying Inertia** for GFM Droop and GFM VSM

Traditional Inertia Estimation for GFM Droop



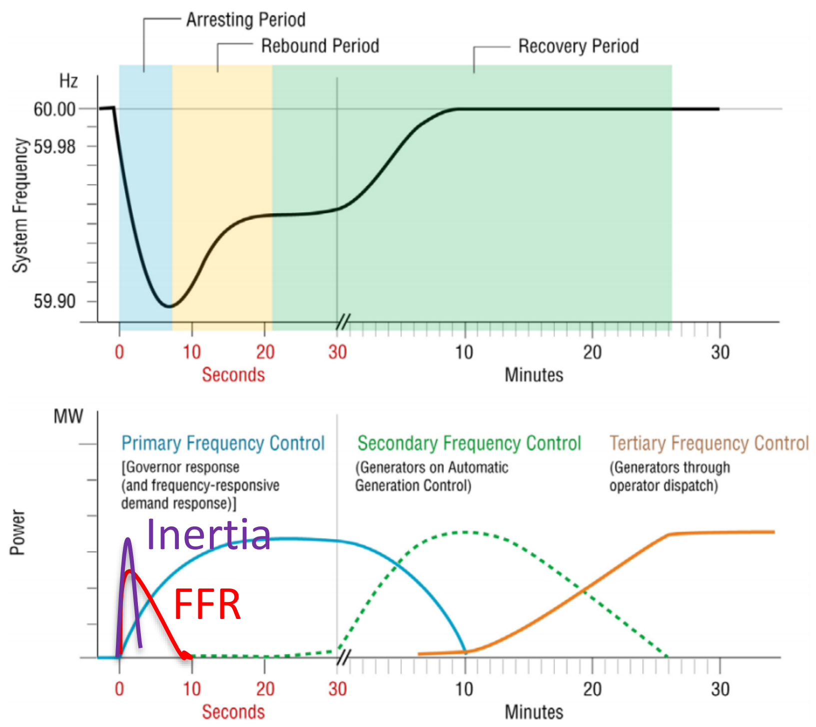
Traditional Inertia Estimation for GFM VSM



In-Depth Analysis Reveals the Need for Revisiting the Definition of “Inertia” and Algorithms for Inertia Estimation

$$\frac{d\omega}{dt} = (P_{gen} - P_{load} - P_{genloss})/2\underline{H}$$

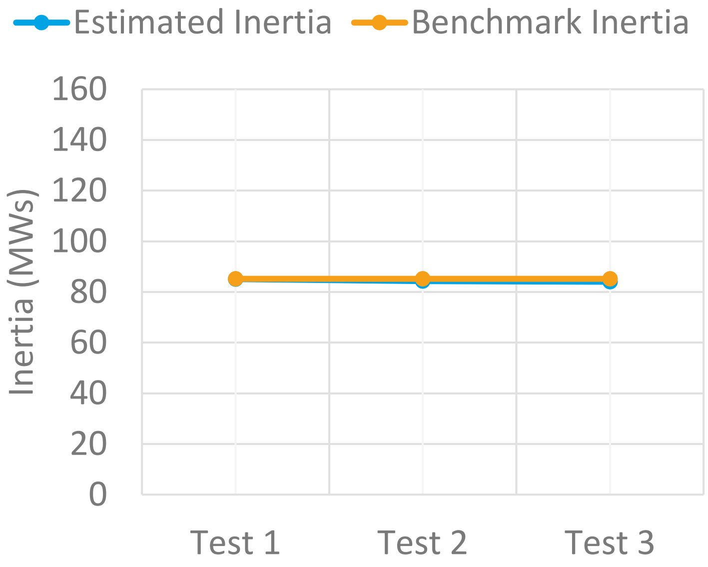
	Traditional Grids	Modern Grids
ROCOF	Natural inertia	Electronics-control-based FFR (Synthetic Inertia(SI)+others)
Frequency Nadir	Inertia + Droop	Electronics-control-based FFR (SI+Others)
Settling Frequency	Droop	Electronics-control-based FFR (Droop+)



Eto, Joseph H. "Use of frequency response metrics to assess the planning and operating requirements for reliable integration of variable renewable generation." (2011).

