# Introduction of WECC Standard Library Grid-Forming Inverter Models

## *-- Model Principle, Validation Using Field Measurements, and Use Cases*


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July 17th, 2025

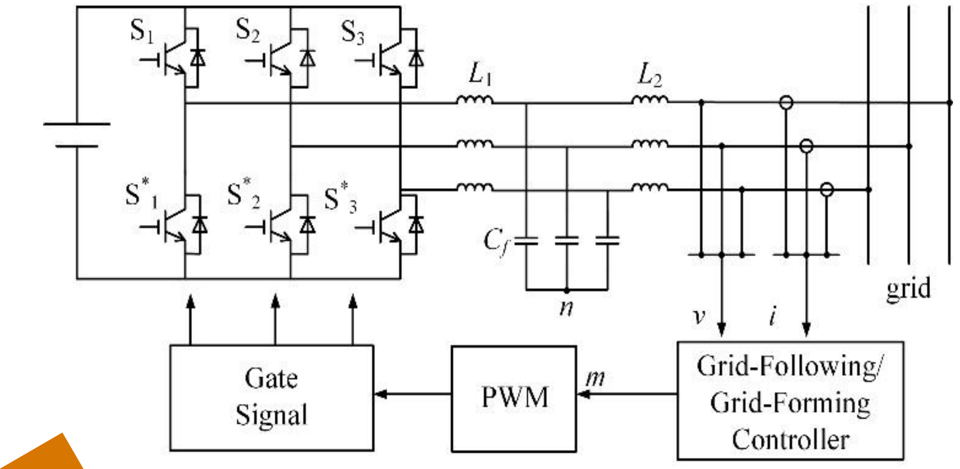

PNNL is operated by Battelle for the U.S. Department of Energy

# Outline

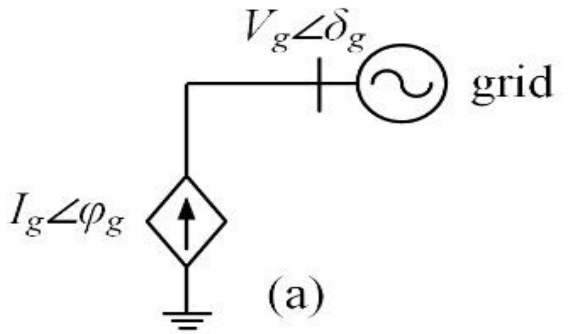
- Introduction
- Model Principle
- Validation Using Field Measurement
- Use Cases
- Conclusion

# Grid-Following VS Grid-Forming

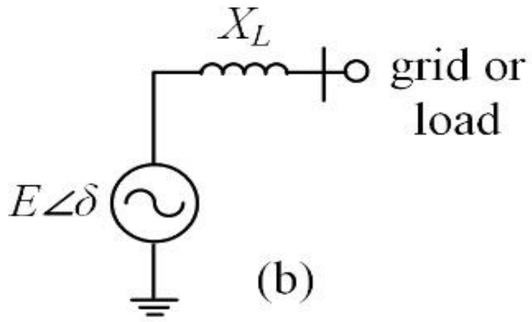
- There are already well-established grid-following (GFL) inverter-based resource (IBR) models in commercial transient stability simulation tools, such as the WECC REGC_*, REEC_*, and REPC_* IBR models
- *However, before we initiated this work, there were no grid-forming inverter (GFM) models in those tools*




Voltage-Sourced Inverter



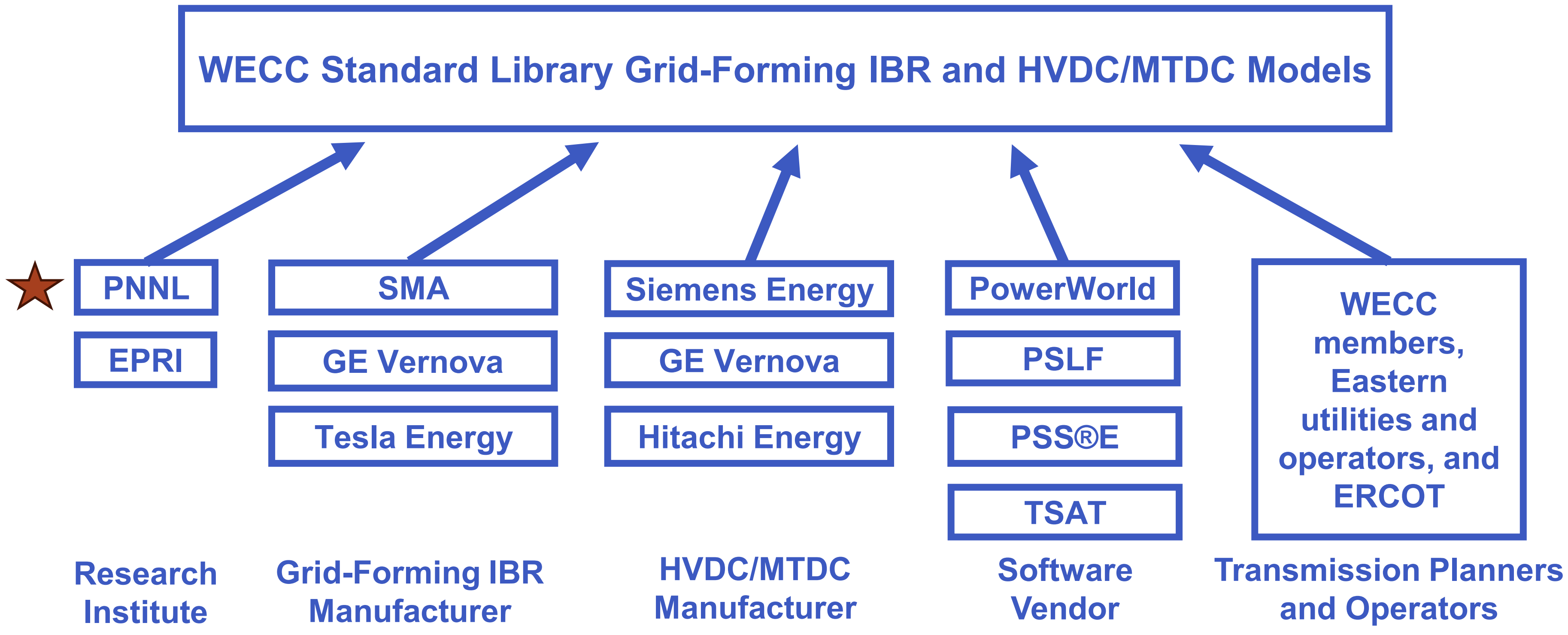

Grid-Following (≈Current Phasor)

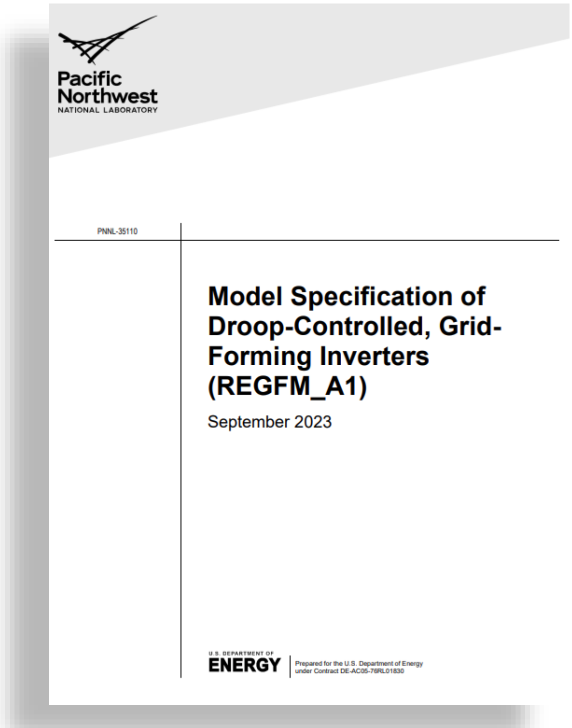



Grid-Forming (≈Voltage Phasor)

# PNNL Leads the Development of Standard Library GFM Models

- PNNL is leading the development of WECC standard library GFM models in collaboration with major manufacturers, software vendors, EPRI, and planners over the past five years funded by DOE UNIFI consortium
- The development of HVDC/MTDC standard library models started in Jan. 2025



Pacific Northwest NATIONAL LABORATORY

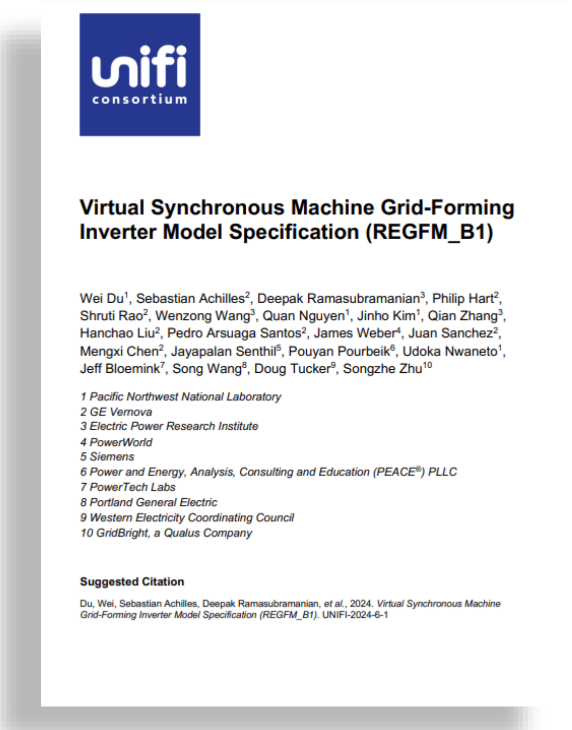
PNNL-35110

**Model Specification of Droop-Controlled, Grid-Forming Inverters (REGFM_A1)**

September 2023

U.S. DEPARTMENT OF ENERGY | Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

REGFM_A1



unifi consortium

**Virtual Synchronous Machine Grid-Forming Inverter Model Specification (REGFM_B1)**

Wei Du[1], Sebastian Achilles[2], Deepak Ramasubramanian[3], Philip Hart[2], Shruti Rao[2], Wenzong Wang[3], Quan Nguyen[1], Jinho Kim[1], Qian Zhang[3], Hanchao Liu[2], Pedro Arsuaga Santos[2], James Weber[4], Juan Sanchez[2], Mengxi Chen[2], Jayapalan Senthil[5], Pouyan Pourbeik[6], Udoka Nwaneto[1], Jeff Bloemink[7], Song Wang[8], Doug Tucker[9], Songzhe Zhu[10]

