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unifi consortium
universal interoperability for grid-forming inverters

Introduction of WECC-Approved GFM Models —*REGFM_A1 and REGFM_B1*

Wei Du, *Ph.D.*
Solar Subsector Manager, Pacific Northwest National Laboratory (PNNL)
Research Associate Professor, Washington State University (Joint Appointment)

Deepak Ramasubramanian, *Ph.D.*
Senior Technical Leader, Electric Power Research Institute (EPRI)

Oct. 22nd, 2024

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Why are Standard Library GFM models Important?

- The standard library models, user-defined positive-sequence phasor models, and EMT models are all very important, and have different application scenarios
- Standard library models are very important for the interconnection-wide base case creation and many other planning studies
- **The FERC Order No. 901** *"require the use of **approved industry generic library IBR models** that accurately reflect the behavior of IBRs during steady state, short-circuit, and dynamic conditions when developing planning, operations, and interconnection-wide models"*
- ***Before we initiated this work, there was no standard library GFM models in commercial transient stability simulation tools***

*We need to develop **accurate, industry-approved standard library GFM models** for transmission planners to help advance the GFM technology toward wide adoption*

WECC-Approved Standard Library GFM Models

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- The WECC Modeling and Validation Subcommittee (MVS) recently approved two GFM models: ***REGFM_A1*** (*approved on 9/27/2023*) and ***REGFM_B1*** (*approved on 5/23/2024*) proposed by UNIFI members
- These models represent two mainstream GFM controls used in industry: ***droop control*** and ***virtual synchronous machine control***
- These two models become the first generation of WECC-approved GFM models, and have been integrated into the simulation tools used by transmission planners worldwide, including PSS/E (V36.1), PSLF (V23.2.8.2), PowerWorld (V23), and TSAT (V24.1)

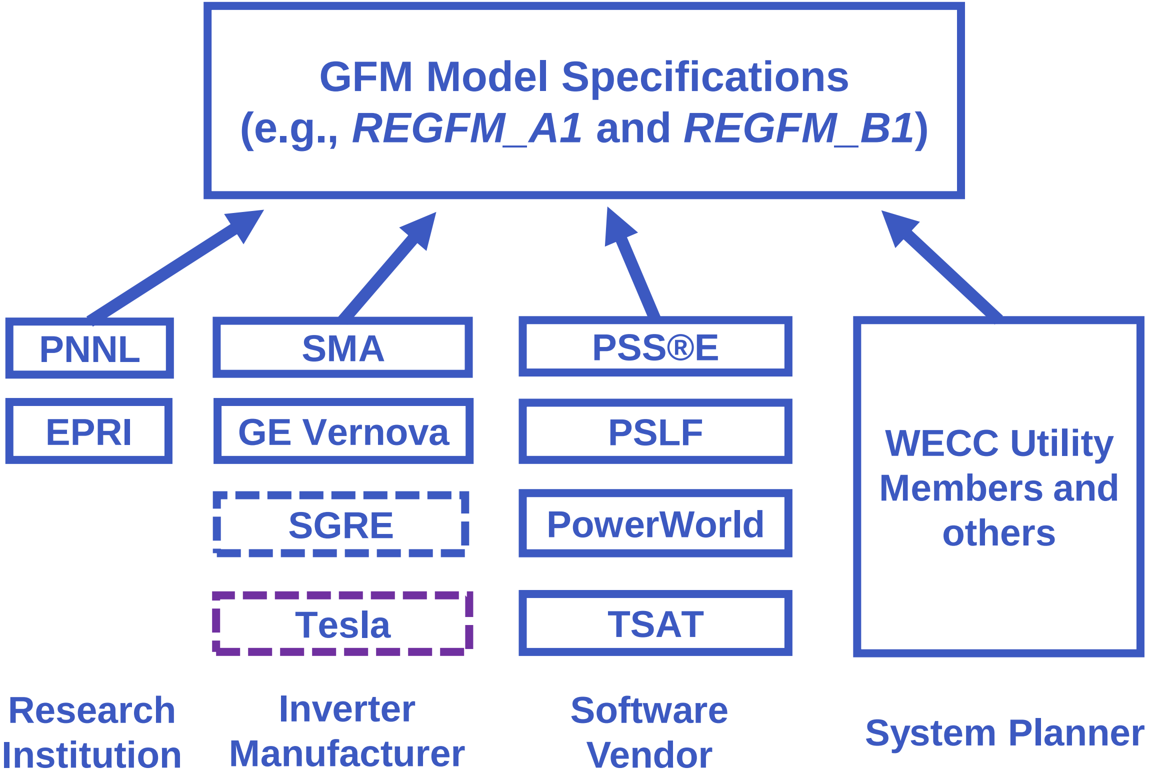
REGFM_A1 Specification

REGFM_B1 Specification

WECC Announcements of REGFM_A1 and REGFM_B1 Model Approvals

How are These Model Specifications Developed?

