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

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Suggested Citation

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

DISCLAIMER

Technical Report

January 2025

Acknowledgments

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 38637. We would like to acknowledge the Western Electricity Coordinating Council (WECC) Modeling and Validation Subcommittee (MVS) for supporting this model development work. In addition, we would also like to acknowledge Hussam Alatrash and Prashant Kansal for their contribution to the model development during their time at Tesla Energy.

1 Introduction

This document describes a standard library grid-forming (GFM) hybrid control inverter-based resource (IBR) model. The GFM hybrid control approach implements both a typical GFM control and a typical grid-following (GFL) control inside one single inverter simultaneously, so that it can take the advantages of both methods without comprising the benefits of a typical GFM. The initial version of model specification was jointly developed by Pacific Northwest National Laboratory (PNNL), Tesla Energy, and EPRI, and it was revised multiple times later to incorporate suggestions from WECC MVS members. Tesla Energy provided main control blocks to support the development of this model specification.

This standard library model is developed to help the utility industry better understand the GFM technology. The model could be used to represent equipment for long-term planning studies where vendor-specific models are not available. As equipment mature and improve, standard library models will be updated to capture the new functionalities of GFMs. It is not intended that these models will always remain representative of all future GFM technologies.

2 Network Interface

The network interface of the standard library GFM hybrid model includes a voltage source behind impedance in parallel with a current source, as shown in Figure 1. R_s+jX_s represents the virtual impedance.

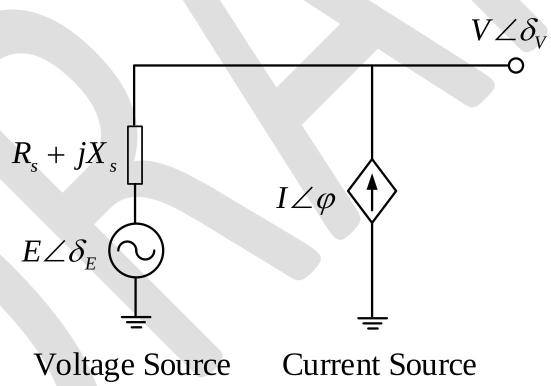

Figure 1 Network interface of the standard library GFM hybrid model.

3 GFM Branch Block Diagrams

The GFM branch implements a typical virtual synchronous machine (VSM) control, as shown in Figure 2. $E_{VSM}\angle\delta_{VSM}$ represents the voltage reference from the GFM control.

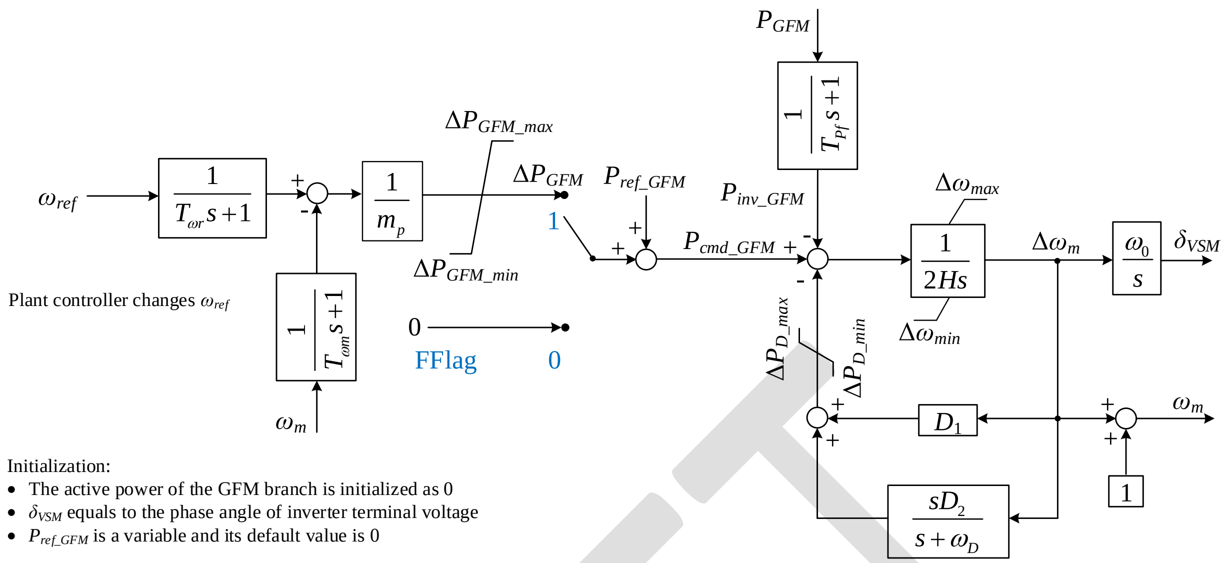

Figure 2 GFM virtual synchronous machine control.