*1 Pacific Northwest National Laboratory*
*2 GE Vernova*
*3 Electric Power Research Institute*
*4 PowerWorld*
*5 Siemens*
*6 Power and Energy, Analysis, Consulting and Education (PEACE®) PLLC*
*7 PowerTech Labs*
*8 Portland General Electric*
*9 Western Electricity Coordinating Council*
*10 GridBright, a Qualus Company*

**Suggested Citation**

Du, Wei, Sebastian Achilles, Deepak Ramasubramanian, *et al.*, 2024. *Virtual Synchronous Machine Grid-Forming Inverter Model Specification (REGFM_B1).* UNIFI-2024-6-1

REGFM_B1

unifi consortium

**Standard Library Grid-Forming Hybrid Control Inverter-based Resource Model Specification (REGFM_C1)**

Wei Du[1], Sai Gopal Vennelaganti[2], Deepak Ramasubramanian[3], Jinho Kim[1], Udoka Nwaneto[1], Quan Nguyen[1], Mostafa Mahfouz[2], Mohammed Nassar[2], Sushrut Thakar[3], Chengwen Zhang[3], Sheik Mohammad Mohiuddin[1], James Weber[4], Mengxi Chen[5], Jayapalan Senthil[6], James Feltes[6], Pouyan Pourbeik[7], Fred Howell[8], Jeff Bloemink[8], Song Wang[9], Doug Tucker[10], Songzhe Zhu[11], Juan Sanchez[12]

*1 Pacific Northwest National Laboratory*
*2 Tesla Energy*
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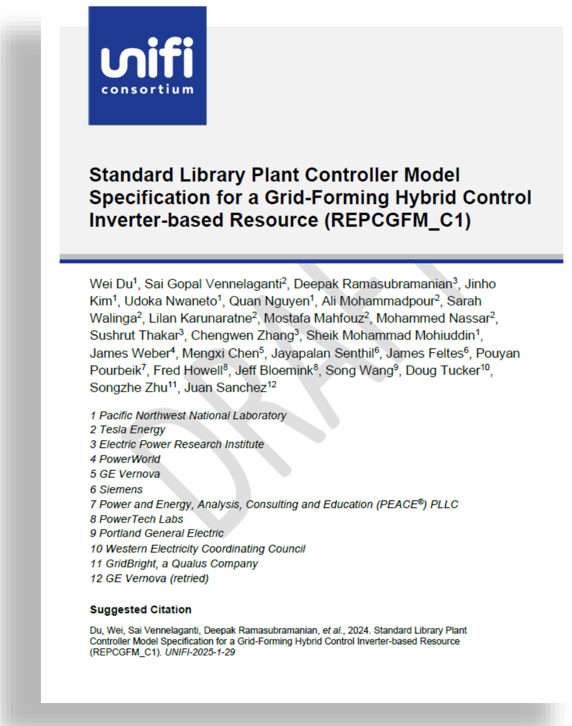
*8 PowerTech Labs*
*9 Portland General Electric*
*10 Western Electricity Coordinating Council*
*11 GridBright, a Qualus Company*
*12 Retired from GE Vernova*

**Suggested Citation**

Du, Wei, Sai Gopal Vennelaganti, Deepak Ramasubramanian, *et al.*, 2024. *Standard Library Grid-Forming Hybrid Control Inverter-based Resource Model Specification (REGFM_C1).* UNIFI-2025-1-28

REGFM_C1



unifi consortium

**Standard Library Plant Controller Model Specification for a Grid-Forming Hybrid Control Inverter-based Resource (REPCGFM_C1)**

Wei Du[1], Sai Gopal Vennelaganti[2], Deepak Ramasubramanian[3], Jinho Kim[1], Udoka Nwaneto[1], Quan Nguyen[1], Ali Mohammadpour[2], Sarah Walinga[2], Lilan Karunaratne[2], Mostafa Mahfouz[2], Mohammed Nassar[2], Sushrut Thakar[3], Chengwen Zhang[3], Sheik Mohammad Mohiuddin[1], James Weber[4], Mengxi Chen[5], Jayapalan Senthil[6], James Feltes[6], Pouyan Pourbeik[7], Fred Howell[8], Jeff Bloemink[8], Song Wang[9], Doug Tucker[10], Songzhe Zhu[11], Juan Sanchez[12]

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*9 Portland General Electric*
*10 Western Electricity Coordinating Council*
*11 GridBright, a Qualus Company*
*12 GE Vernova (retried)*

**Suggested Citation**

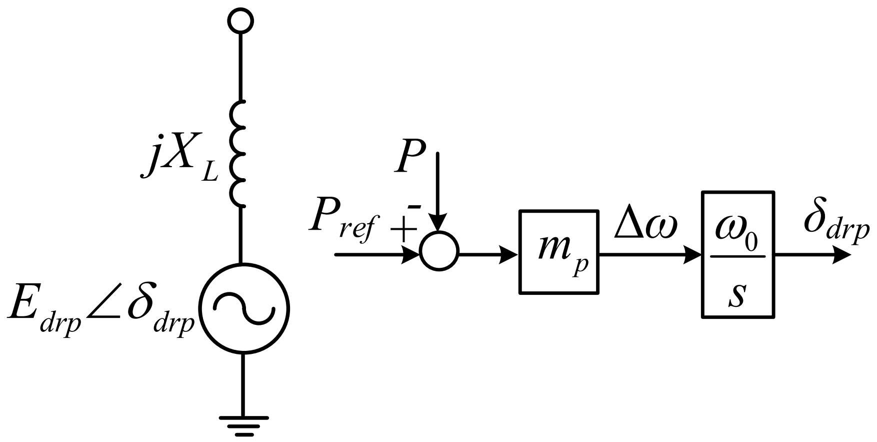
Du, Wei, Sai Vennelaganti, Deepak Ramasubramanian, *et al.*, 2024. Standard Library Plant Controller Model Specification for a Grid-Forming Hybrid Control Inverter-based Resource (REPCGFM_C1). *UNIFI-2025-1-29*

REPCGFM_C1

# Key Control Features in Standard Library GFM Models

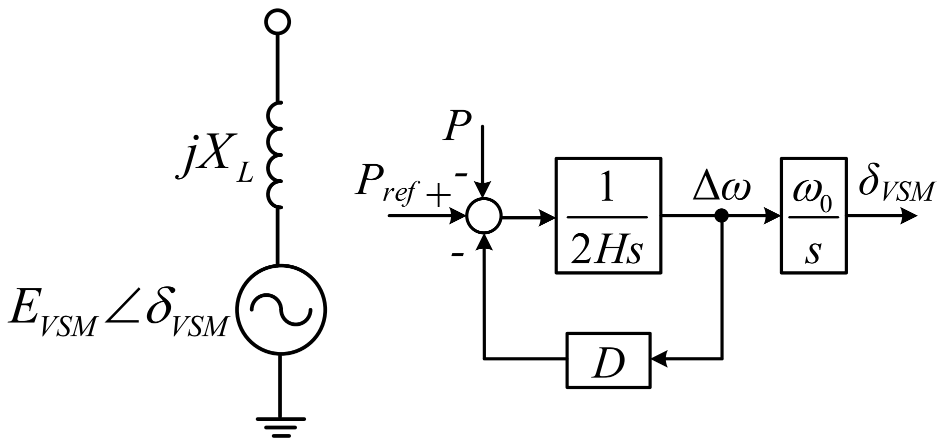
- REGFM_A1 is based on droop control
- REGFM_B1 is based on virtual synchronous machine (VSM) control
- REGFM_C1 is based on GFM + GFL hybrid control
- These models also describe controls for GFMs under various constraints such as *P* and *Q* limiting, current limiting, and fault ride-through

## REGFM_A1



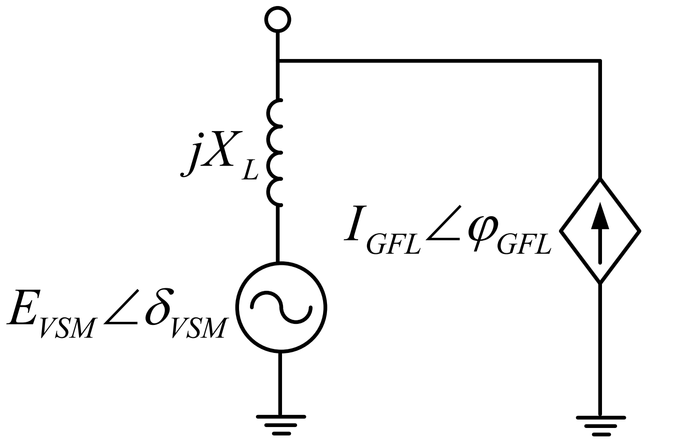

GFM Droop Control

## REGFM_B1




GFM VSM Control

## REGFM_C1




GFM Hybrid Control
(VSM + GFL)