- The original REGFM_A1 model specification was developed by PNNL leveraging the previous DOE CERTS Microgrid project
- The original REGFM_B1 model specification was developed by PNNL, GE, and EPRI supported by UNIFI
- These specifications were proposed to WECC MVS, and a significant amount of time has been spent on addressing the questions and comments raised by the members
- The specifications have been revised multiple times to incorporate reasonable suggestions from additional OEMs, software vendors, and system planners



Acknowledgement

- I'd like to thank all the dedicated contributors for developing the WECC-approved standard library GFM models

REGFM_A1 Model Contributors

Name	Organization
Wei Du	Pacific Northwest National Laboratory
Robert H. Lasseter	University of Wisconsin-Madison
Christian Hardt	SMA Solar Technology AG
Song Wang	Portland General Electric
Songzhe Zhu	GridBright, a Qualus Company
Yuan Liu	Pacific Northwest National Laboratory
Quan Nguyen	Pacific Northwest National Laboratory
Jinho Kim	Pacific Northwest National Laboratory
Hongtao Ma	North American Electric Reliability Corporation
Pouyan Pourbeik	Power and Energy, Analysis, Consulting and Education (PEACE®) PLLC
Deepak Ramasubramanian	Electric Power Research Institute
Juan Sanchez	General Electric
Jayapalan Senthil	Siemens PTI
James Weber	PowerWorld
Jeff Bloemink	PowerTech Labs
Doug Tucker	Western Electricity Coordinating Council
Sophie Xu	Pacific Gas and Electric
Zhenyu Huang	Pacific Northwest National Laboratory
Francis K. Tuffner	Pacific Northwest National Laboratory
Renke Huang	Pacific Northwest National Laboratory

REGFM_B1 Model Contributors

Name	Organization
Wei Du	Pacific Northwest National Laboratory
Sebastian Achilles	General Electric
Deepak Ramasubramanian	Electric Power Research Institute
Philip Hart	General Electric
Shruti Rao	General Electric
Wenzong Wang	Electric Power Research Institute
Quan Nguyen	Pacific Northwest National Laboratory
Jinho Kim	Pacific Northwest National Laboratory
Qian Zhang	Electric Power Research Institute
Hanchao Liu	General Electric
Pedro Arsuaga Santos	General Electric
James Weber	PowerWorld
Juan Sanchez	General Electric
Mengxi Chen	General Electric
Jayapalan Senthil	Siemens PTI
Pouyan Pourbeik	Power and Energy, Analysis, Consulting and Education (PEACE®) PLLC
Udoka Nwaneto	Pacific Northwest National Laboratory
Jeff Bloemink	PowerTech Labs
Song Wang	Portland General Electric
Doug Tucker	Western Electricity Coordinating Council
Songzhe Zhu	GridBright, a Qualus Company

Introduction of REGFM_A1 Model

Block Diagrams of REGFM_A1

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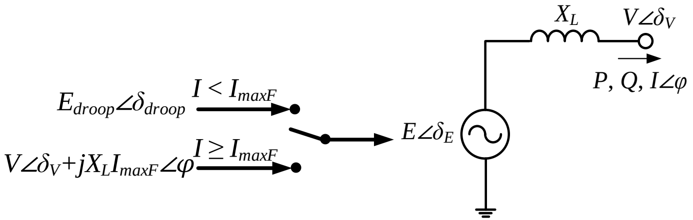
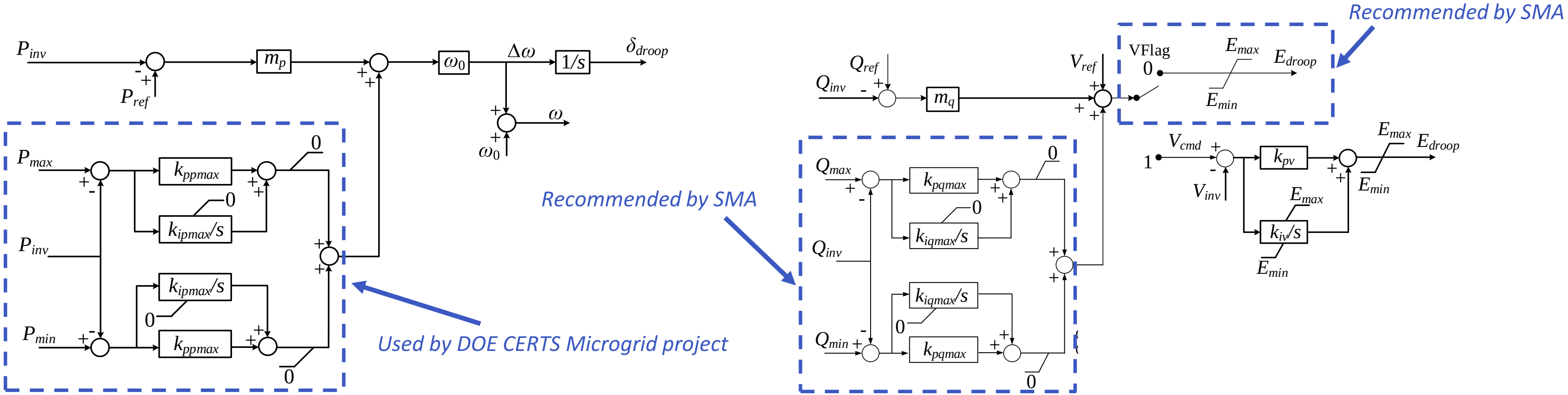
- The REGFM_A1 model includes
  - Voltage phasor behind impedance representation
  - *P*-*f* and *Q*-*V* droop controls
  - Steady state *P* and *Q* limiting
  - Transient fault current limiting (≈ virtual impedance)
- Most of control blocks came from the DOE CERTS Microgrid Project
- SMA suggested to add the *Q* limiting block, and the V_{flag}=0 option