P_{GFM} represents the pre-limited active power of the GFM branch, which is calculated using (1). In (1), $I_{VSM}\angle\varphi_{VSM}$ represents the current reference generated by the GFM branch, which is calculated using (2). P_{GFM} is a per-unit value on the inverter rating base.

$$P_{GFM} = \mathrm{Re}(V\angle\delta_V \cdot \overline{I_{VSM}\angle\varphi_{VSM}}) \tag{1}$$

$$I_{VSM}\angle\varphi_{VSM} = \frac{E_{VSM}\angle\delta_{VSM} - V\angle\delta_V}{R_s + jX_s} \tag{2}$$

Figure 3 shows the voltage control block diagram.

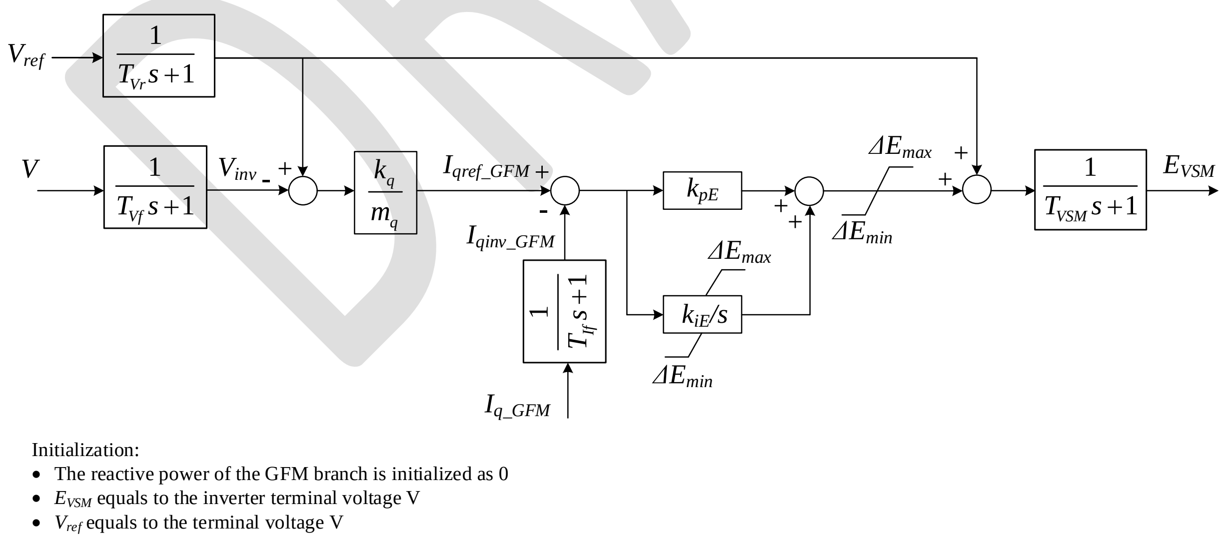

Figure 3 GFM voltage control.

In (3), I_{q_GFM} refers to the reactive current of the GFM branch. I_{q_GFM} is a per-unit value on the inverter rating base.

$$I_{q\_GFM} = I_{VSM} \sin(\delta_V - \varphi_{VSM}) \quad (3)$$

It is important to note that the output P_{GFM} and Q_{GFM} of the GFM branch are initialized at 0. When interfacing with the plant controller, the plant controller will always dispatch the output P and Q of the GFM branch to be close to 0.

4 GFL Branch Block Diagrams

The GFL branch implements a typical GFL control, as shown in Figure 6. $I_{GFL}\angle\varphi_{GFL}$ represents the current reference from the GFL control.