# Standard Library GFM Models in Commercial Tools

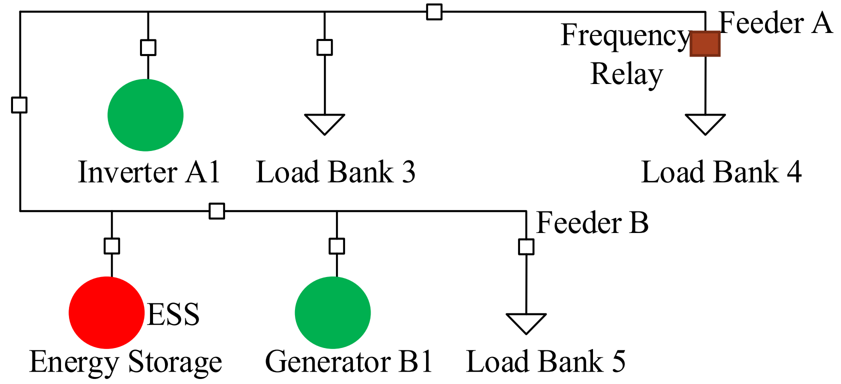
- These models represent the first generation of industry-approved standard library GFM models and have been integrated into leading commercial transient stability simulation tools
- *These models have been either partially or fully validated against field data or detailed electromagnetic transient (EMT) models from manufacturers*

| | REGFM_A1 (GFM Droop Control) | REGFM_B1 (Virtual Synchronous Machine) | REGFM_C1 and REPCGFM_C1 (GFM Hybrid Control) |
|---|---|---|---|
| **Siemens PSS/E** | V36.1 | V36.1 | Implemented |
| **GE PSLF** | V23.2.8.2 | V23.2.8.2 | Implementing |
| **PowerWorld Simulator** | V23 | V23 | V24 |
| **Powertech Labs TSAT** | V24.1 | V24.1 | Implemented |
| **DigSilent PowerFactory** | V2025 | Implementing | Implementing |

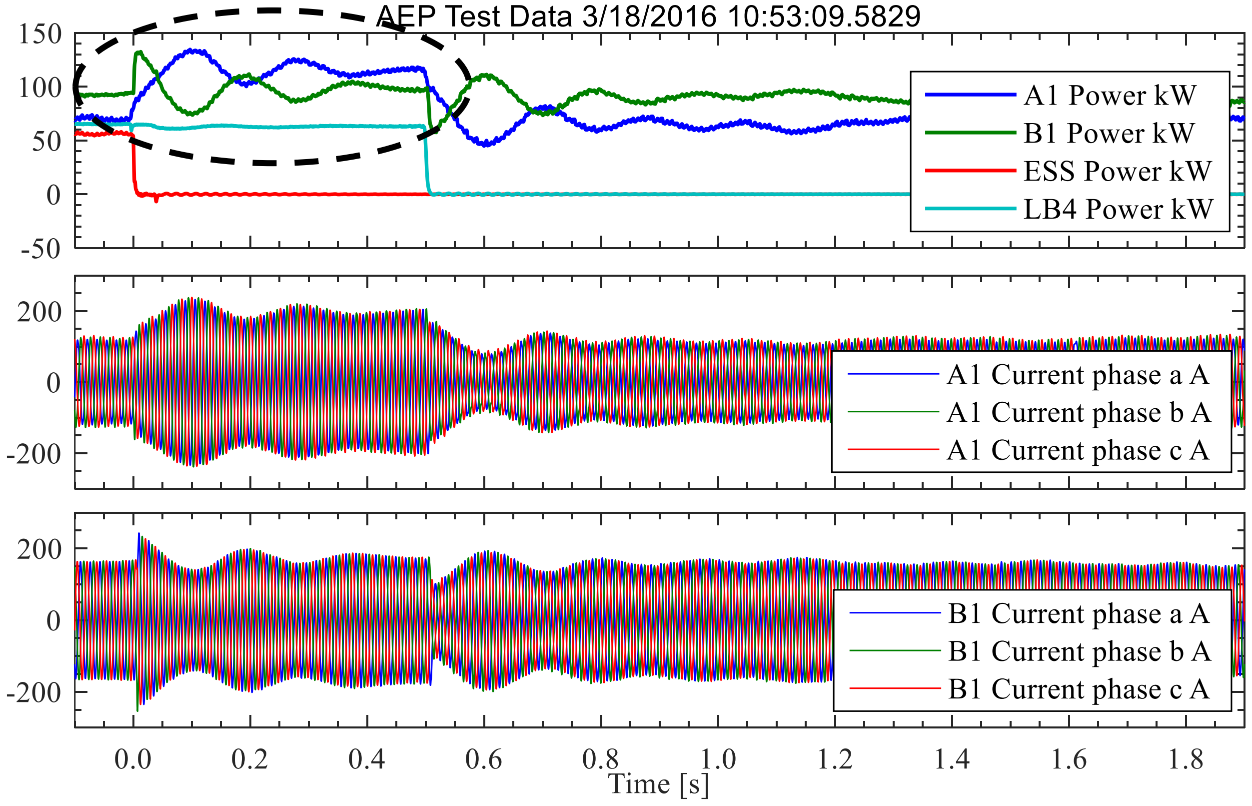
*PSS/E is used by 2,000+ organizations across 140+ countries, PowerWorld is used by 1,000+ organizations across 70 countries, and PowerFactory is used by 2,500+ organizations across 170+ countries, etc.*

# GFM Model Validation (REGFM_A1)

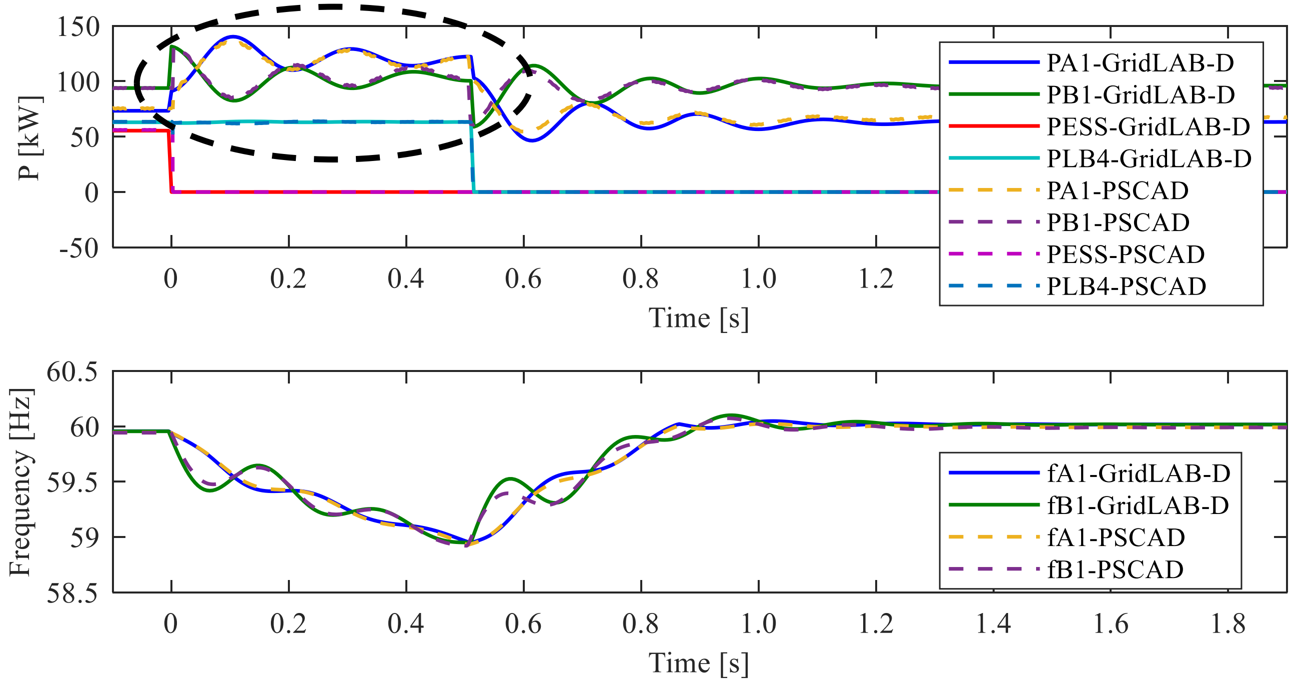
- After the trip of the third unit (ESS), the natural gas generator and the natural gas grid-forming inverter can work in a stable manner in the islanded mode
- The field test results, EMT simulation, and phasor simulation all match well