Transient fault current limiting (≈ *virtual impedance*)

Voltage phasor behind impedance



P-*f* droop and active power limiting

Q-*V* droop and reactive power limiting

REGFM_A1 Model Validation against SMA GFM Test

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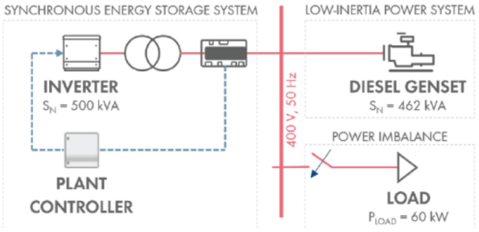
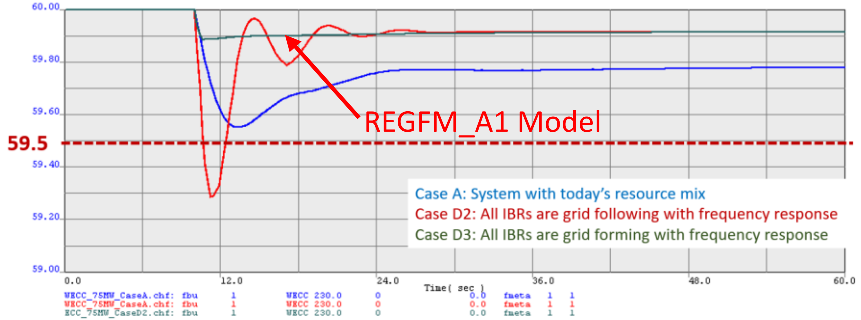
- REGFM_A1 simulation results match the SMA hardware testing results
  - Case study was performed on the micro-WECC system for frequency regulation
  - IBR penetration level: 73%, 10% headroom
- ***Both the simulation and hardware testing show that droop-controlled GFM can significantly improve the system frequency response***



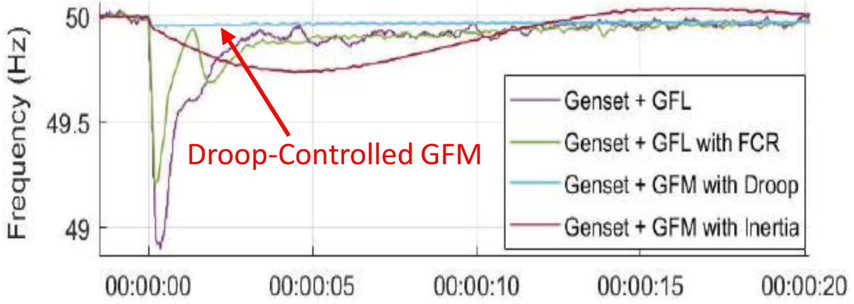
SMA Test System

73% penetration of GFMs in the micro-WECC system



(Simulation credit: Dmitry, BPA)

SMA Hardware Test Results [1]



[1] A. Knobloch *et al.*, "Synchronous energy storage system with inertia capabilities for angle, voltage and frequency stabilization in power grids," *11th Solar & Storage Power System Integration Workshop (SIW 2021)*, 2021, pp. 71-78

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Applicability and Limitation of REGFM_A1

- The REGFM_A1 model can be used for many scenarios. However, it does not include advanced current limiting and fault ride-through (FRT) controls that are implemented by some OEMs
- This is because many OEMs consider those controls as proprietary technologies
- During a long-term fault (e.g., a 25-cycle fault), the REGFM_A1 may lose synchronism to the grid
  - *OEMs' black-box models are recommended to study those long-term severe faults*
- The UNIFI team is evaluating various candidate methods, and plan to include them in the next version (*e.g., REGFM_A2*)

Recommended Scenarios of Using REGFM_A1	Not Recommended Scenarios of Using REGFM_A1
• Frequency response • Islanding and islanded operation • trip of generators and lines • typical faults with a normal clearing time • Overload testing	• long-term severe faults (e.g., a 25-cycle delayed clearing fault)