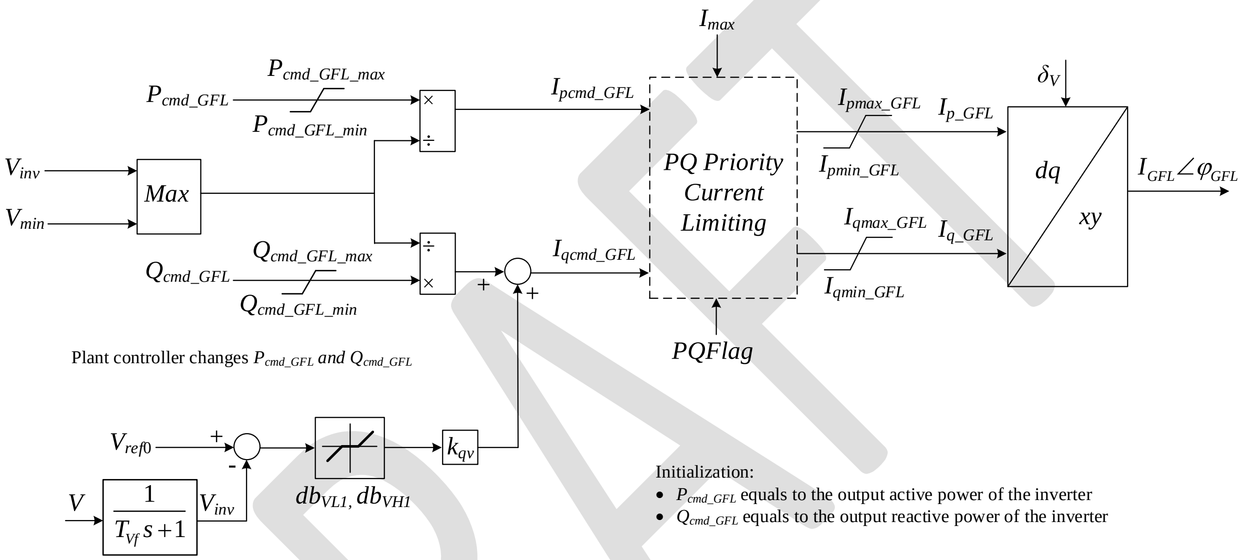

Figure 4 GFL control.

PQ Priority Current Limiting Algorithm

Q Priority (PQFlag=0)	P Priority (PQFlag=1)
$I_{q\max\_GFL} = k_f I_{\max}$	$I_{p\max\_GFL} = k_f I_{\max}$
$I_{q\min\_GFL} = -I_{q\max\_GFL}$	$I_{p\min\_GFL} = -I_{p\max\_GFL}$
$I_{p\max\_GFL} = \begin{cases} \sqrt{I_{\max}^2 - I_{q\_GFL}^2}, I_{\max}^2 \geq I_{q\_GFL}^2 \\ 0, I_{\max}^2 < I_{q\_GFL}^2 \end{cases}$	$I_{q\max\_GFL} = \begin{cases} \sqrt{I_{\max}^2 - I_{p\_GFL}^2}, I_{\max}^2 \geq I_{p\_GFL}^2 \\ 0, I_{\max}^2 < I_{p\_GFL}^2 \end{cases}$
$I_{p\min\_GFL} = -I_{p\max\_GFL}$	$I_{q\min\_GFL} = -I_{q\max\_GFL}$

Figure 5 PQ Priority Current Limiting Algorithm.

$$\mathrm{Re}(I_{GFL}\angle\varphi_{GFL}) = I_{p\_GFL} \cos\delta_V + I_{q\_GFL} \sin\delta_V \quad (4)$$

$$\mathrm{Im}(I_{GFL}\angle\varphi_{GFL}) = I_{p\_GFL} \sin\delta_V - I_{q\_GFL} \cos\delta_V \quad (5)$$

5 Current Limiting Algorithm

The current limiting algorithm is implemented algebraically in the positive-sequence phasor domain model. The current reference generated by the GFM branch can be written as:

$$I_{VSM}\angle\varphi_{VSM} = \frac{E_{VSM}\angle\delta_{VSM} - V\angle\delta_V}{R_s + jX_s} \tag{6}$$

The total current reference from the GFM branch and GFL branch can be written as:

$$I_{total}\angle\varphi_{total} = I_{VSM}\angle\varphi_{VSM} + I_{GFL}\angle\varphi_{GFL} \tag{7}$$

When I_{total} is larger than I_{max}, the current limiting algorithm will be activated. The current limiting algorithm is implemented in a way that the current magnitude is limited at I_{max}, and the current phase angle remains unchanged.

Define the following factor:

$$k = \frac{I_{total}}{I_{\max}} \tag{8}$$

Dividing (7) by k, the following equation holds:

$$I_{\max}\angle\varphi_{total} = \frac{I_{VSM}\angle\varphi_{VSM}}{k} + \frac{I_{GFL}\angle\varphi_{GFL}}{k} \tag{9}$$

Equation (9) shows that the magnitude of the total output current can be limited at I_{max} by reducing the current references of both the GFL branch and GFM branch.

Therefore, the following current limiting algorithm is used to determine the final internal voltage phasor of the GFM branch and the final the internal current phasor of the GFL branch. In this way, the magnitude of the total output current from the two branches will be limited at I_{max}, and the phase angle of the total output current remains unchanged compared to the case without current limiting.