CERTS/AEP Microgrid Testbed




Field test results from CERTS/AEP testbed




EMT and phasor simulation results

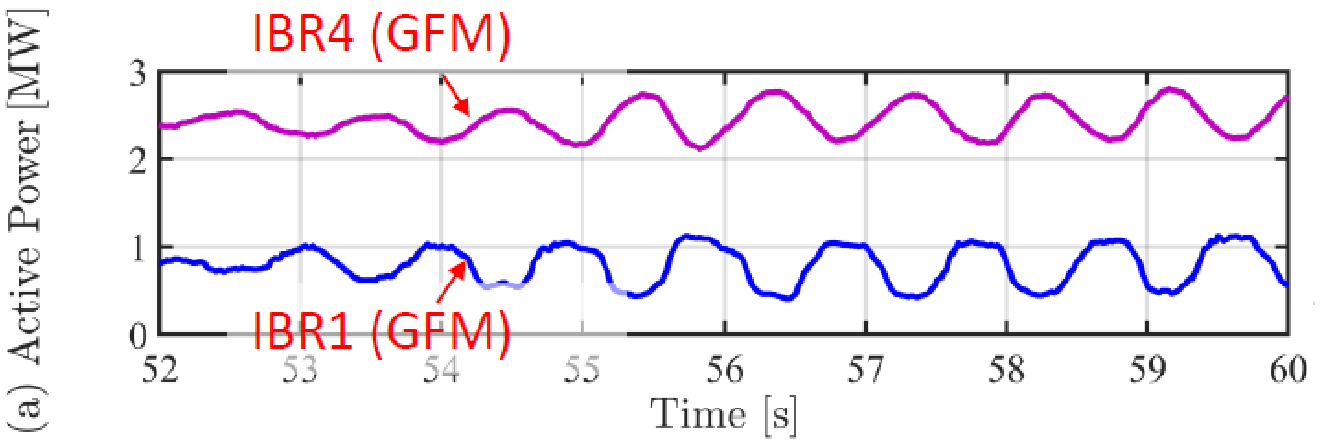
----*EMT*

——*Phasor REGFM_A1*

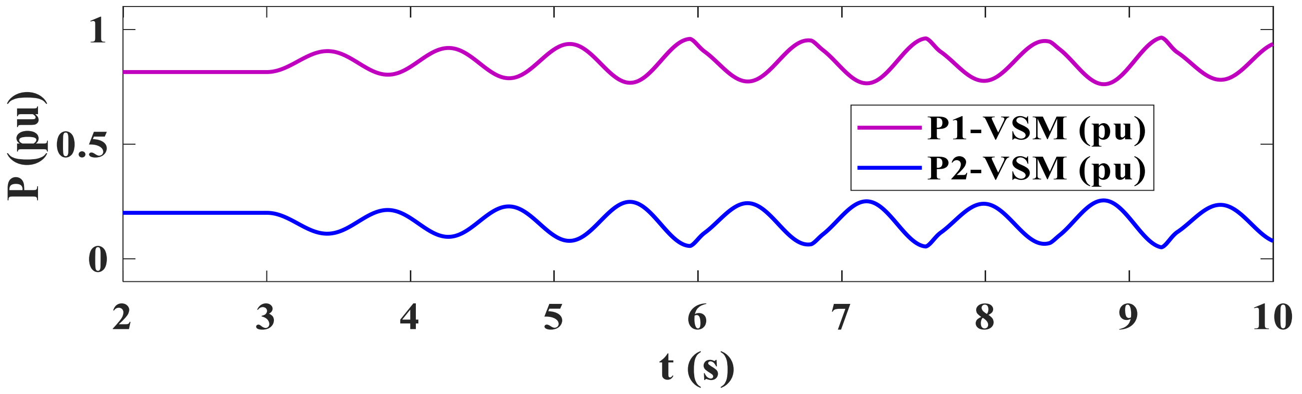

[1] Du, Wei, Robert H. Lasseter, and Amrit S. Khalsa. "Survivability of autonomous microgrid during overload events." *IEEE Transactions on Smart Grid* 10, no. 4 (2018): 3515-3524.

# GFM Model Validation (REGFM_B1)

- The REGFM_B1 model can be parameterized to reproduce the 1 Hz oscillation happened in the Kauai island
- If parameters are not set appropriately (e.g., *inertia*, *damping*, *plant controller parameters*), there could also be oscillations between two GFM units, especially for virtual synchronous machine GFMs, just like those oscillations happened to real synchronous machines




Field results. Event: on Apr. 30th, 2023, two GFMs oscillate against each other, and the oscillation frequency is 1 Hz. (Source: Jin Tan, NREL)




The REGFM_B1 model can reproduce the 1 Hz oscillation by tuning the parameters.

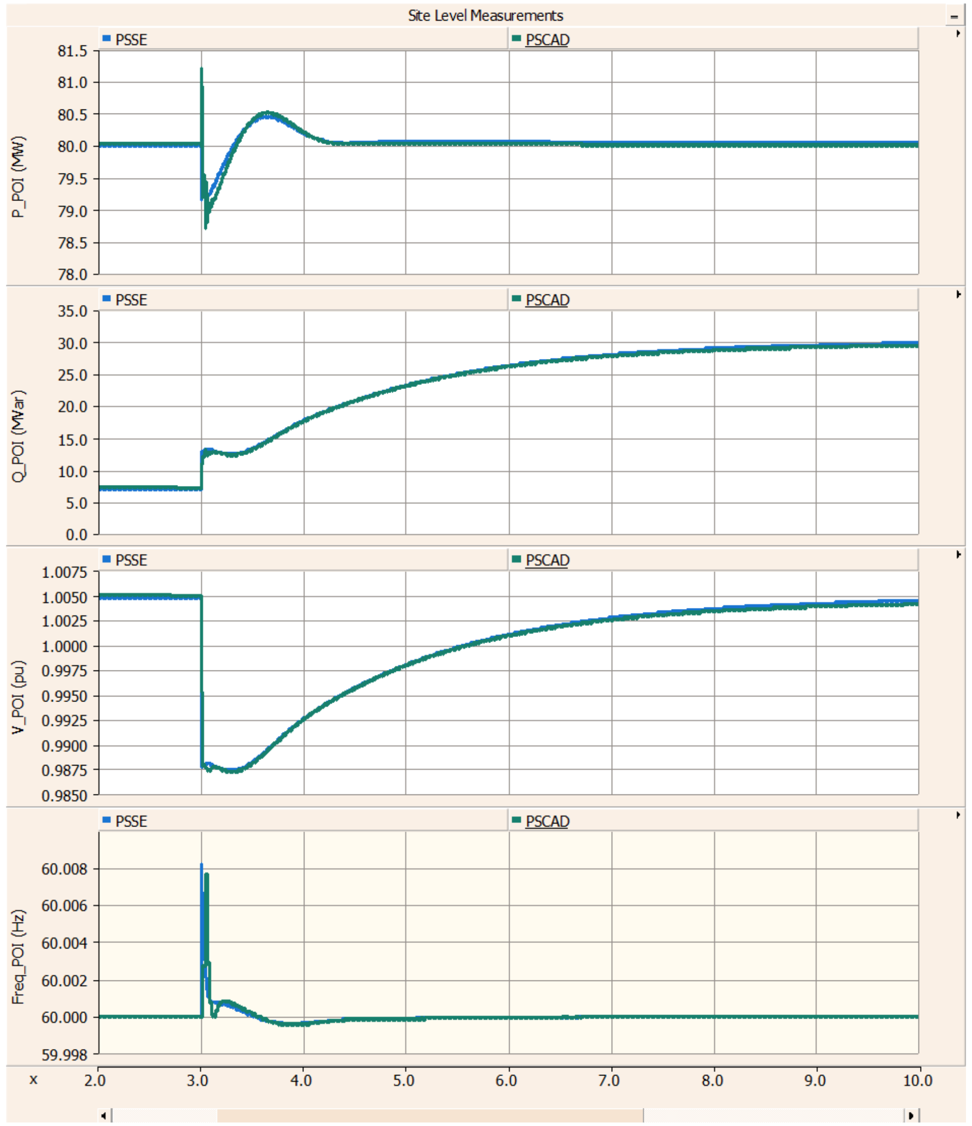
# GFM Model Validation (REGFM_C1 and REPCGFM_C1)

- The REGFM_C1 + REPCGFM_C1 models have been fully validated against Tesla Energy's black-box PSCAD model under various conditions