Introduction of REGFM_B1 Model

Introduction of REGFM_B1 Model

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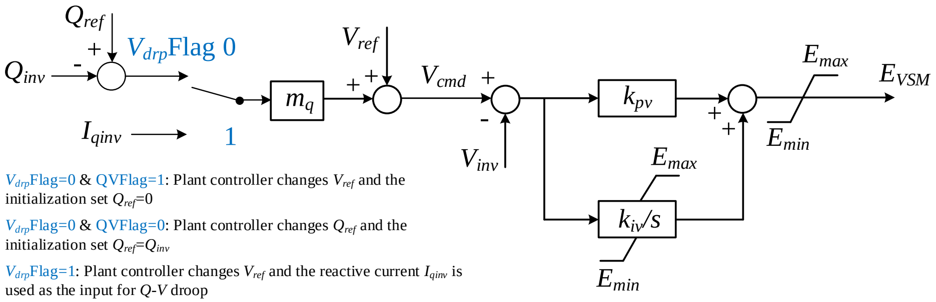
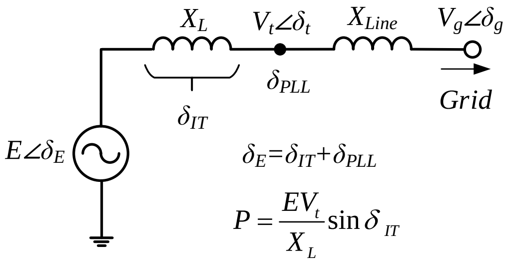
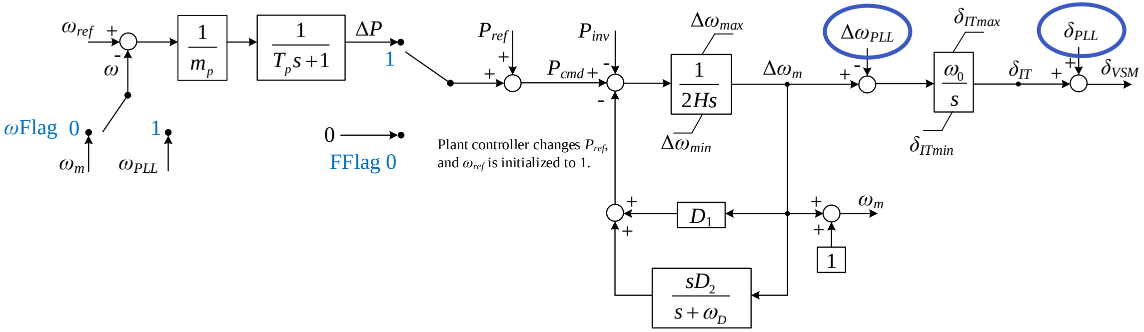
- The REGFM_B1 includes the voltage control block and the VSM/inertial control block
- A PLL is used to get the angle of the terminal voltage, and the VSM/inertial block controls the angle difference δ_{IT}
- The use of PLL is different from its use in grid-following inverters (GFLs)
- The PLL can be considered as not existent during normal operation (when $\delta_{ITmin} < \delta_{IT} < \delta_{ITmax}$)



Voltage control block



Voltage phasor behind impedance



VSM/inertial control block

Steady State Current Limiting in REGFM_B1

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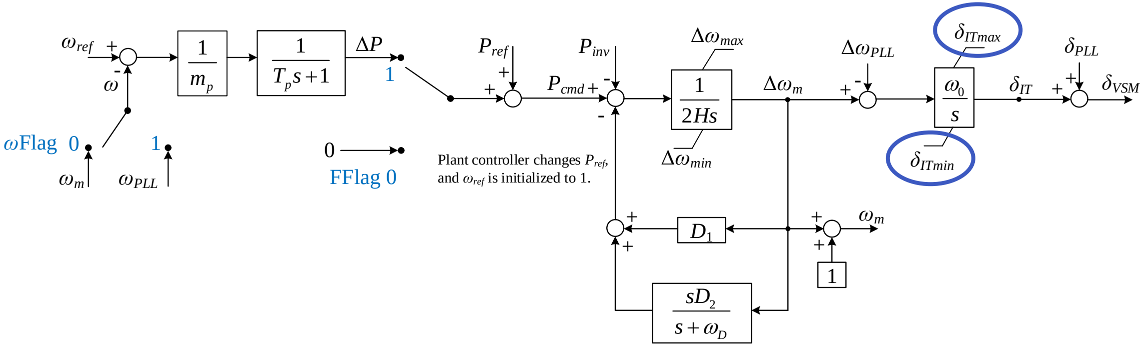
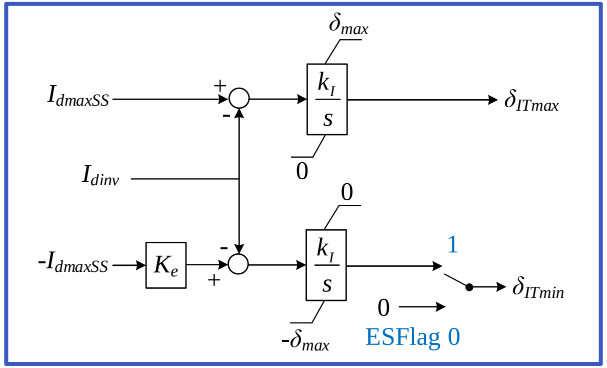
- GE provided an advanced current limiting solution, including the steady state ***active and reactive current limiting*** controls
- The active current I_{dinv} is limited by regulating δ_{ITmax} and δ_{ITmin}



VSM/inertial control block

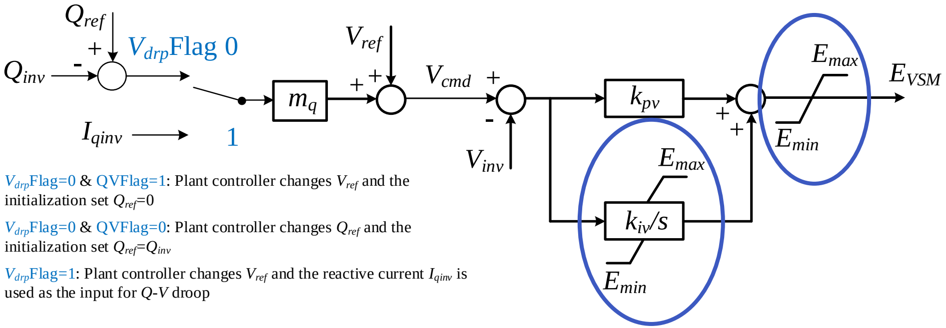


Active current I_d limiting

[1] Larsen EV, Delmerico RW, inventors; General Electric Co, assignee. Battery energy storage power conditioning system. United States patent US 5,798,633. 1998 Aug 25.