GFM VSM Inertia Estimation Varies and May Differ from Nameplate Value

Model-based Analysis of GFM VSM: Estimated v.s. Nameplate value



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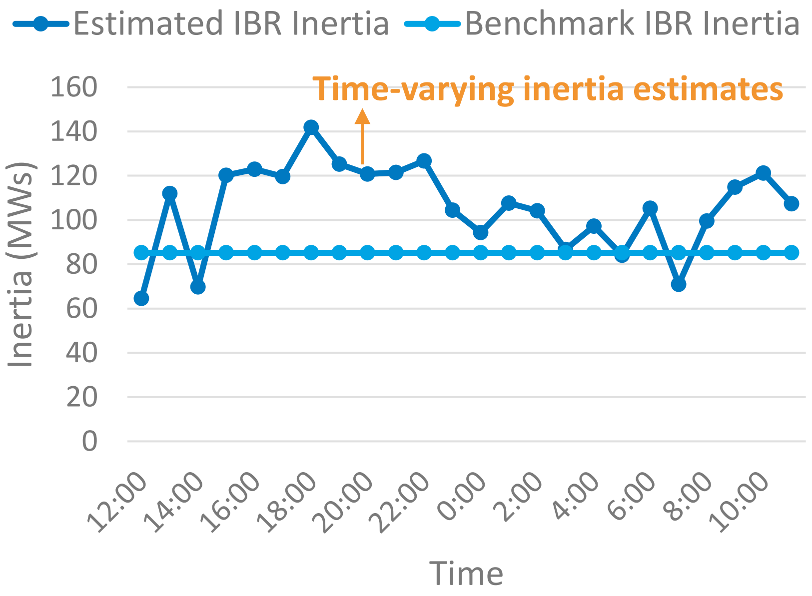
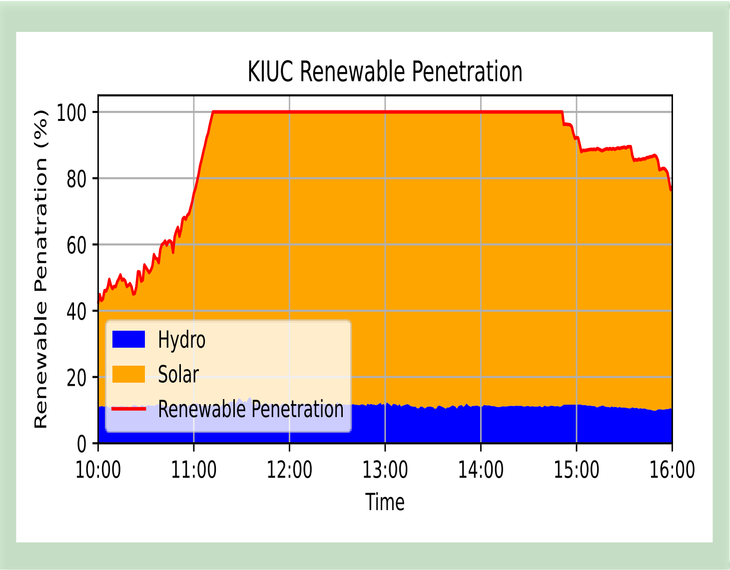
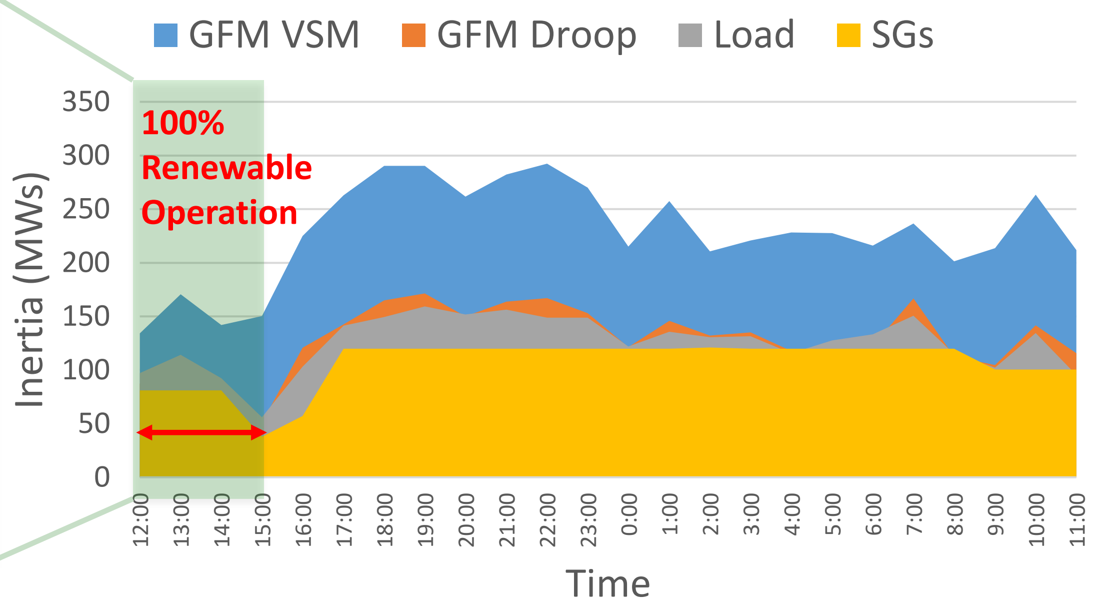
Field testing of 24-hour inertia of a GFM VSM: Estimated v.s. Nameplate value