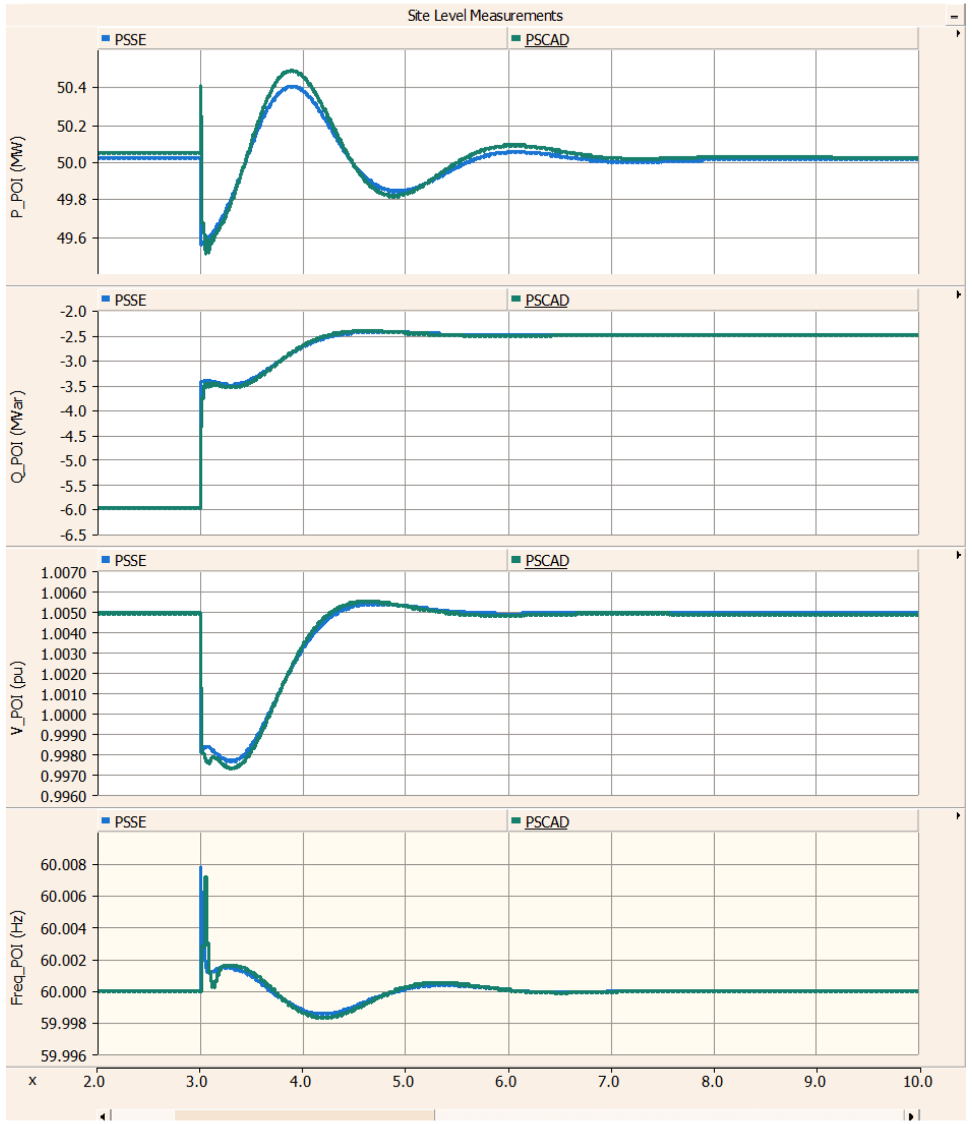
## Grid Voltage Step down

**Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model**
**Green Line: Tesla's black-box PSCAD Model**

**High SCR and X/R Ratio**
(**SCR=10, X/R=10**)




**Low SCR and X/R Ratio**
(**SCR=1.5, X/R=3**)




*Simulation credit: Tesla Energy*

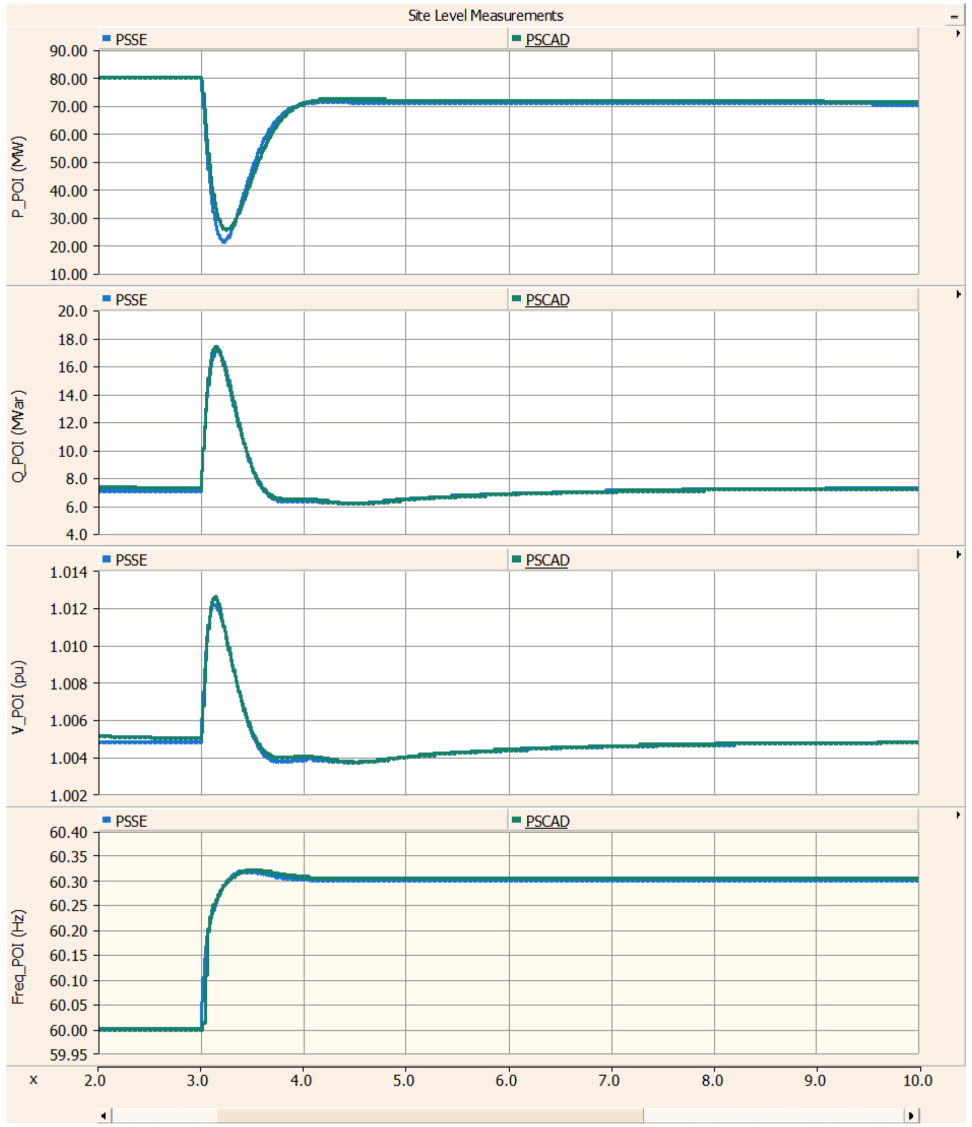
# GFM Model Validation (REGFM_C1 and REPCGFM_C1)

- The REGFM_C1 + REPCGFM_C1 models have been fully validated against Tesla Energy’s black-box PSCAD model under various conditions

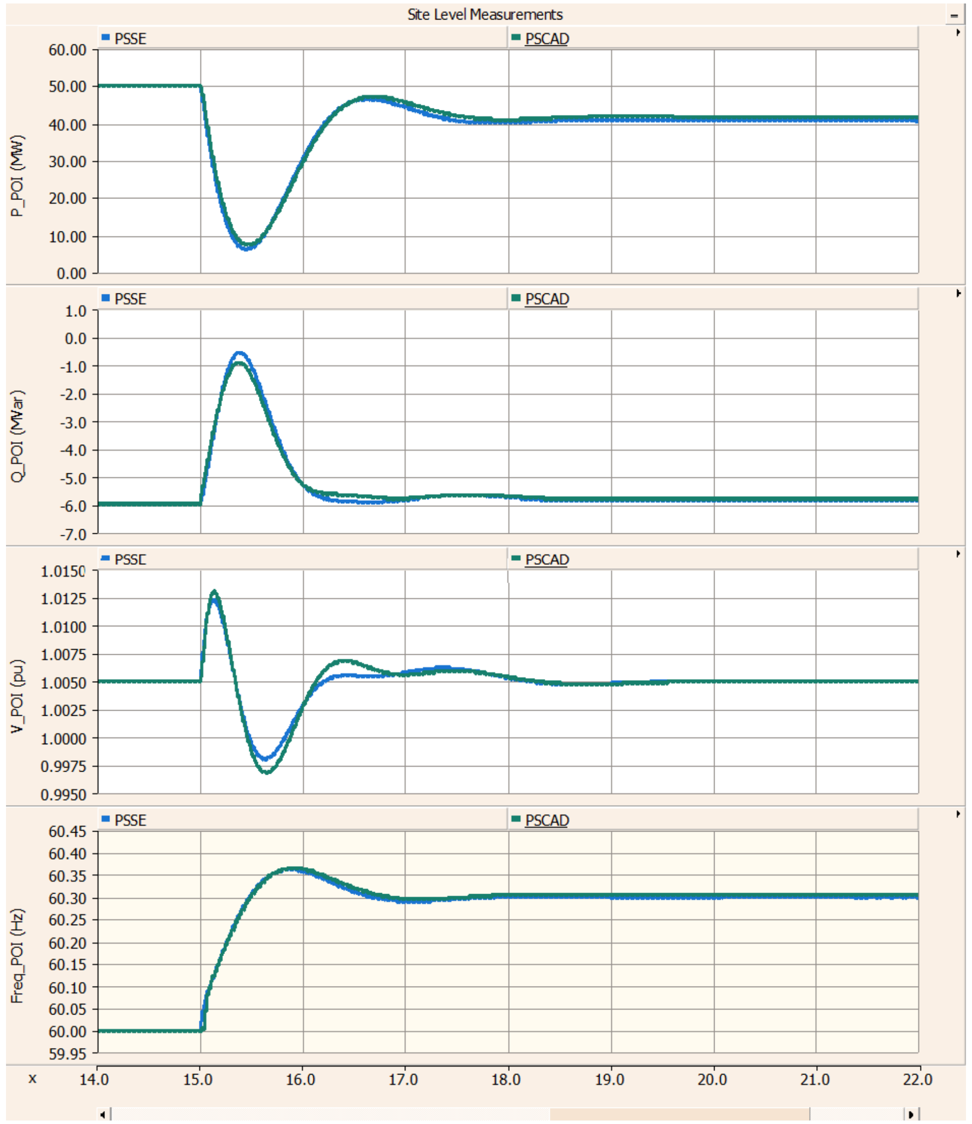
## Grid Frequence Step up

**Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model**
**Green Line: Tesla’s black-box PSCAD Model**

### High SCR and X/R Ratio (SCR=10, X/R=10)




### Low SCR and X/R Ratio (SCR=1.5, X/R=3)




*Simulation credit: Tesla Energy*

# GFM Model Validation (REGFM_C1 and REPCGFM_C1)

- The REGFM_C1 + REPCGFM_C1 models have been fully validated against Tesla Energy's black-box PSCAD model under various conditions

