

# Grid Forming Mitigating Weak Grid Oscillations

March 18, 2026

2026 ESIG Spring Workshop



# Agenda

Grid Strength

Online Estimation of SCR

Grid Stability

GFM Inverters: Enhanced Stability & Damping

Tesla's Grid-Forming Approach

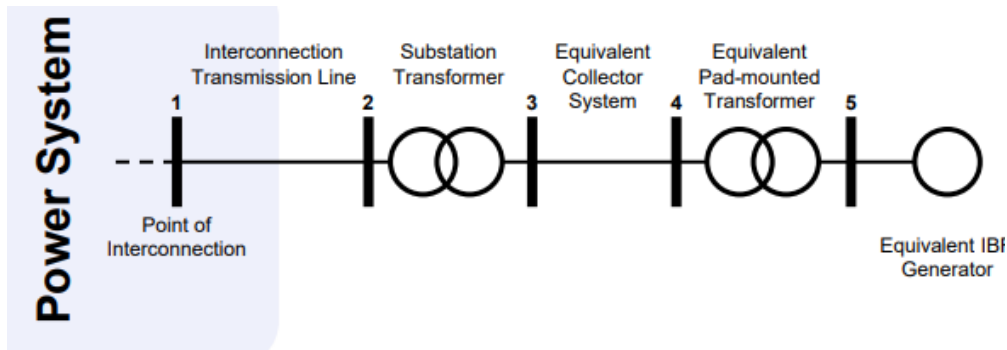
Q&A



# Grid Strength

# Traditional SCR (Short Circuit Ratio) Calculation Method

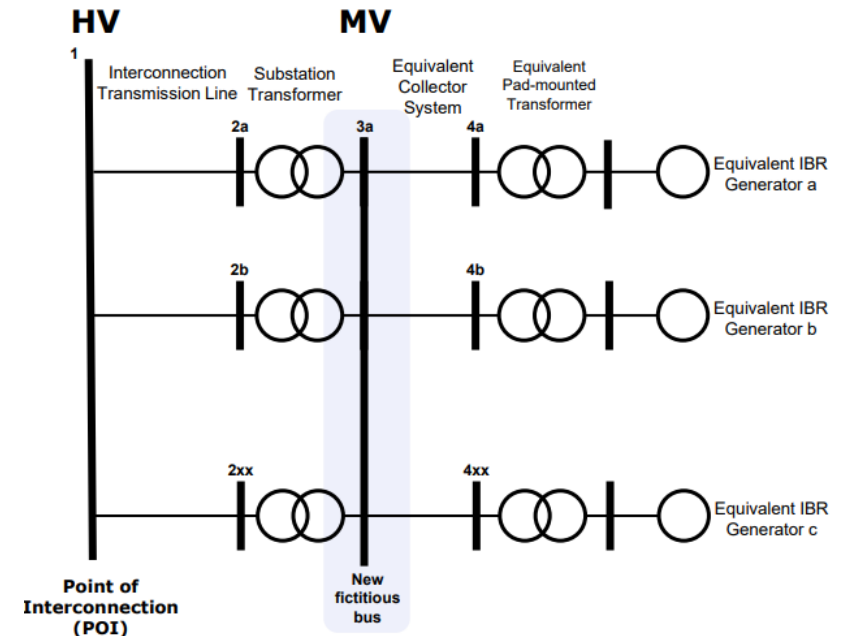
$$SCR = \frac{MVA_{SC}}{rated\ MW_{@POI}}$$



- This calculation treats the rest of the grid at the POI as an infinite source with fixed voltage and frequency.
- It does not account for the impact of nearby inverter-based resources (IBRs).
- It does not account for self-limiting co-located PV+BESS sites.

# CSCR (Composite Short Circuit Ratio) Calculation Method


$$CSCR = \frac{MVA_{SC}}{\sum_{k=0}^n MW_{IBR}}$$



Source: CIGRE, Working Groups B4.62 Connection of Wind Farms to Weak AC networks, 2016

- This calculation considers the impact of IBRs on the local transmission system
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## Traditional SCR (Short Circuit Ratio) Calculation Method

$$SCR = \frac{MVA_{SC}}{rated\ MW_{@POI}}$$


- For example, an MVA short-circuit strength of 15,000 MW at the POI results in an SCR of 30 for a 500 MW site, without considering nearby IBRs.
- This can be calculated using information that is typically readily available to generator owners.

## CSCR (Composite Short Circuit Ratio) Calculation Method

$$CSCR = \frac{MVA_{SC}}{\sum_{k=0}^n MW_{IBR}}$$



- For example, an MVA short-circuit strength of 18,000 MW at the POI with nearby 8000MW IBRs translates to CSCR= 2.25
- This can be calculated only by the system operator and utility as full grid information is required.

# SCR Calculation Using PMU Data

- Grid is assumed as a Thevenin equivalent circuit
- The short-circuit ratio is computed by:

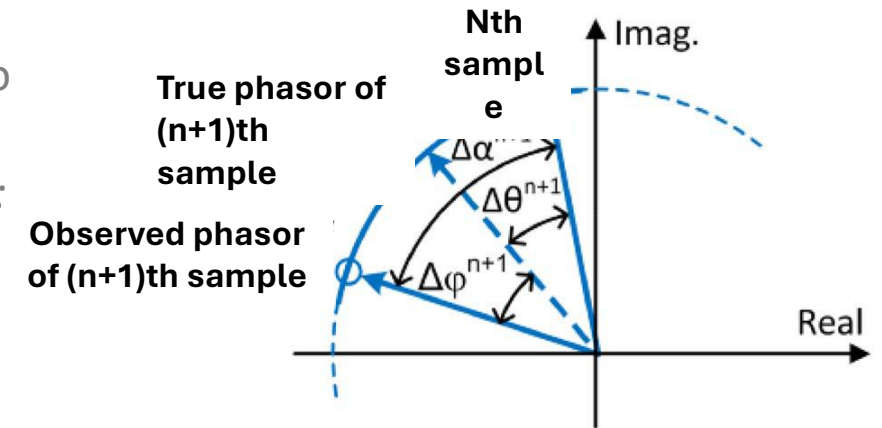
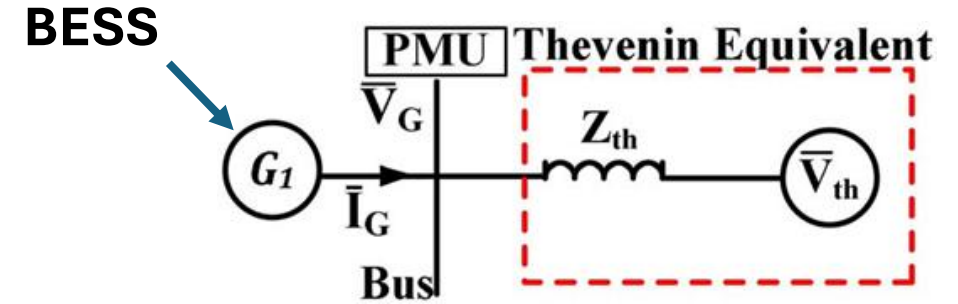
$$SCR = \frac{SCC}{S_{nom}}, SCC = \frac{|V_{th}^2|}{Z_{th}} \sim \frac{1}{Z_{th}}$$