A Second Look at the Result



24 hour Inertia Estimation of KIUC grid



- SGs and IBRs and load contribute to the overall system inertia

Conclusion

“Inertia Monitoring” from a Device Perspective

- **Grid-forming VSM** can significantly enhance **grid stability** by providing responses within the inertial timeframe through “**Synthetic inertia**’ and “**fast frequency responses”**.
- **Droop-based Grid-forming** and **Grid following IBR** can provide “**fast frequency responses”** in the inertial timeframe.
- **Fast Power and Frequency Control** of IBRs can reduce the “**Inertia Needs**” from rotating machines such as synchronous generators.
- However, **the measured time-varying inertia** of IBRs of poses challenges for grid operators and planners in accurately **quantifying and utilizing** FFR from IBR contributions.

Future Outlook

"Inertia Monitoring" from a System Perspective

- It is easy to obtain a measured "inertia" value in the field, but it is more critical to understand how accurate it is? What does this value mean? What's the critical "inertia" floor for grid operation?
- There is a need to revisit the **concept of inertia**, refine **inertia monitoring algorithms**, and develop a deeper **understanding of the essence of system inertia**.
  - **Traditional grids:** Power System Inertia = rotating inertia.
  - **Modern grids:** Power System Inertia depends on how it is defined.

When, Where and How much does Power System Need what?

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- Joy Zhao

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(PHIL; UGA; Test Plan)

Kelsey Horowitz
(PHIL; Field testing)

- **Kelsey Horowitz (Lead)**
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- Aaron Madtson
- Etc.