Steady State Current Limiting in REGFM_B1

- The reactive current I_{qinv} is limited by regulating the saturation limits E_{max} and E_{min}
- The steady state current limiting control can utilize the PQ priority algorithm

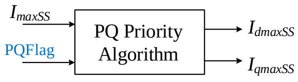


Voltage control block

$$E_{\min} = \sqrt{(V_{inv} - I_{q\max} X_L)^2 + (I_{dinv} X_L)^2}$$

$$E_{\max} = \sqrt{(V_{inv} + I_{q\max} X_L)^2 + (I_{dinv} X_L)^2}$$

Reactive current limiting



I_{maxSS} refers to the steady-state current limit

PQ Priority Algorithm

Q Priority (PQFlag=0)	P Priority (PQFlag=1)
$I_{q\max SS} = k_f I_{\max SS}$	$I_{d\max SS} = k_f I_{\max SS}$
$I_{d\max SS} = \begin{cases} \sqrt{I_{\max SS}^2 - I_{qinv}^2}, & I_{\max SS}^2 \ge I_{qinv}^2 \\ 0, & I_{\max SS}^2 < I_{qinv}^2 \end{cases}$	$I_{q\max SS} = \begin{cases} \sqrt{I_{\max SS}^2 - I_{dinv}^2}, & I_{\max SS}^2 \ge I_{dinv}^2 \\ 0, & I_{\max SS}^2 < I_{dinv}^2 \end{cases}$

PQ Priority Algorithm to determine I_{dmaxSS} and I_{qmaxSS}

[1] Larsen EV, Delmerico RW, inventors; General Electric Co, assignee. Battery energy storage power conditioning system. United States patent US 5,798,633. 1998 Aug 25.

1 s Fault

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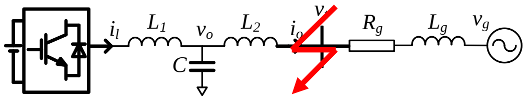
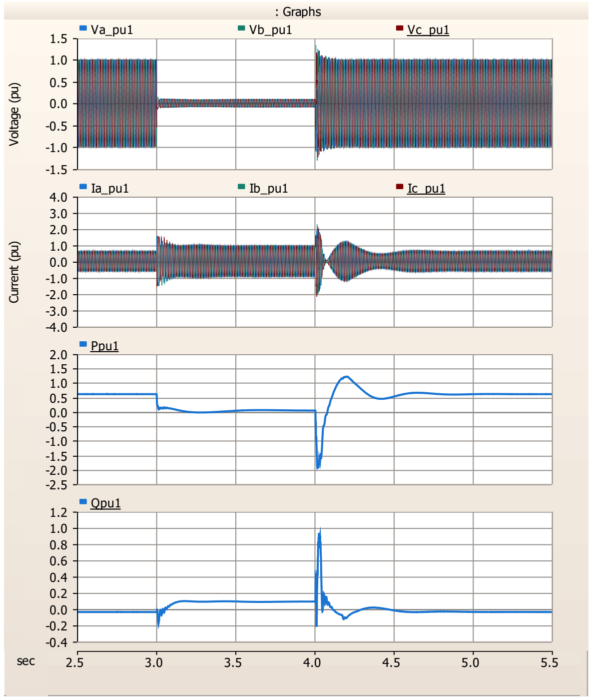
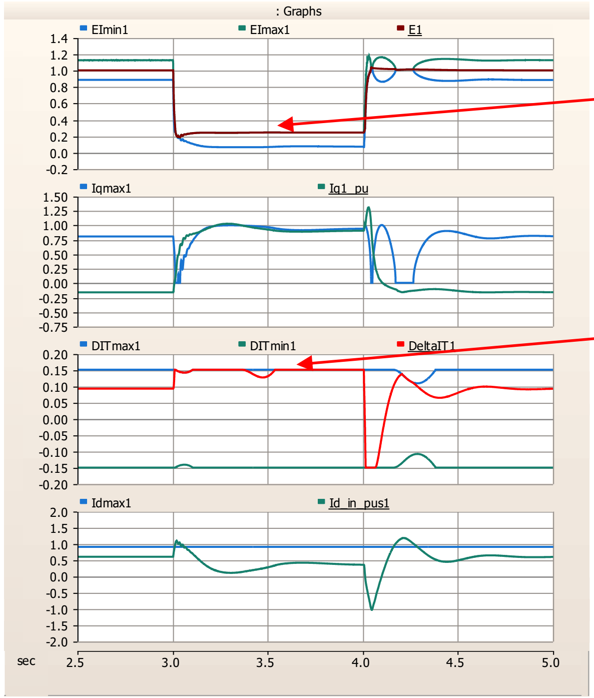
- The transient current limiting clips the current at I_{maxF} = 1.5 pu
- The steady-state current limiting later limits the current at I_{maxSS} = 1 pu
- ***No critical clearing time for REGFM_B1***
- ***A real synchronous machine cannot ride-through such a long-term fault***