- PMU has a constant sampling rate based on nominal frequency
- However, due to variation of frequency, a phase drift will occur leading to estimation error
- The phase drift is compensated to achieve a more accurate estimation by [1]:

$$Z_{th} = \frac{V_{G1} e^{-j\Delta\phi^{n+1}} - V_{G0}}{I_{G1} e^{-j\Delta\phi^{n+1}} - I_{G0}}$$

$$\Delta\phi^{n+1} = \Delta\alpha^{n+1} - \Delta\theta^{n+1},$$

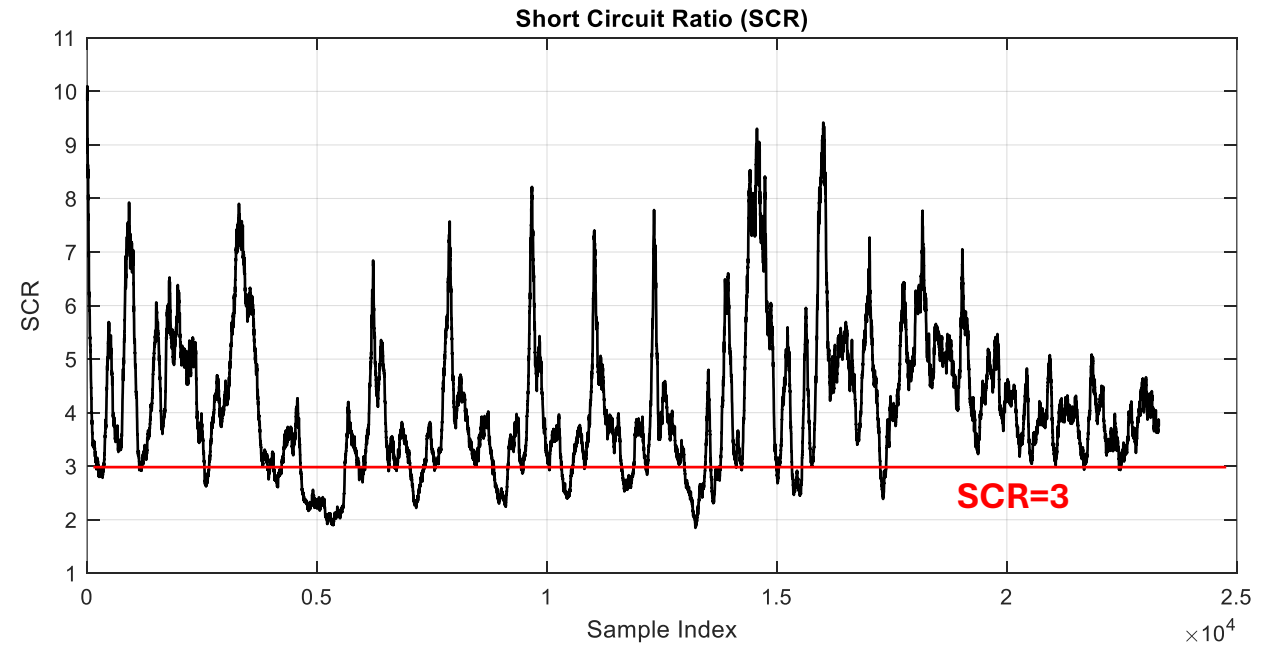
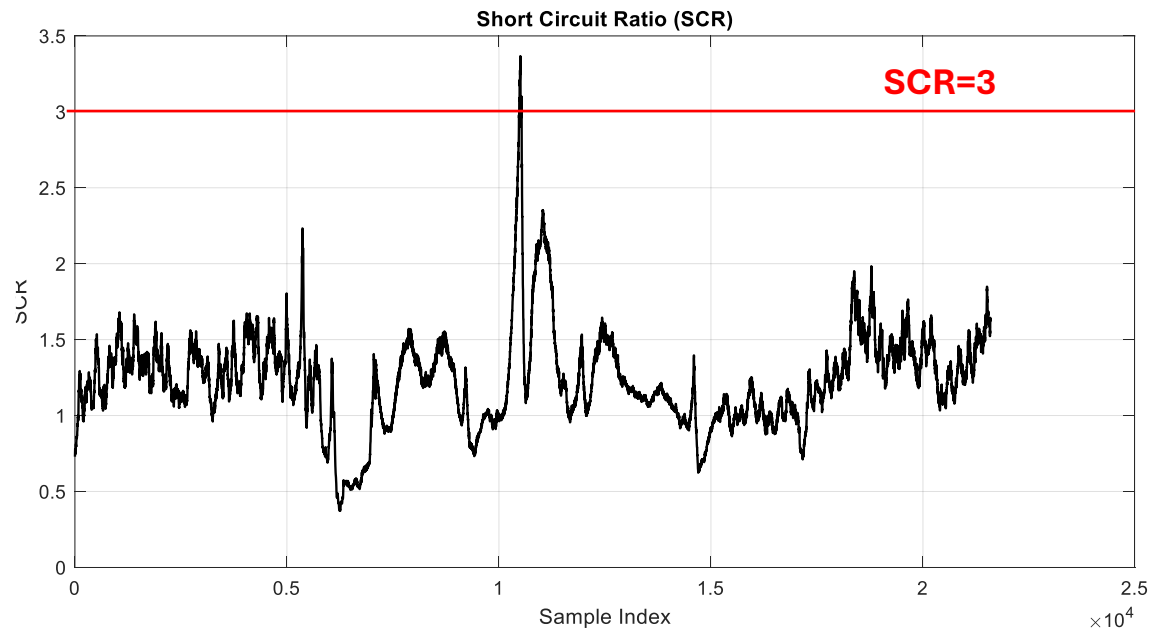
$$\Delta\theta^{n+1} = 2\pi \int_{t_0}^t \Delta f(t) dt$$