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(KIUC control Room; Field testing)

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For Further Reading

Probing signal-based inertia estimation:

1. J. Peng, J. Tan, P. Koralewicz, E. Mendiola, S. Dong, A. Hoke, K. Horowitz "Probing Signal-Based Inertia and Frequency Response Estimation for Power Systems With High Levels of Inverter-Based Resources," IEEE PESGM 2024.
2. Xinlan Jia, Zhihao Jiang, He Yin, Yi Zhao, Yilu Liu, Jin Tan, Andy Hoke, Jiangkai Peng, Przemyslaw Koralewicz, Emanuel Mendiola, Ezequiel Hernandez, Juan Bellido, Kelsey Horowitz, Aaron Madtson, Brad Rockwell, Cameron Kruse, "Probing-based Real-time Inertia Estimation Tool Implementation," North American Synchrophasor Work Group Meeting, April 2024.
3. Xinlan Jia, Zhihao Jiang, He Yin, Yi Zhao, Yilu Liu, Jin Tan, Andy Hoke, Jiangkai Peng, Przemyslaw Koralewicz, Emanuel Mendiola, Ezequiel Hernandez, Juan Bellido, Kelsey Horowitz, Aaron Madtson, Brad Rockwell, Cameron Kruse, "Probing-based Real-time Inertia Estimation Software Field Implementation and PHIL Testing," 14th International Renewable Energy Congress (IREC 2023).
4. Z. Jiang, Y. He, H. Li, Y. Liu, J. Tan, A. Hoke, B. Rockwell, C. Kruse, "Probing-Based Inertia Estimation Method Using Hybrid Power Plant" IEEE PESGM 2023.

Further Reading

1. He Yin, Wei Qiu, Yuru Wu, Lingwei Zhan, Wenpeng Yu, Jin Tan, Andy Hoke, Cameron J. Kruse, Brad W. Rockwell, Yilu Liu, "Point-On-Wave-based Anomaly Detection and Categorization in Low Inertia Power Systems", IEEE Transaction of Power Systems.
2. He Yin, Wei Qiu, Yuru Wu, Shutang You, Jin Tan, Andy Hoke, Cameron J. Kruse, Brad W. Rockwell, Yilu Liu, Journal paper, "Field Measurement and Analysis of Frequency and RoCoF for Low-Inertia Power Systems", in IEEE Transactions on Industrial Electronics, doi: 10.1109/TIE.2023.3303622.
3. Hongyu Li, Shutang You, Jin Tan, Andy Hoke, Yilu Liu, Paper of 'A physical and practical method for inertia estimation using the ambient and its application in Hawaii grids', IEEE Trans on Power Systems.
4. H. Yin, Yuru Wu, Wei Qiu, Chujie Zeng, Shutang You, Jin Tan, Andy Hoke, Cameron J. Kruse, Brad W. Rockwell, Kelcie Ann Kawamura, Yilu Liu, "Precise ROCOF estimation algorithm for low inertia power grids." Electric Power Systems Research, Aug. 2022.

The method of probing-signal inertia estimation is protected under the NREL software record: SWR-24-28.

Question?

Acknowledgment: This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number #37772 and 52373.

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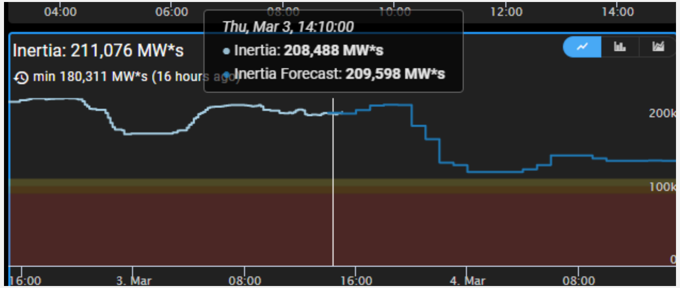
Inertia Estimation: State-of-Art