A single-GFM Infinite-Bus System



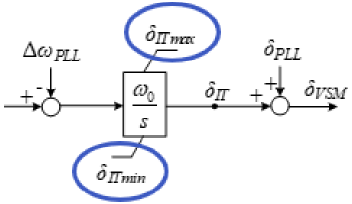


I_q is limited by E_{max}/E_{min} controller

$$E_{\min} = \sqrt{(V_{inv} - I_{q\max} X_L)^2 + (I_{dinv} X_L)^2}$$

$$E_{\max} = \sqrt{(V_{inv} + I_{q\max} X_L)^2 + (I_{dinv} X_L)^2}$$

I_d is limited by the saturation limits δ_{ITmax} and δ_{ITmin}



1 s Fault (PSS/E and PSCAD comparison)

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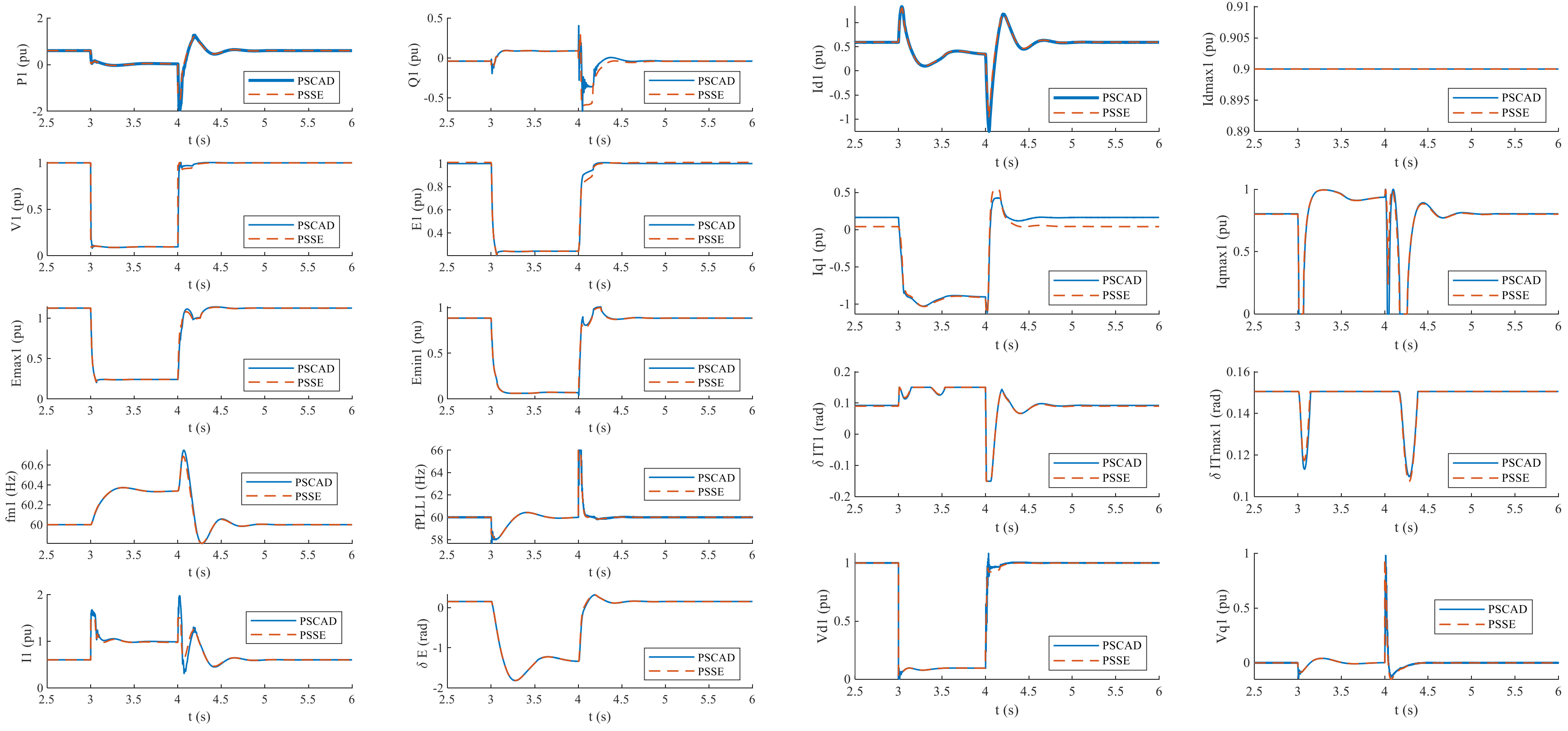
- For GFMs that do not use inner current loops, the positive-sequence models can capture their transient behaviors very well



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Summary of REGFM_A1 and REGFM_B1

Key Features in REGFM_A1 and REGFM_B1

	REGFM_A1	REGFM_B1
Normal Mode (*No limits reached*)	Droop Control	Virtual Synchronous Machine
Abnormal Mode (*Hit the limits*)	• Steady state active and reactive power limiting • Transient current limiting (≈ virtual impedance) • No advanced current limiting/FRT control (There is a critical clearing time)	• Transient current limiting (≈ virtual impedance) • Steady state active and reactive current limiting • PQ priority algorithm to determine steady state I_d and I_q • Advanced FRT control (No critical clearing time)

[1] https://www.wecc.org/Administrative/WDu-MVS-Model%20Benchmarking%20REGFM_A1%20Model_May%202023.pdf
[2] https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/12%20-%20DuW%20-%20Virtual%20Synchronous%20Machine%20Model%20-%20REGFM-B1_May%202024.pdf&action=default&DefaultItemOpen=1