[1] Alinezhad, Bahman, and Hossein Kazemi Karegar. "On-line Thévenin impedance estimation based on PMU data and phase drift correction." IEEE Transactions on Smart Grid 9.2 (2016): 1033-1042.

# SCR Calculation Using PMU Data

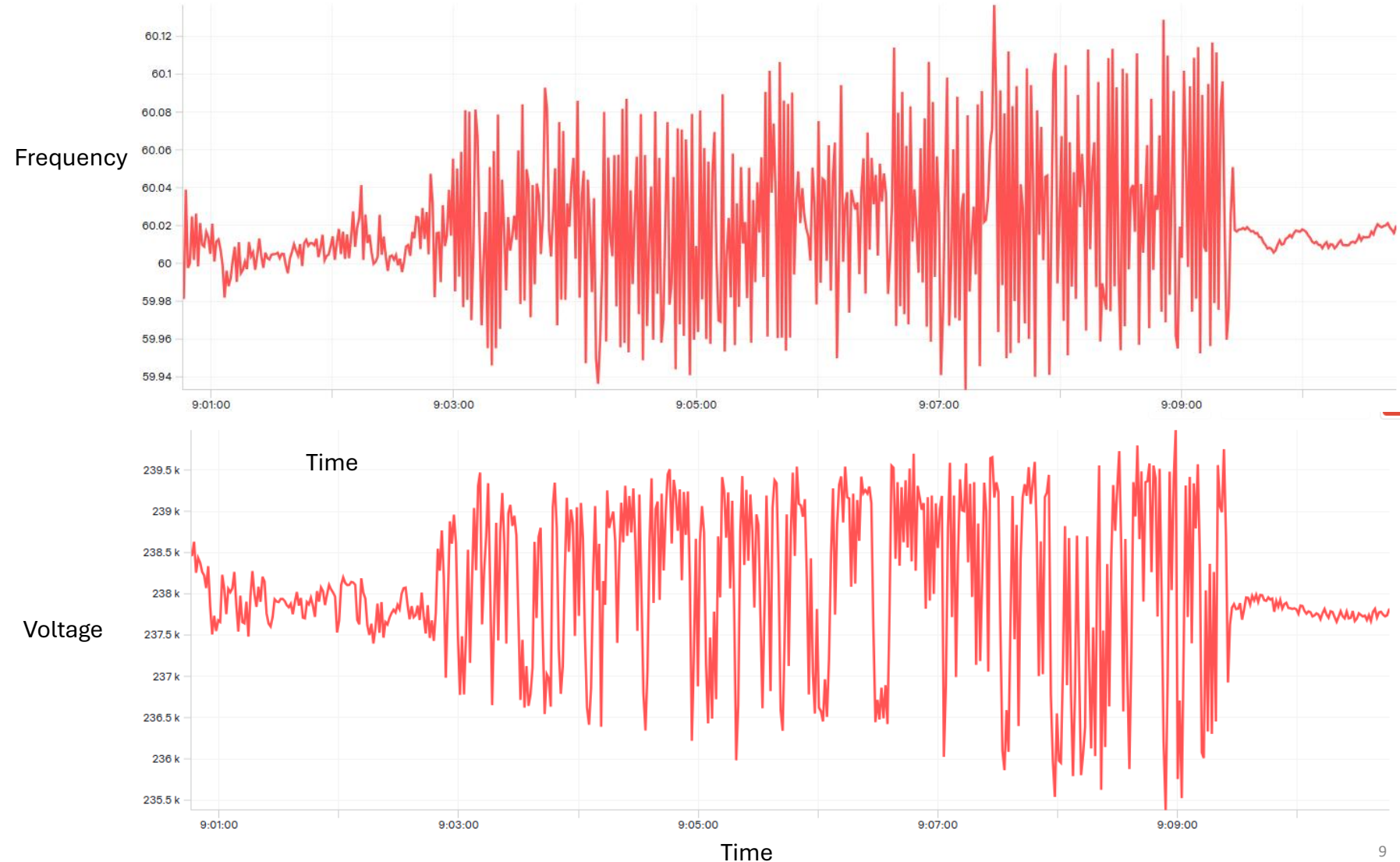
- Grid strength varies in real-time



# Grid Stability

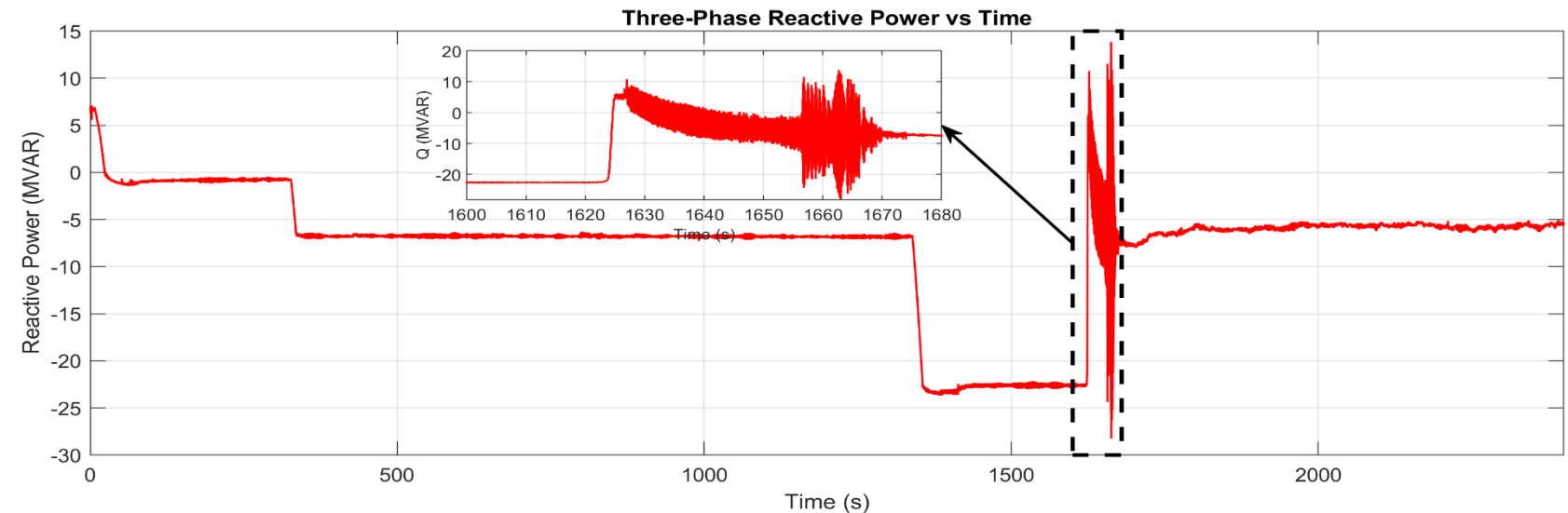
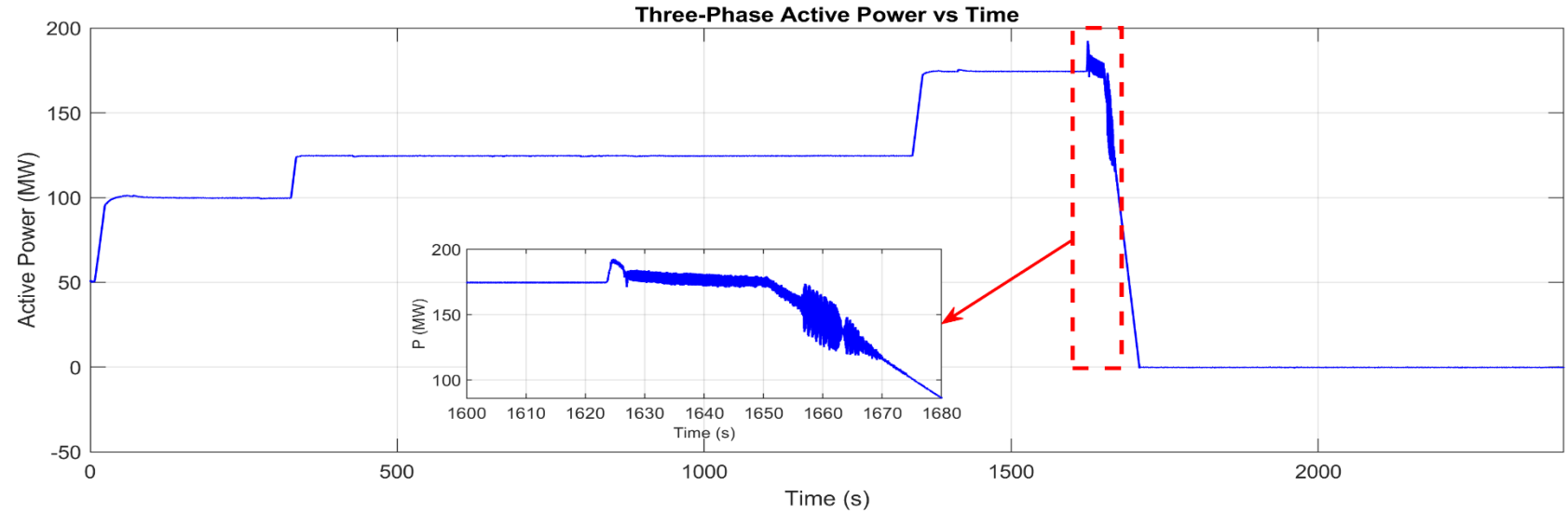
# Case Study : PLL instability ( Weak Grid)

- PLL instability occurred when PV and BESS were operating, as additional IBRs reduce the grid's effective SCR.
- Frequency/P and Voltage/Q oscillations occurring simultaneously suggest a PLL instability.
- The oscillation speed indicates that the issue is not related to upstream PPC controls.



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# **GFM Inverters: Enhanced Stability & Damping**

# A CHIL-Based Demonstration of How Grid-Forming Technology Mitigates On-Site Oscillations in a PV+BESS Facility Connected to a Weak Grid

- Enabling GFM on Megapacks helps to dampen oscillations.
- Megapacks provide a strong and stable voltage source for the PV inverters, helping stabilize control issues under weak-grid.
- Enabling GFM on Megapacks requires only a small software settings update with no hardware changes.
- Tesla has real-world experience enabling this at sites as large as 250 MW.