Inertia Estimation Methods Overview

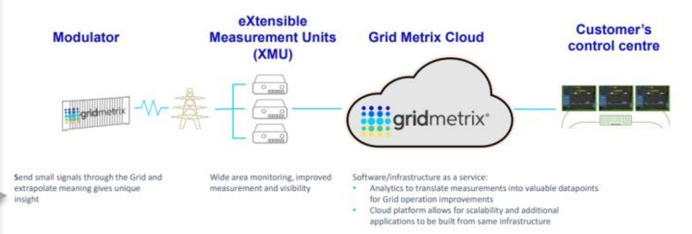
Methods	Input data			Performance		
	EMS	PMU	Event information	Includes load, IBR, and others	Results impacted by FFR and load damping	Real time
Dispatch-based	√	×	×	×	×	√
Event-driven	×	√	√	√	√	×
Ambient signal	×	√	×	√	√	√
Probing signal	×	√	×	√	√	√

http://cigre.ru/research_commitets/ik_rus/c2_rus/materials/library/WBN022%20-%20C2.C4.41%20-%20Dec20.pdf

Since 2016, **ERCOT** implemented real-time inertia estimation in control room.

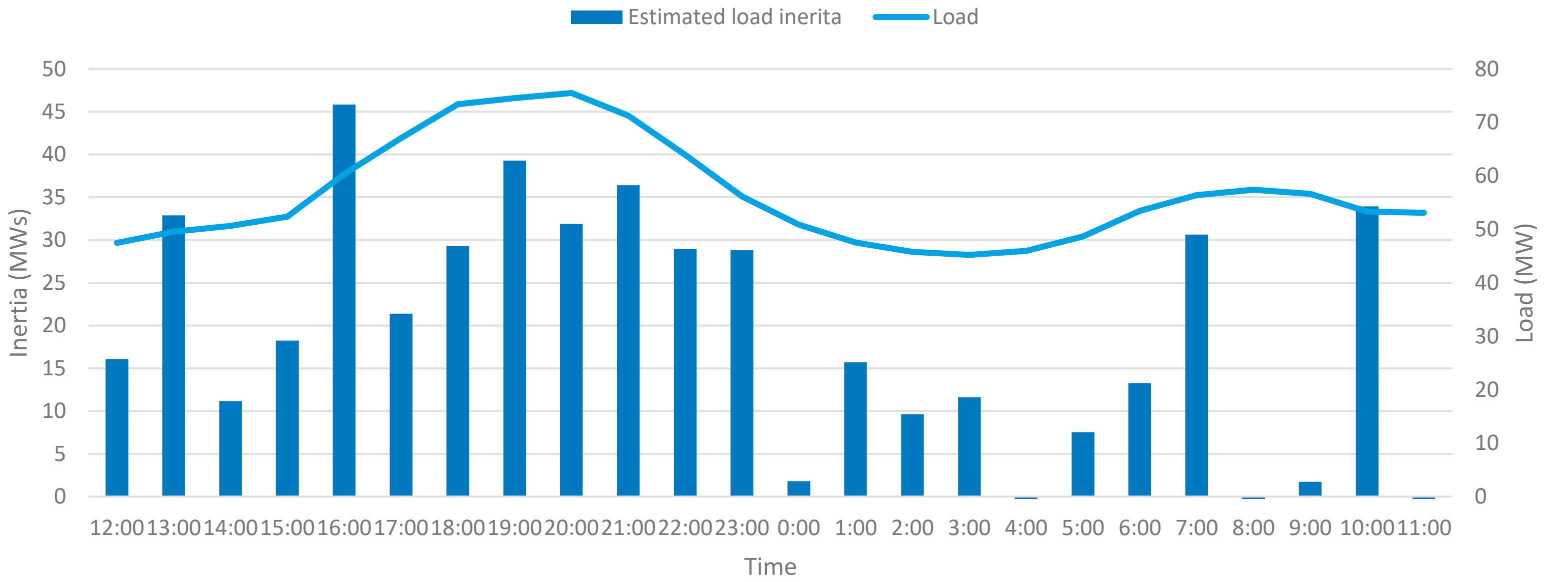


In 2019, **Great Britain** contracted 2 "first-of-their-kind" inertia tools from GE and Reactive Technology.



Load Inertia Quantification

Load inertia tends to increase proportionally with the load, exhibiting a linear relationship between the two.