Industry Users of REGFM_A1 and REGFM_B1

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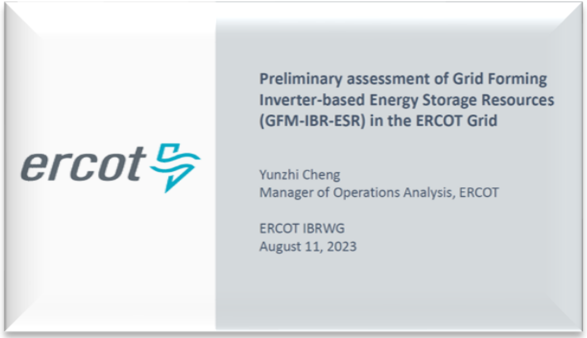
- Multiple utility entities are working with UNIFI team on evaluating how GFMs impact their grids using the REGFM_A1 and REGFM_B1 models. Below are few examples


WECC

Grid Forming Inverters

Grid Forming Advisory Group 7/17/2023

WECC report of GFM technology


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


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

Preliminary Simulation Results from Industry Using REGFM_A1

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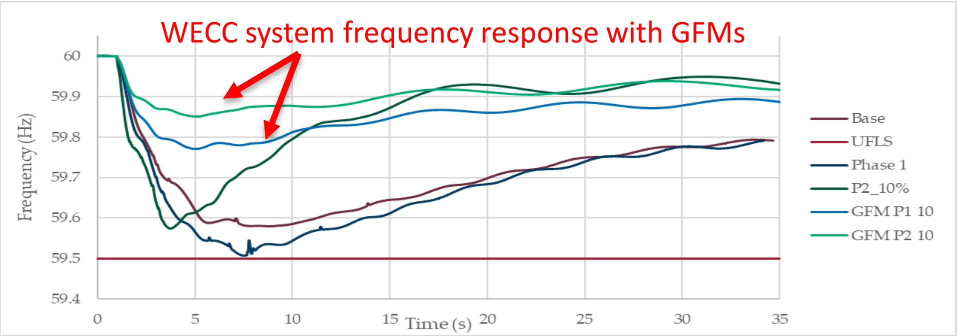
- GFMs with sufficient headroom can significantly improve the system frequency response
- GFMs can mitigate oscillations in weak systems

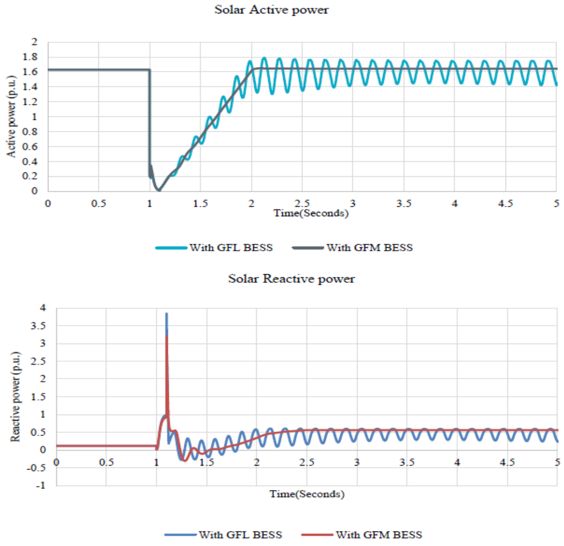
WECC report

ERCOT Presentation



GFMs can improve the frequency stability of the WECC System (*Source: WECC*)

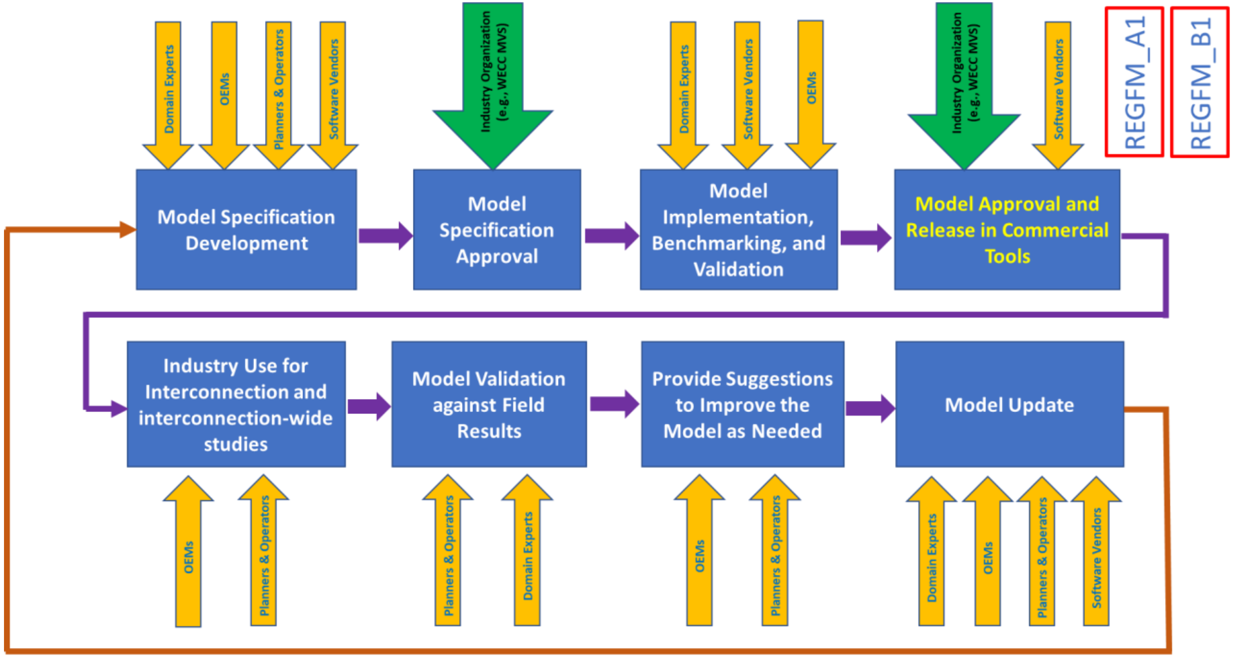
WECC Recommendation*: Planning Coordinators should strongly consider GFM technology when replacing synchronous generators with IBRs. They should be designed to provide reliable and robust performance that supports high IBR penetration in the Western Interconnection.*