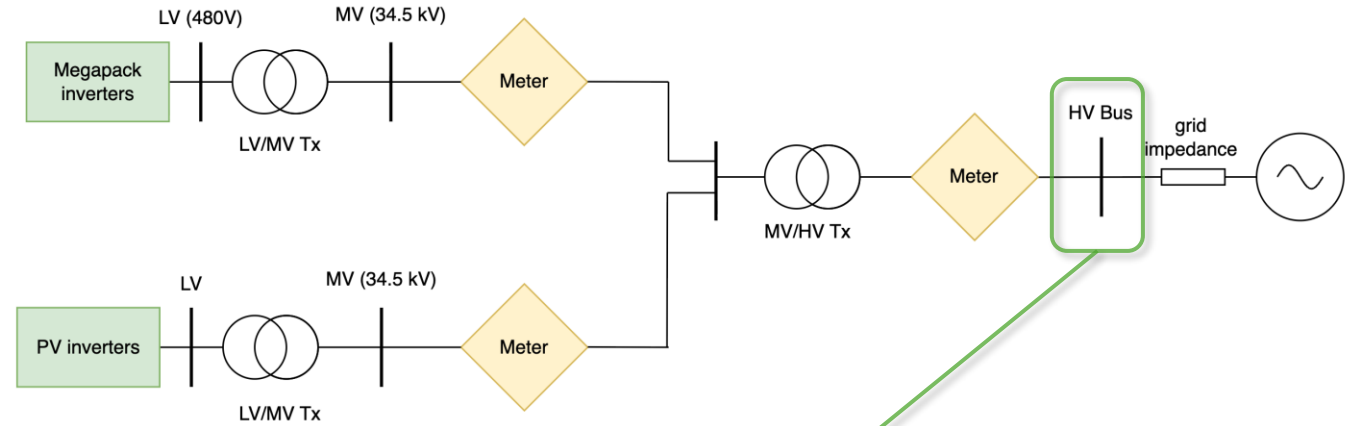
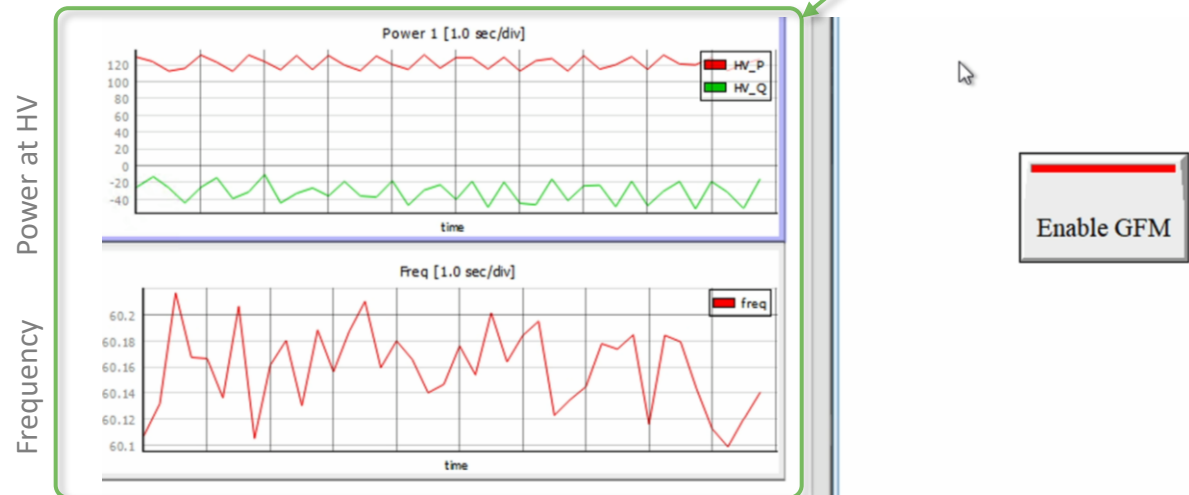
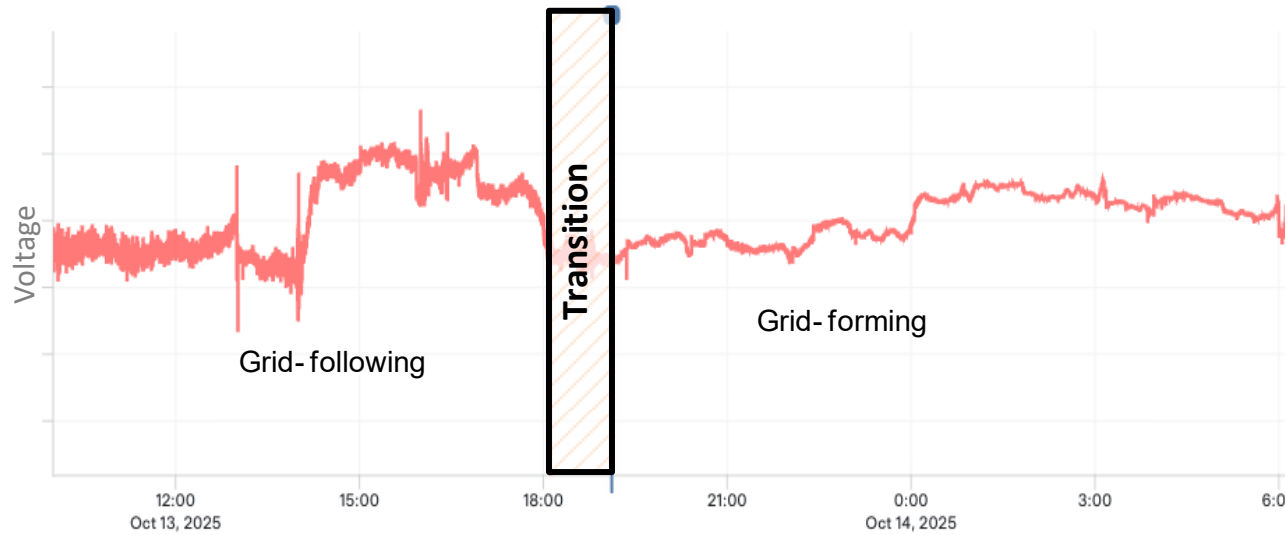