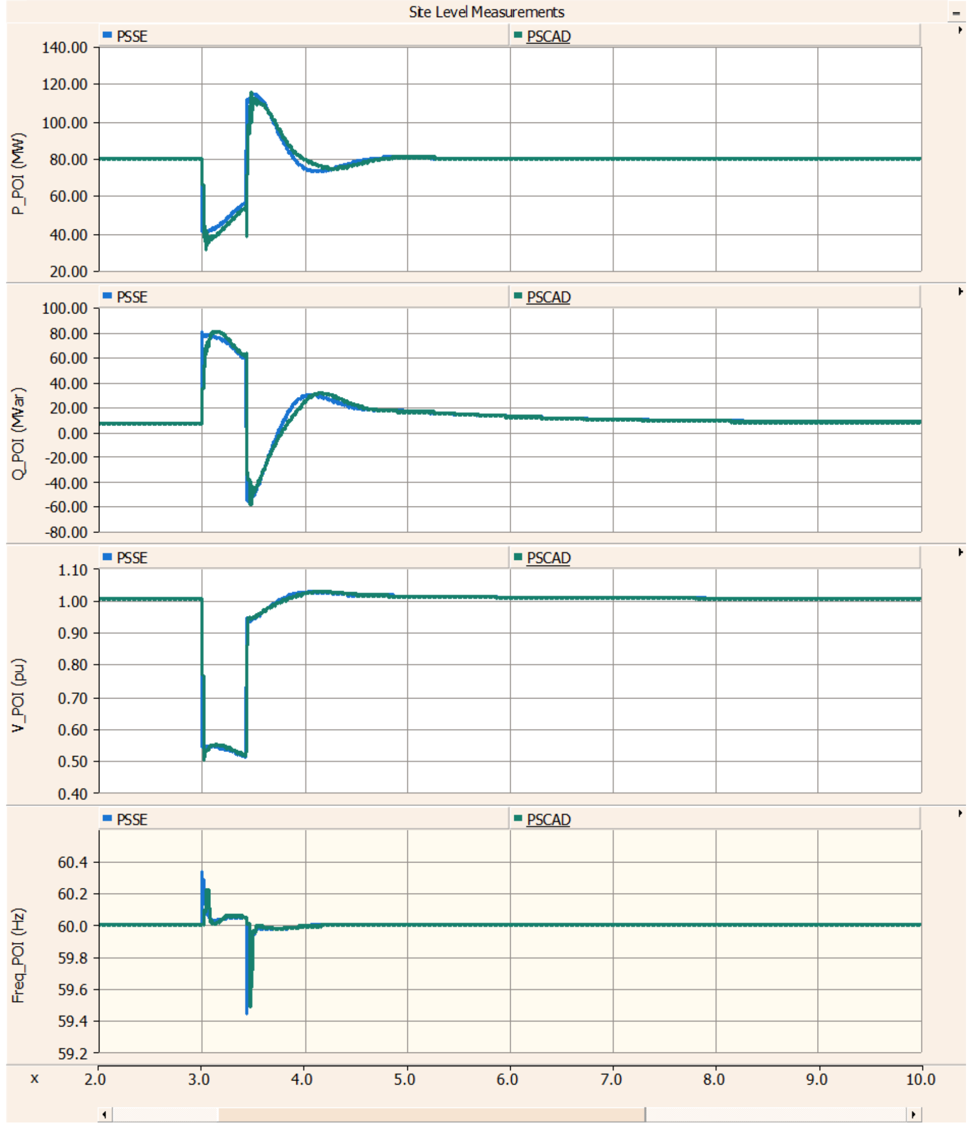
## High Impedance Fault

**Blue Line: REGFM_C1 + REPCGFM_C1 PSS/E Model**
**Green Line: Tesla's black-box PSCAD Model**

***GFMs can work in both strong and weak grids without the need to tune parameters***

***For GFMs, positive-sequence phasor models can accurately capture their dynamics for transient stability studies***

**High SCR and X/R Ratio**
(**SCR=10, X/R=10**)

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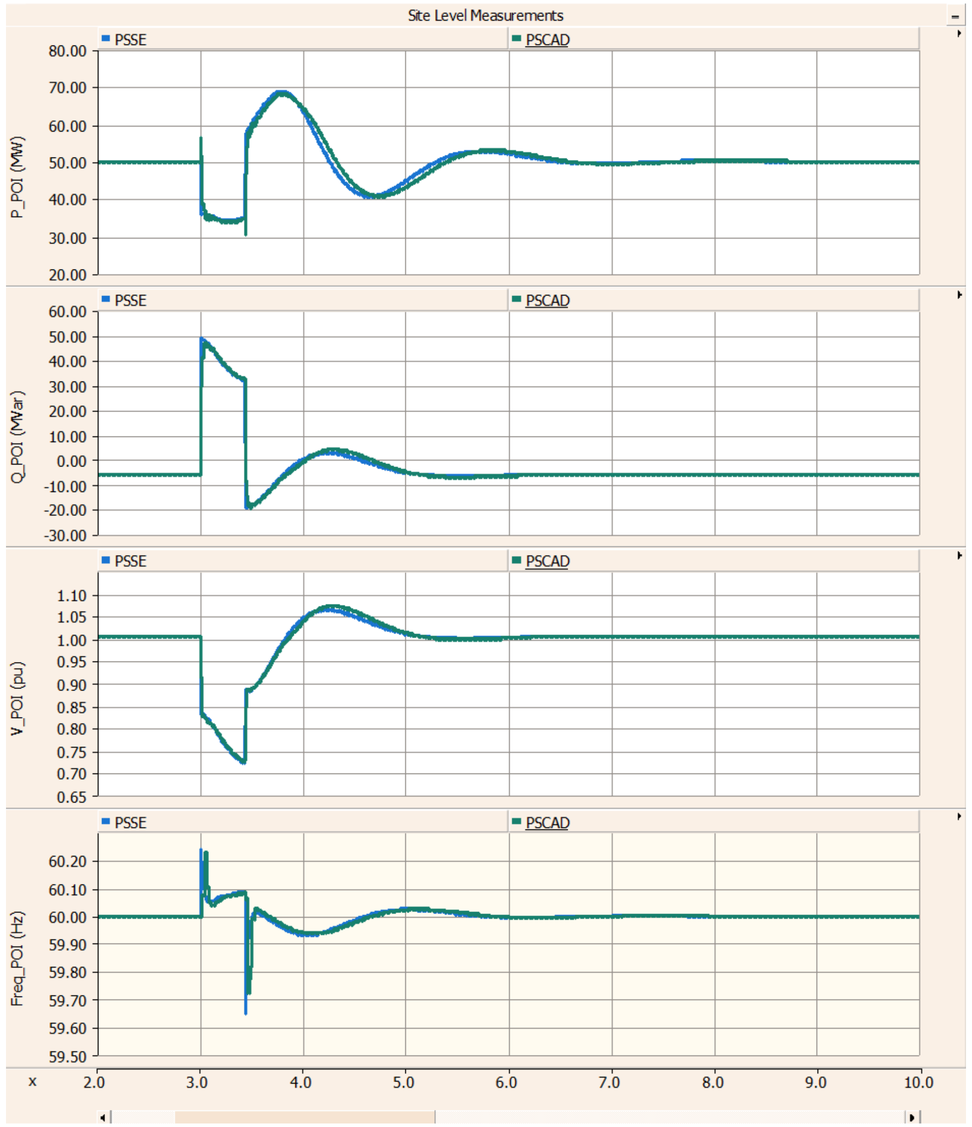



*Simulation credit: Tesla Energy*

# Industry Use of Standard Library GFM Models

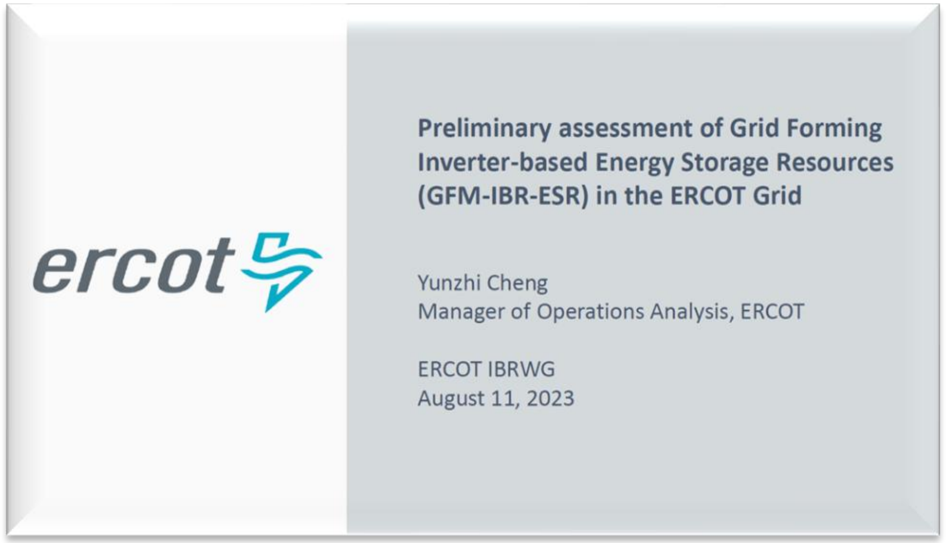
- Multiple utility entities are working with UNIFI team on evaluating how GFMs impact their grids using these models. Below are few examples

WECC

Grid Forming Inverters

Grid Forming Advisory Group 7/17/2023

WECC report of GFM technology [1]



ercot

Preliminary assessment of Grid Forming Inverter-based Energy Storage Resources (GFM-IBR-ESR) in the ERCOT Grid

Yunzhi Cheng
Manager of Operations Analysis, ERCOT

ERCOT IBRWG
August 11, 2023

ERCOT presentation of GFM technology [2]

cigre Canada

CIGRE-646 2023 CIGRE Canada Conference
Vancouver, British Columbia, September 25-28, 2023

Value and Gain of Grid-Forming Inverters for ROCOF and Frequency Regulation in Island Grids