GFMs can mitigate the oscillation in the weak system in ERCOT (*Source: ERCOT*)

Conclusions and Future Work

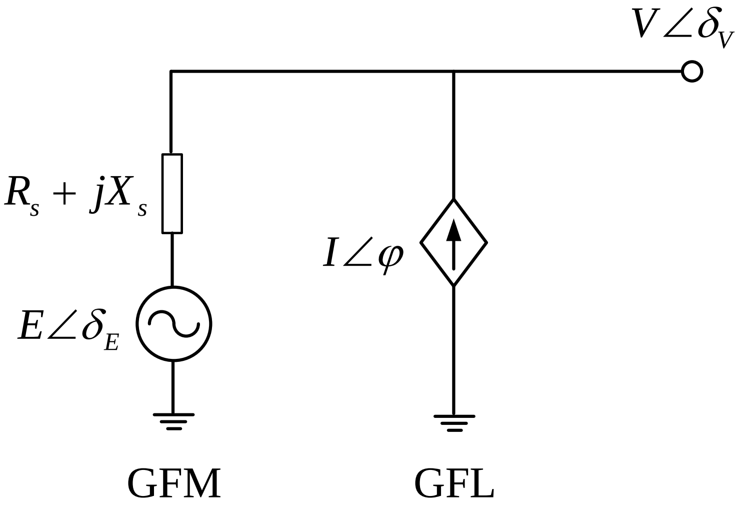
- The REGFM_A1 and REGFM_B1 represent the first two ***WECC-approved standard library GFM models***, and have been integrated into the simulation tools used by transmission planners worldwide, including PSS/E (V36.1), PSLF (V23.2.8.2), PowerWorld (V23), and TSAT (V24.1)
- As the GFM technology continues 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 **inverter manufacturers**, **software vendors**, **system planners**, and **research institutes**



As the GFM technology continues to evolve, these models need to be further validated and updated on a regular basis

Immediate Next Step

- The UNIFI Modeling and Simulation team is currently working with ***Tesla***, and ***WECC MVS*** on developing a third representative GFM technology used in industry
- This third representative GFM technology uses the hybrid GFM+GFL approach, and both the GFM and GFL control algorithms are implemented in a single inverter, and those two control algorithms run in parallel simultaneously



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Wei Du
Wei.du@pnnl.gov

Deepak Ramasubramanian
dramasubramanian@epri.com

THANK YOU

1 Hz Oscillation in Kauai Island

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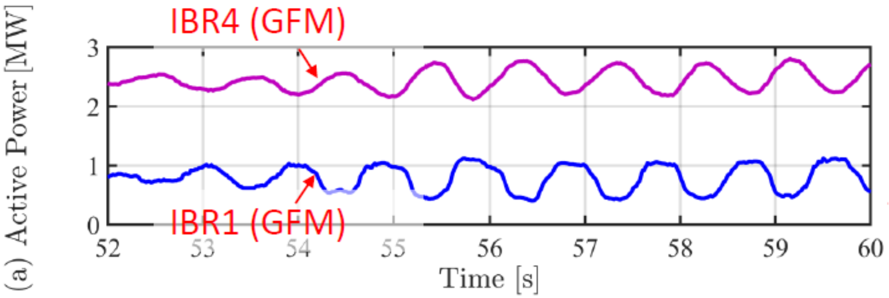
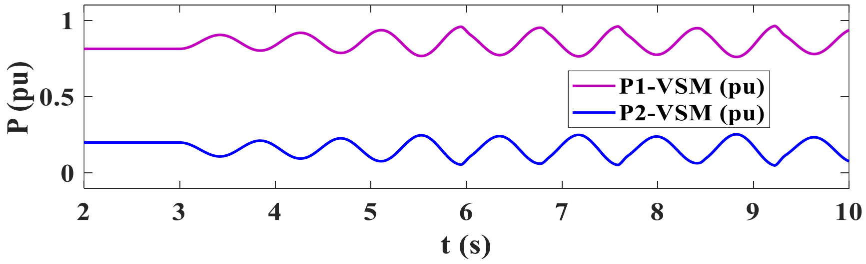
- The REGFM_B1 model can be parameterized to reproduce the 1 Hz oscillation happened in the Kauai island
- The UNIFI team will further analyze the root cause for this oscillation mode



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.