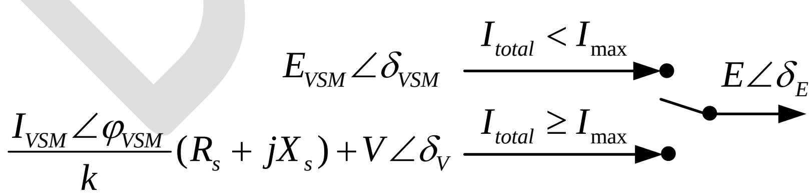

Figure 6 Current limiting algorithm for the GFM branch.

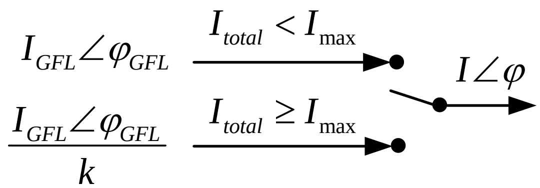

Figure 7 Current limiting algorithm for the GFL branch.

Table 1 Model Main Circuit and Controller Parameters

Symbol	Description	Unit	Example Value
FFlag	A flag to determine whether the power-frequency droop is enabled (FFlag=1) or disabled (FFlag=0).	NA	1
PQFlag	A flag to determine whether P priority (PQFlag=1) or Q priority (PQFlag=0) is selected.	NA	0
R_s	Virtual resistance. (0 pu ≤ R_s ≤ ¼X_s)	pu	0.05
X_s	Virtual reactance. (0.04 pu ≤X_s≤0.4 pu)	pu	0.2
m_q	*Q-V* droop gain of the GFM branch.	pu	0.4
k_q	A binary value that is either 0 or 1.	NA	1
k_{pE}	Proportional gain of the voltage PI loop of the GFM branch.	pu	0.333
k_{iE}	Integral gain of the voltage PI loop of the GFM branch.	pu/s	3.333
ΔE_{max}	Upper limit of the volage PI loop of the GFM branch.	pu	0.2083
ΔE_{min}	Lower limit of the volage PI loop of the GFM branch.	pu	-0.2083
T_{Vr}	Time constant of low-pass filter of the GFM branch.	s	0.025
T_{VSM}	Time constant of low-pass filter of the GFM branch.	s	0.3183
T_{Vf}	Time constant of low-pass filter of the GFM branch.	s	0.02
T_{If}	Time constant of low-pass filter of the GFM branch.	s	0.01
H	Inertia time constant of the GFM branch.	s	1.6
D_1	Damping of the GFM branch.	pu	0
D_2	Transient damping of the GFM branch.	pu	90
ω_D	Angular frequency of the washout block of the GFM branch.	pu	3.14
m_p	*P-f* droop gain of the GFM branch.	pu	0.041667
ΔP_{GFM_max}	Upper limit of the VSM droop output	pu	1.36
ΔP_{GFM_max}	Lower limit of the VSM droop output	pu	-1.36
ΔP_{D_max}	Upper limit of the VSM damping output	pu	1.5
ΔP_{D_min}	Lower limit of the VSM damping output	pu	-1.5
$\Delta\omega_{max}$	Upper limit of the VSM integrator of the GFM branch	pu	0.1667
$\Delta\omega_{min}$	Lower limit of the VSM integrator of the GFM branch	pu	-0.3333
$T_{\omega r}$	Time constant of low-pass filter of the GFM branch.	s	0.025
$T_{\omega m}$	Time constant of low-pass filter of the GFM branch.	s	0.3183
T_{Pf}	Time constant of low-pass filter of the GFM branch.	s	0.02
$P_{cmd\_GFL\_max}$	Upper limit of the active power reference for the GFL branch	pu	0.8
$P_{cmd\_GFL\_min}$	Lower limit of the active power reference for the GFL branch	pu	-0.8
$Q_{cmd\_GFL\_max}$	Upper limit of the reactive power reference for the GFL branch	pu	0.6
$Q_{cmd\_GFL\_min}$	Lower limit of the reactive power reference for the GFL branch	pu	-0.6
V_{min}	Lower voltage limit of the GFL branch.	pu	0.88
V_{ref0}	Voltage reference of the GFL branch.	pu	1.0
k_{qv}	Voltage control factor of the GFL branch.	pu	2
db_{VL1}	Lower threshold of the deadband of the GFL branch.	pu	-0.12
db_{VH1}	Upper threshold of the deadband of the GFL branch.	pu	0.12
k_f	A factor to determine I_{qmax} (PQFlag=0) or I_{dmax} (PQFlag=1) of the GFL branch. If k_f=0, the software should reset it to be 1 and generate a warning message.	pu	1
I_{max}	Maximum output current	pu	1.2
ω_0	Rated angular frequency. Software tools typically have this value specified in the solution environment, so this will not be listed as an input parameter of the model	rad/s	376.99

References

[1] Sai Gopal Vennelaganti, Mostafa Mahfouz. Tesla Inverter Controls Block Diagrams (Unpublished).

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