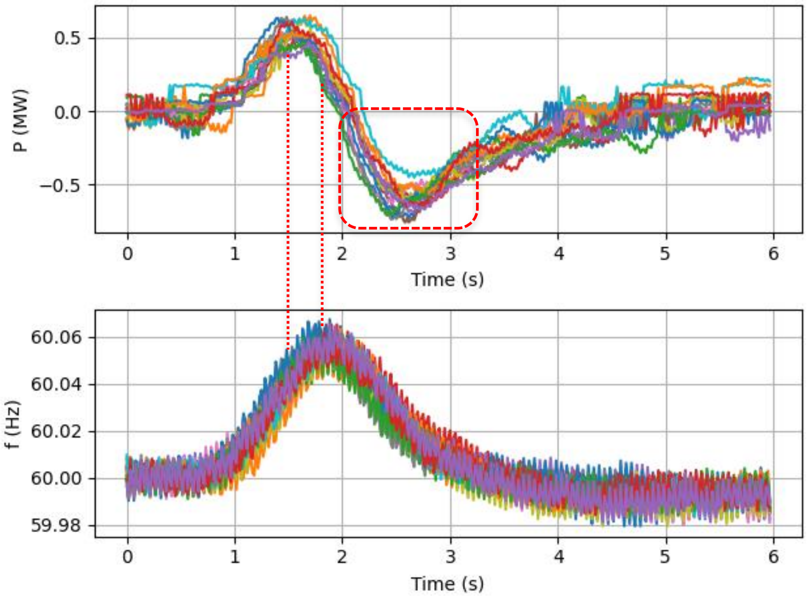
Regression result: $\mathbf{Load\ Inertia} = \mathbf{0.348} \times \mathbf{Load}$

Typical load inertia contribution ranges from 0.1 – 1 according to literature.

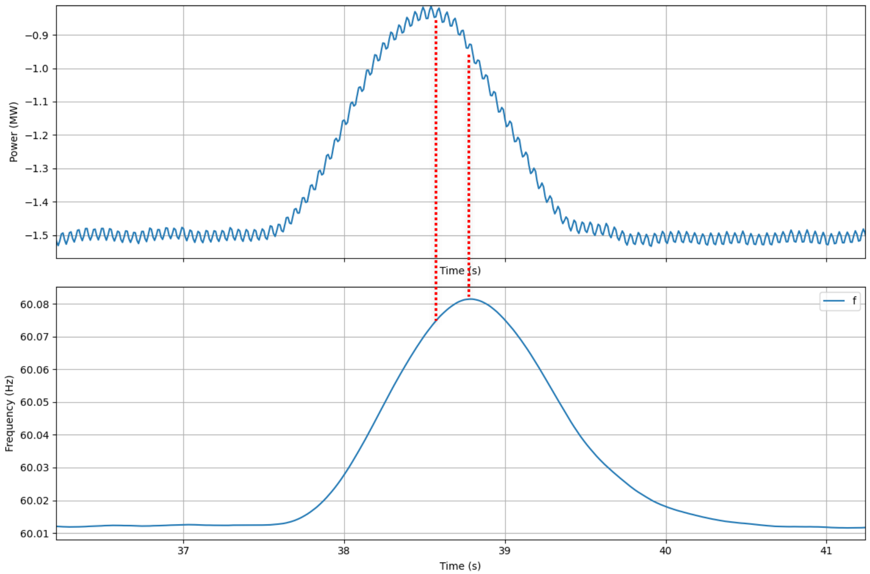
Thiesen, Henning, and Clemens Jauch. 2020. "Determining the Load Inertia Contribution from Different Power Consumer Groups" *Energies* 13, no. 7: 1588. https://doi.org/10.3390/en13071588

IBR Inertia Quantification: GFM VSM

Field test results: GFM VSM (IBR 4)



Field Data



Simulation Data

- Field results differ significantly from the simulation results of a generic VSM.
- **Modelling gap**: Variants of VSM control with **additional control loops** have contribute to these performance differences.