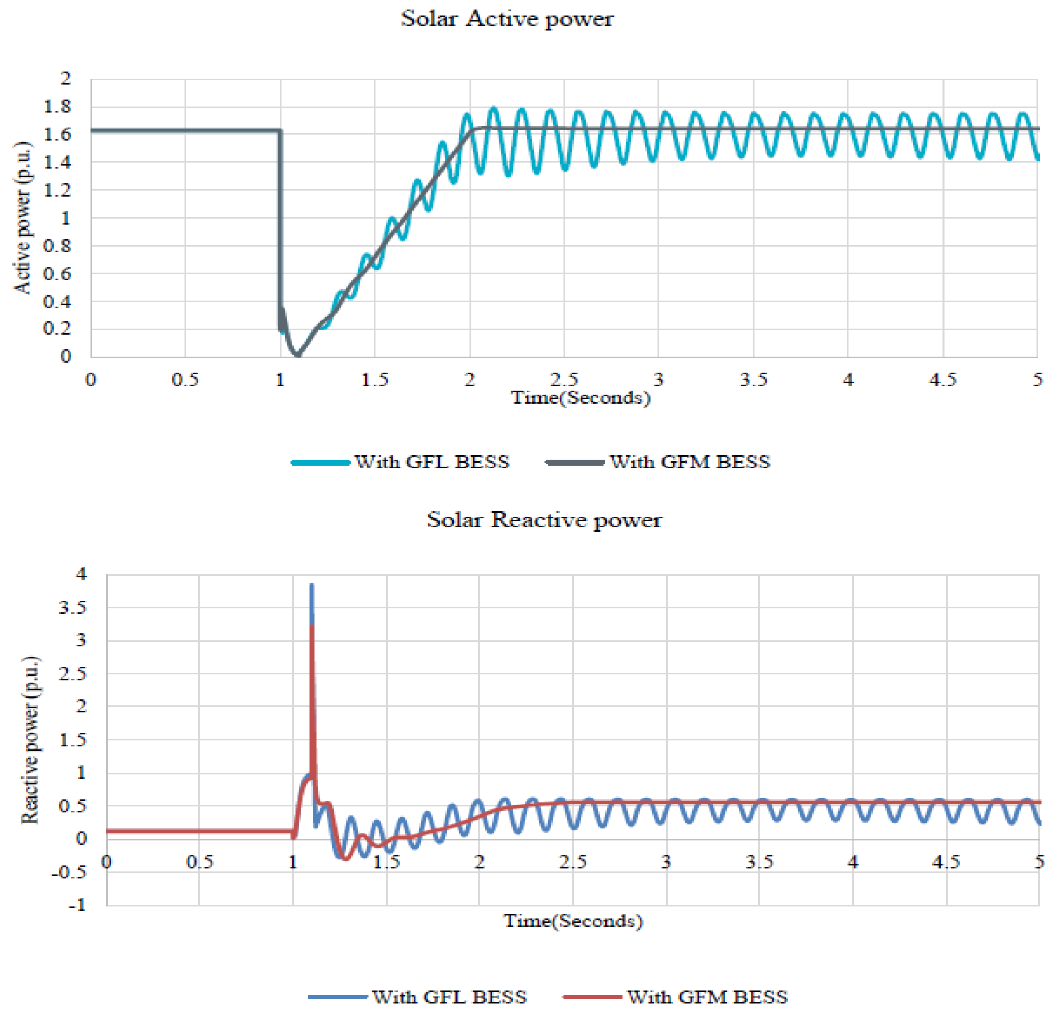
Matin Rahmatian[1], Alexandre Nassif[2], Xiaoyuan Fan[3], Marcelo Elizondo[3], Wei Du[3], Hisham Othman[1]
[1]Quanta Technology
[2]LUMA Energy
[3]Pacific Northwest National Laboratory

Puerto Rico (LUMA Energy) case study of GFM technology

[1] https://www.wecc.org/wecc-document/2566
[2] https://www.ercot.com/files/docs/2023/08/11/GFM_ERCOT_IBRWG%2808112023%29.pdf

# Case 1: Stability Enhancement in Weak Systems

- A local area (138kV) in the ERCOT grid has been identified with stability issue due to weak grid, causing stability issues when integrating renewables
- A GFM BESS model (REGFM_A1) was used to replace the original GFL model. The results in both PSSE and PSCAD tests show stable response for both N 1 and N-1-1 and no stability constraint is needed if the BESS is equipped with proper GFM capability



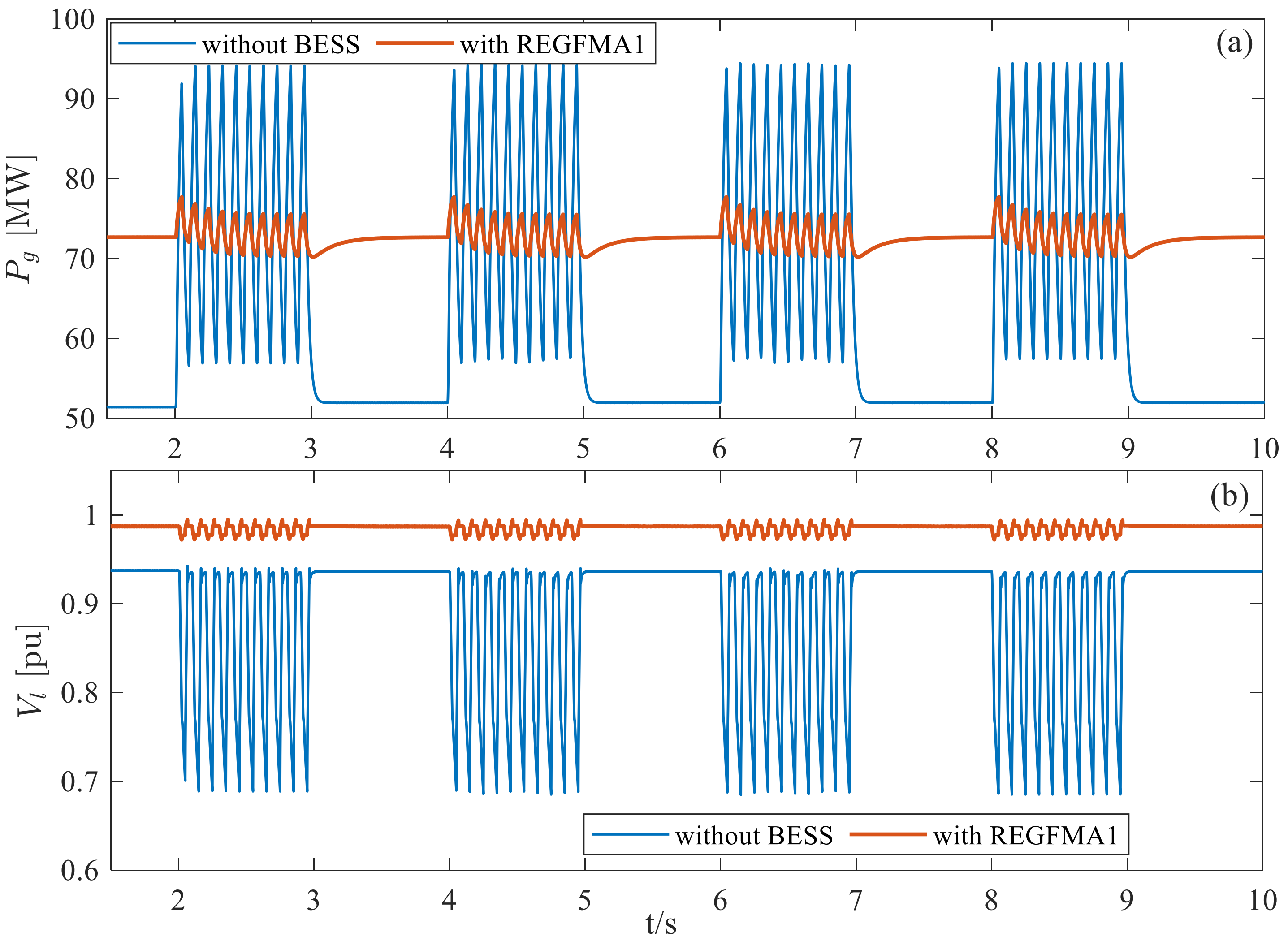

Stability Improvement of a Weak System [1]


ERCOT Presentation on GFMs

[1] https://www.ercot.com/files/docs/2023/08/11/GFM_ERCOT_IBRWG%2808112023%29.pdf

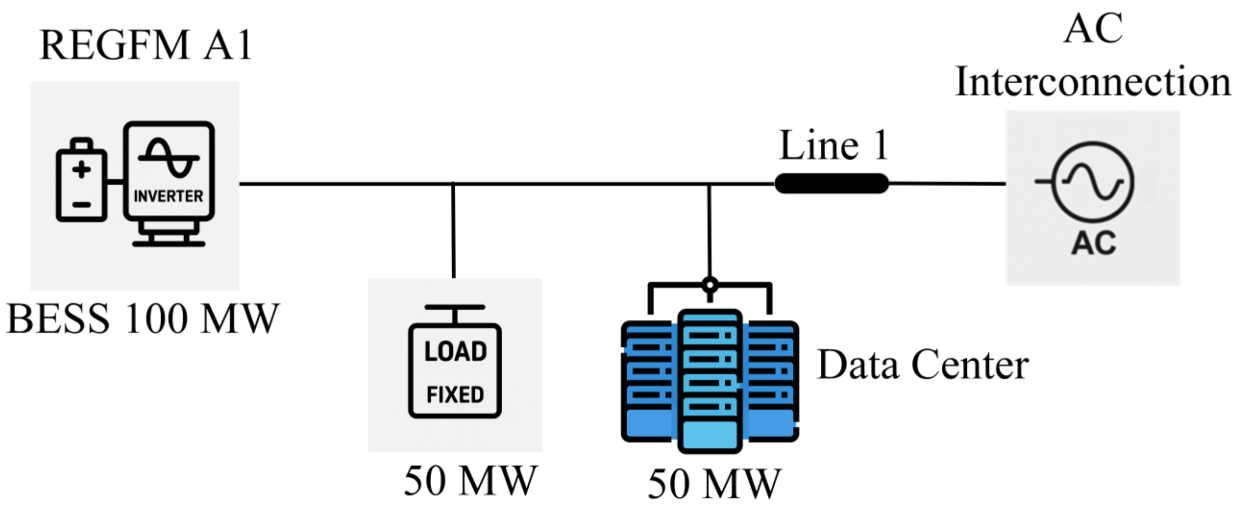
# Case 2: Data Center Application

- AI training data centers can cause fast load fluctuations (5-30 Hz)
- The GFM BESS can mitigate the load fluctuation and improve the local voltage stability
- Advanced controls can be added on the GFM BESS to further improve the control effect