Fig. generic PV+BESS site in a weak grid condition

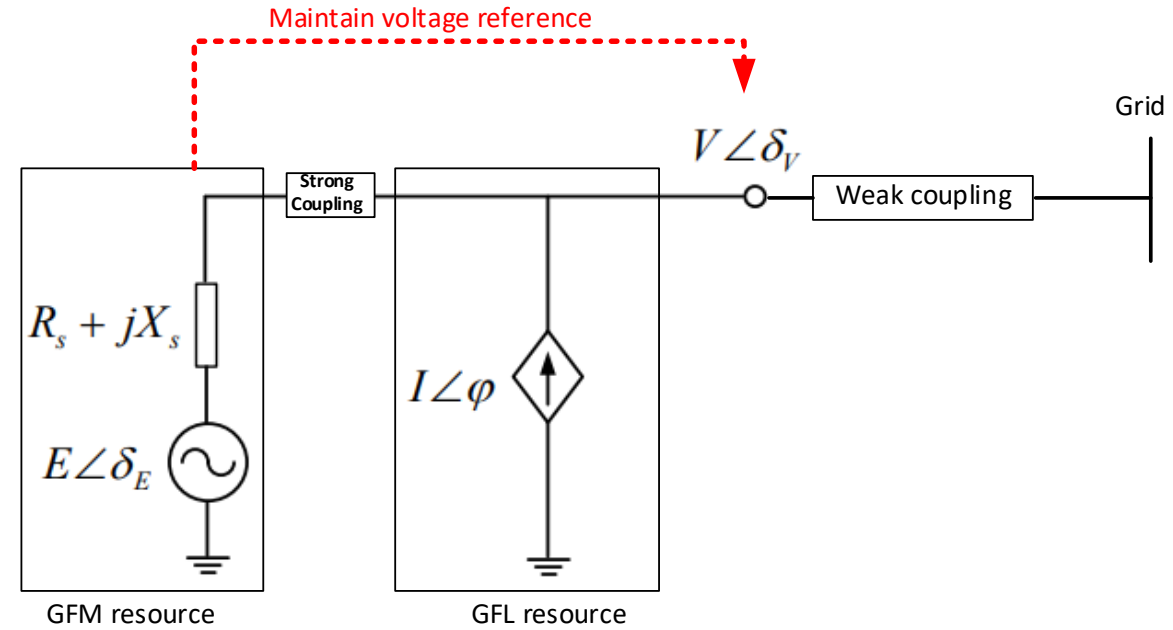


# How GFM resolves oscillation issues

- Voltage source provides a strong and stable voltage reference for nearby GFL IBRs.
- This improves GFL PLL stability.
- The fast response of GFM control helps suppress oscillations that cannot be mitigated by the slower upstream PPC.



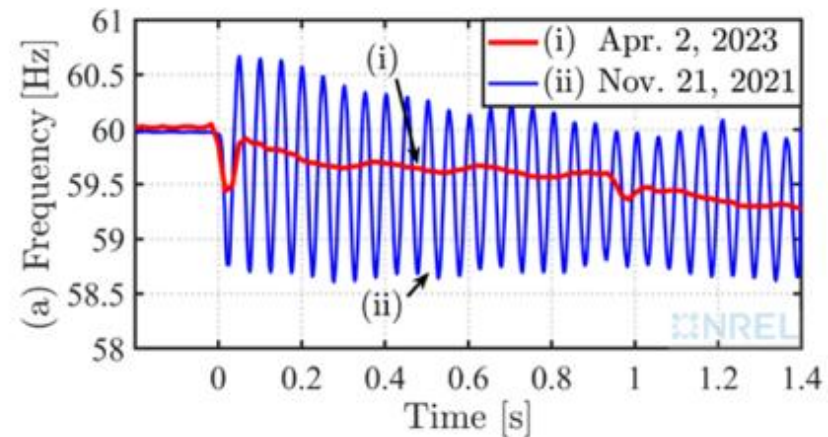
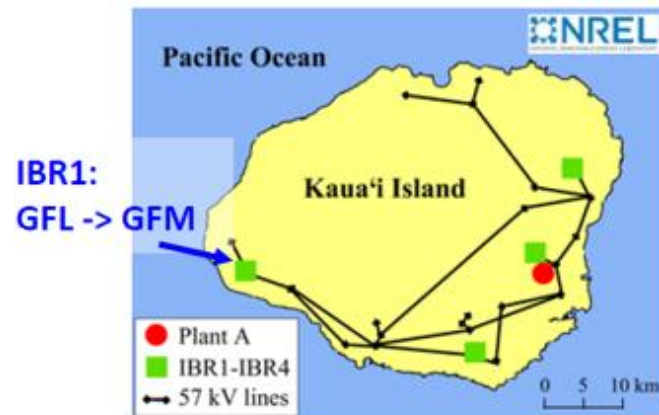
GFM enabled on-site and shows significant improvement



# Challenges in System Damping for Renewable-Dominated Grids

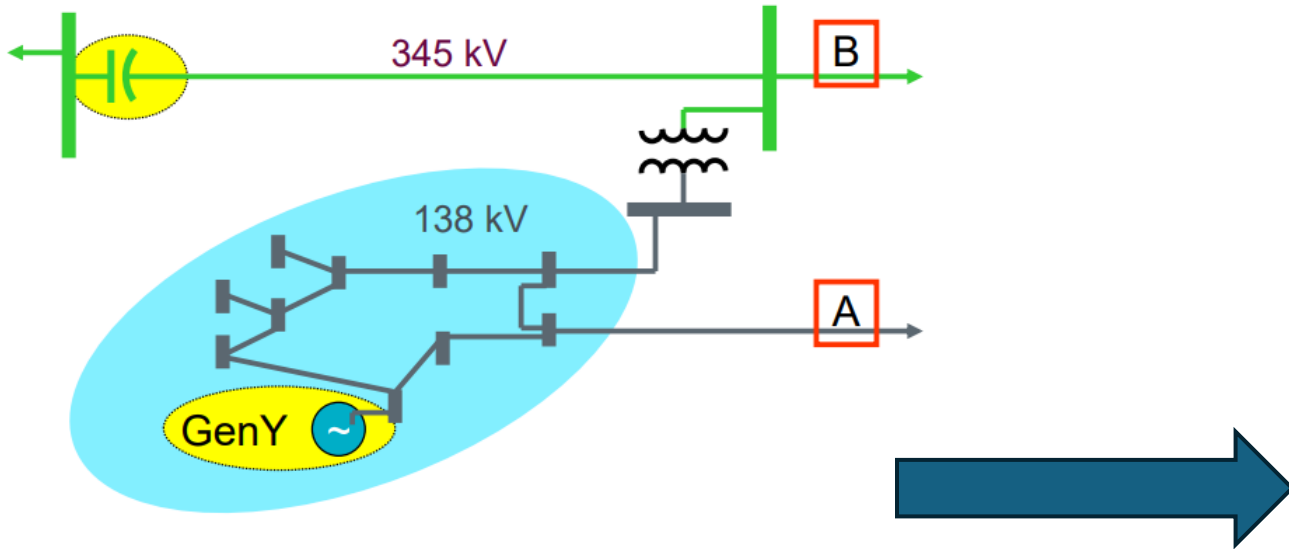
GFM BESS will be the only reliable 24/7 damping source moving forward