GFM BESS can mitigate the forced oscillation caused by LELs

**SCR=2, load fluctuation frequency: 10 Hz**

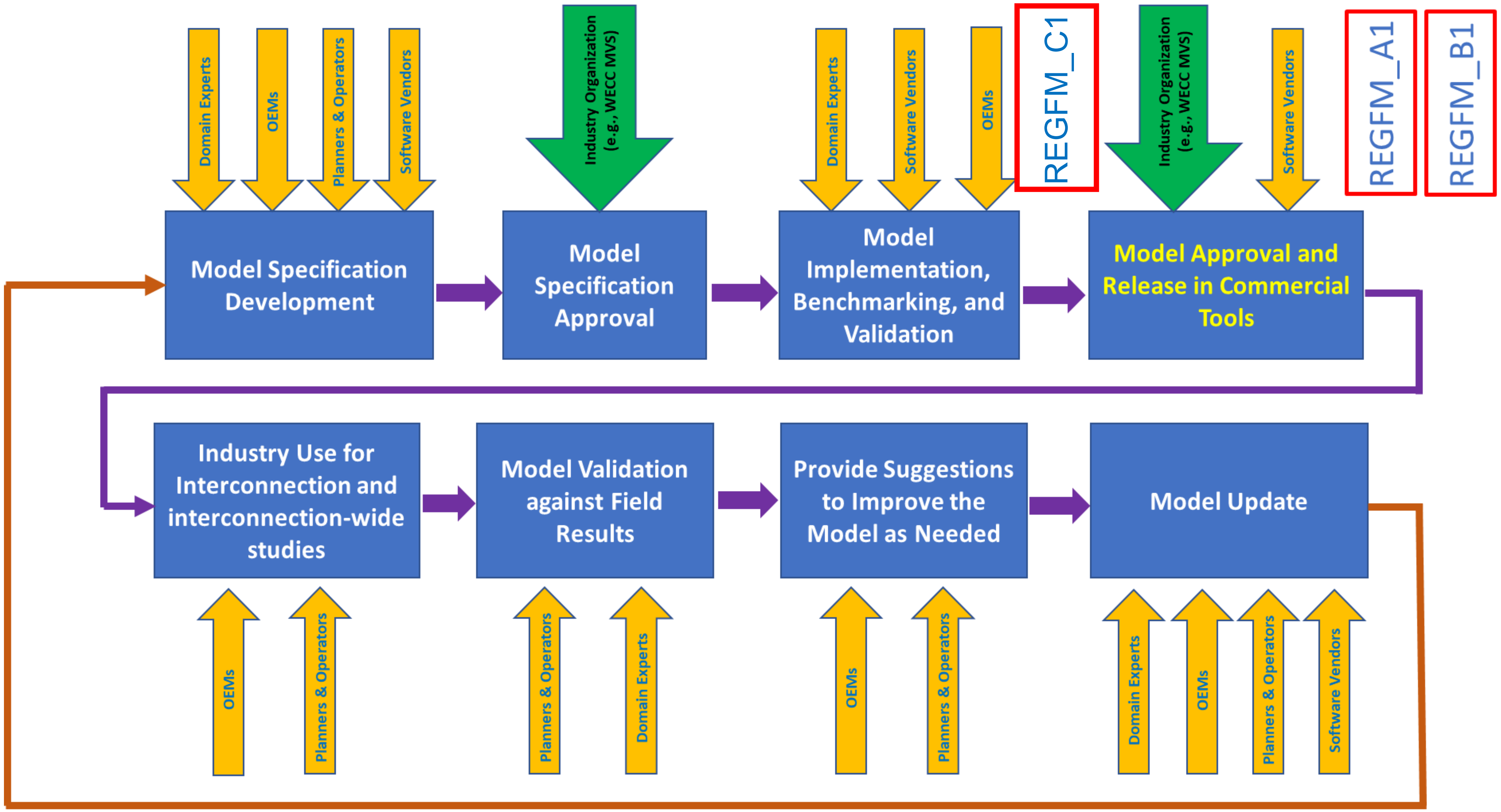



One-line diagram of the studied system

# Summary

- Introduced the WECC standard library GFM models (REGFM_A1, REGFM_B1, and REGFM_C1 and REPCGFM_C1)
- Presented model validation against field test results and EMT simulation results
- Presented three use cases: frequency response, weak systems, and large electric load
- The study results show that GFMs can improve the stability in a weak system, and mitigate the forced oscillations caused by large electric loads

# Lifecycle of Standard Library GFM Model Development




*As the GFM technology continues to evolve and more GFMs are deployed in the field, these models need to be further validated and updated on a regular basis in collaboration with **manufacturers**, **software vendors**, **planners**, and **research institutes***

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# Thank you

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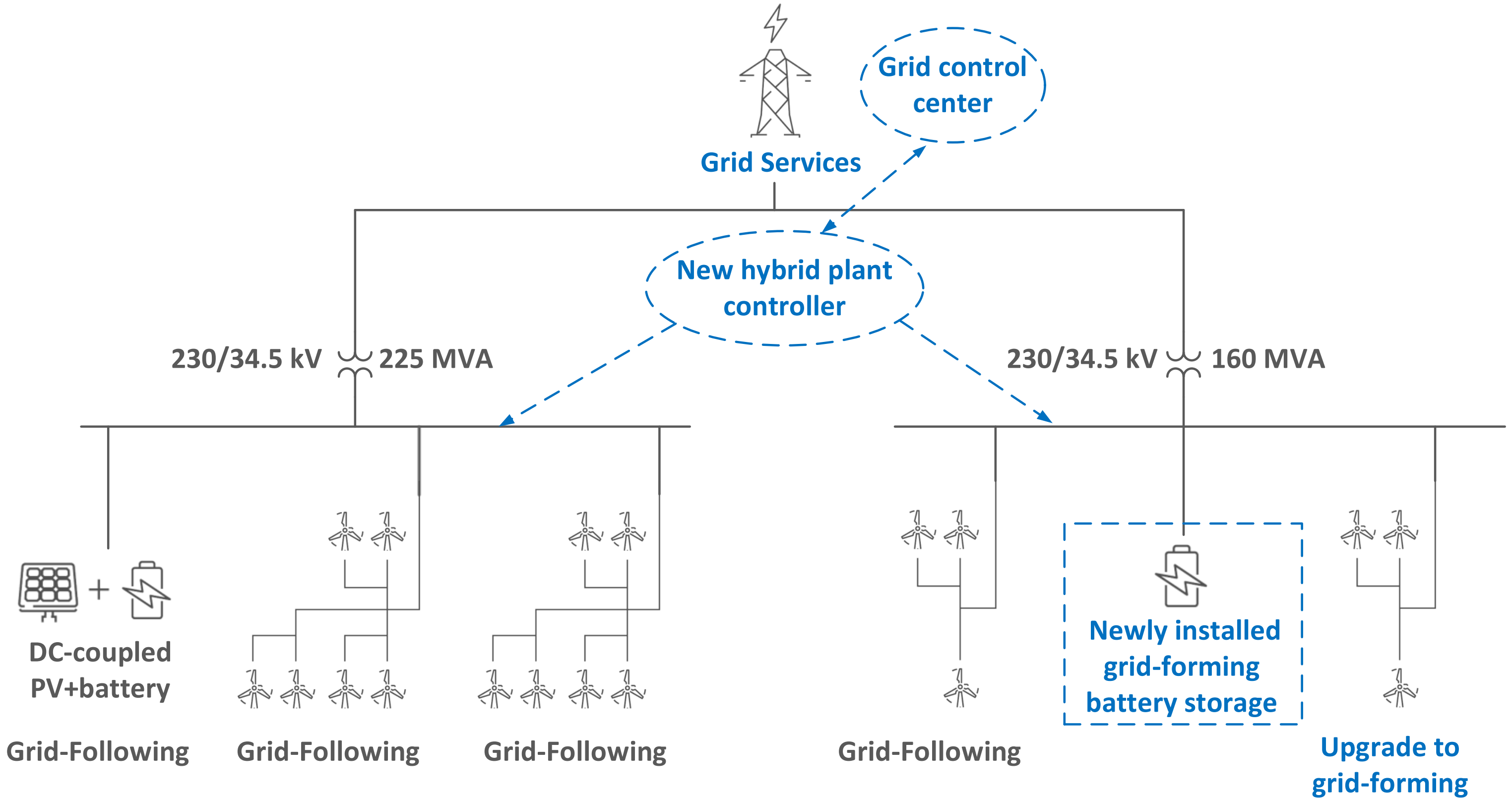
# Grid-Forming Inverter Demonstration at the Nation's First Wind/Solar/Storage Hybrid Power Plant

- Wheatridge Renewable Energy Facility is North America's first energy center to combine wind, solar, and battery storage in one location, with 300 MW of wind, 50 MW of solar, and 30 MW of energy storage systems

Wheatridge wind, solar and battery storage power plant




This will be the first time that **grid-forming wind and battery storage** connected to the US bulk power grid at the same location

Portland General Electric
Project Lead

GE VERNOVA

Pacific Northwest National Laboratory

Bonneville Power Administration

NextEra Energy

The University of Texas at Austin

Portland State University