- Retirement of synchronous generators is reducing available PSS, resulting in damping reduction of inter-area power oscillations
- Damping controllers in wind and solar farms—if present—may not be reliable, as these are variable energy resources by nature
- Emerging high-frequency oscillations from IBRs cannot be addressed by conventual PSS or POD
- Synchronous condensers can introduce negative damping to the system, making the damping shortfall even worse
- GFM BESS is the best solution to maintain and enhance system damping for existing low-frequency inter-area power oscillations, while also providing robust damping for newly emerging high-frequency oscillations



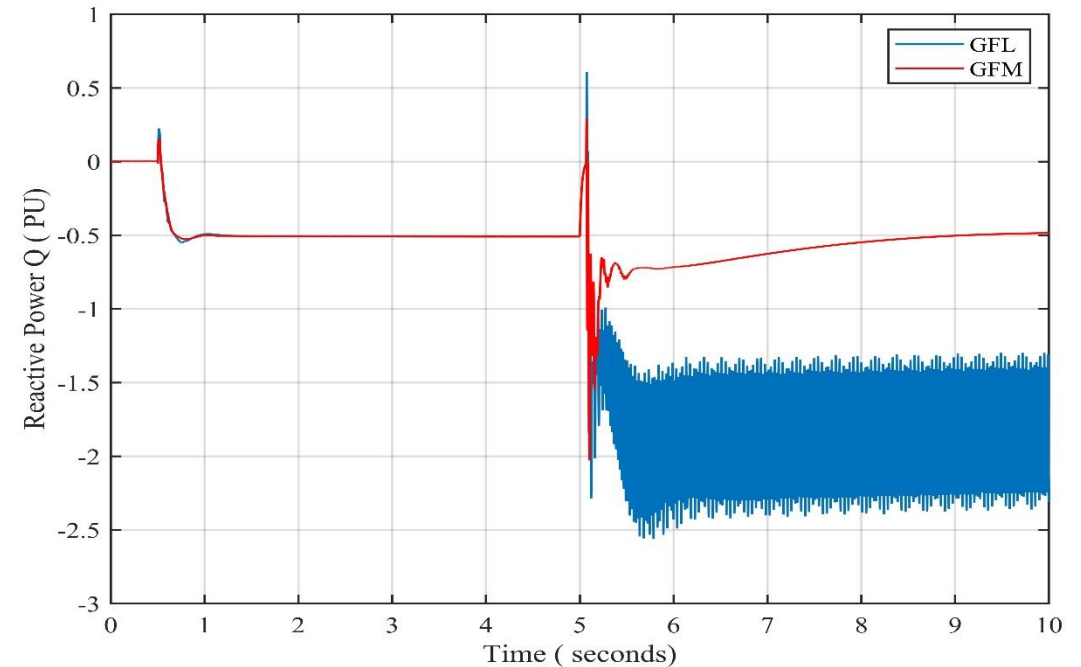
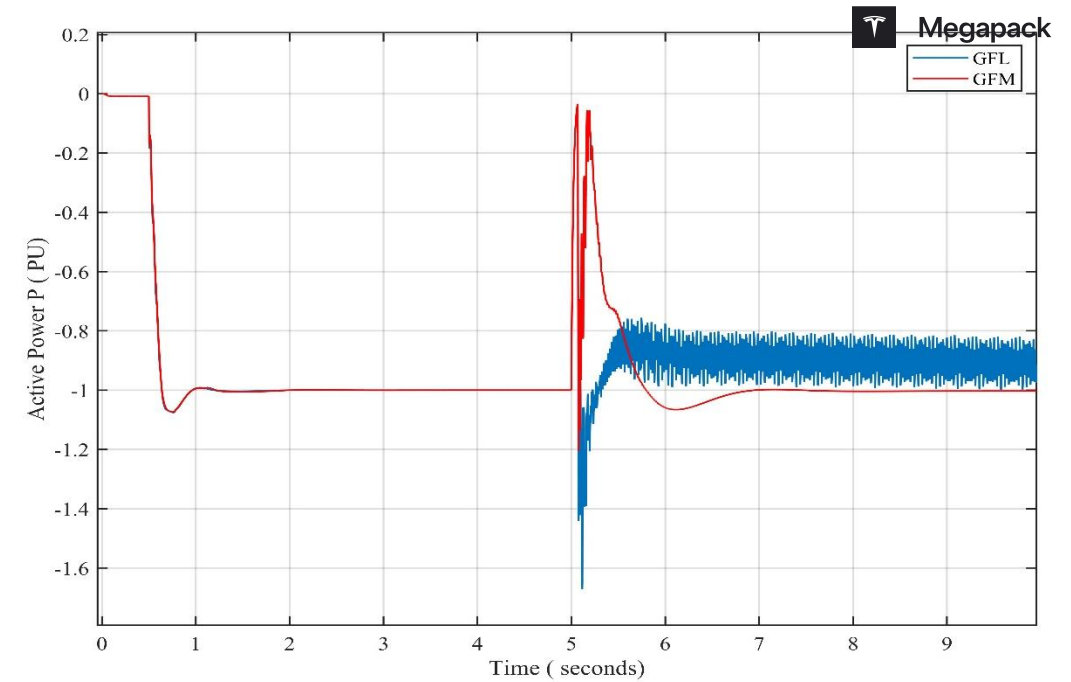
NREL, [Stabilize High-IBR Power Systems with Grid-Forming Inverters](#), 26/03/2024.

# Interaction with Series Capacitors (SSO)



Outages "A" and "B" make the generator "radial" to the series capacitor

file:///C:/Users/monassar/Downloads/Dealing-with-System-Oscillation-%E2%80%93-IBR-Interconnection-and-Operation-Yunzhi-Cheng.pdf



# Tesla Grid-Forming Deployed and Operating Globally

## Across Grid-Tied, Utility-Scale Projects

Operating Utility-Scale Grid-Forming Projects  
As of March 2026:

3.2 GW

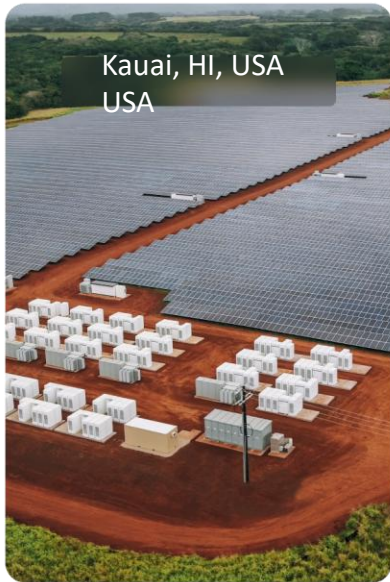
7.5 GWh



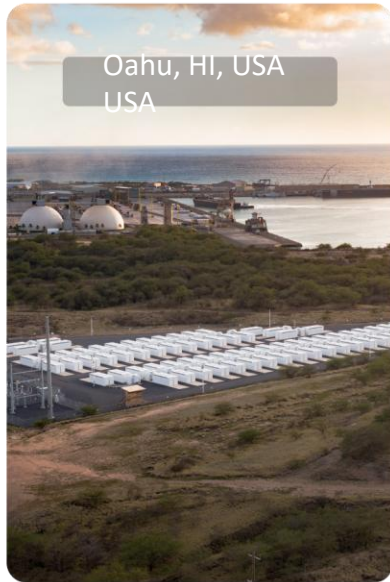
NM, USA  
USA



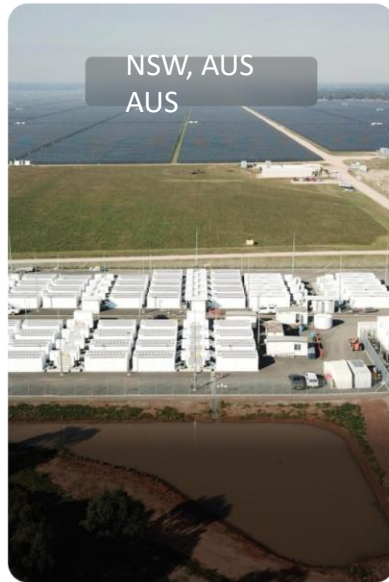
NSW, AUS



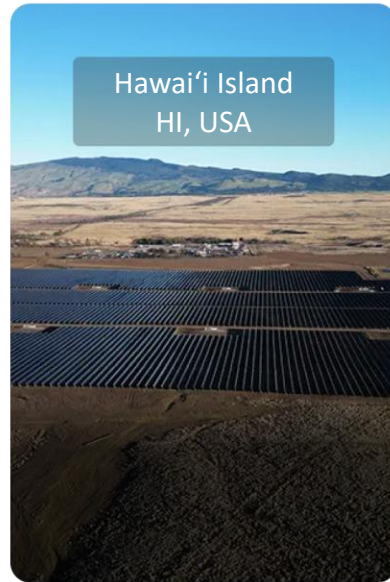
Kauai, HI, USA  
USA



Oahu, HI, USA  
USA



NSW, AUS  
AUS



Hawai'i Island  
HI, USA

Shallow Basket

50 MW      200 MWh

Commissioned 2025  
Grid-Forming 2025

Hornsdale

150 MW      193 MWh

Commissioned 2017, Expanded 2020  
Grid-Forming 2022

KIUC

13 MW      52 MWh

Commissioned 2017  
Grid-Forming 2018

KES

185 MW      565 MWh

Commissioned 2023  
Grid-Forming & Blackstart 2023

Riverina & Darlington

150 MW      300 MWh

Commissioned 2023  
Grid-Forming 2023

Hale Kuawehi

30 MW      120 MWh

Commissioned 2025  
Grid-Forming 2025

# Tesla Megapack's Grid-Forming (GFM) Approach

Megapack's GFM operates as a standalone voltage-frequency source, containing two paths: **Power Dispatcher & Virtual Machine**

REGFM_A1	GFM Droop Control GFM
REGFM_B1	Virtual Synchronous Machine
REGFM_C1 and REPCGFM_C1	GFM Hybrid Control



## Standard Library Grid-Forming Hybrid Control Inverter-based Resource Model Specification (REGFM\_C1)

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

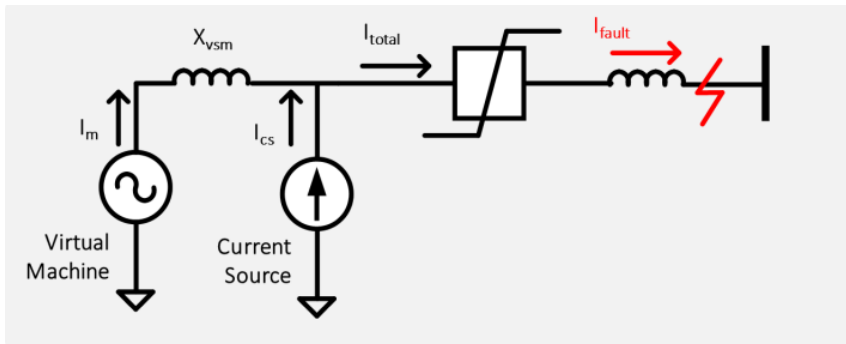
- 1 Pacific Northwest National Laboratory
- 2 Tesla Energy
- 3 Electric Power Research Institute
- 4 PowerWorld
- 5 GE Vernova
- 6 Siemens
- 7 Power and Energy, Analysis, Consulting and Education (PEACE®) PLLC
- 8 PowerTech Labs
- 9 Portland General Electric
- 10 Western Electricity Coordinating Council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



## Standard Library Plant Controller Model Specification for a Grid-Forming Hybrid Control Inverter-based Resource (REPCGFM\_C1)

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

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Source: Tesla PESGM 2024 Presentation

[https://www.wecc.org/sites/default/files/documents/meeting/2025/11%20-%20DuW%20-%20Model%20Specifications%20of%20Grid-Forming%20Hybrid%20Control%20and%20Plant%20control%20REGFM\\_C1%20and%20REPCGFM\\_C1\\_January%202025.pdf](https://www.wecc.org/sites/default/files/documents/meeting/2025/11%20-%20DuW%20-%20Model%20Specifications%20of%20Grid-Forming%20Hybrid%20Control%20and%20Plant%20control%20REGFM_C1%20and%20REPCGFM_C1_January%202025.pdf)



Thank You – Q&A

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