

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

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## **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  $1.V \angle \delta_v$  refers to the inverter terminal voltage.  $R_s+jX_s$  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.

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

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

Figure 3 shows the voltage control block diagram.



- E<sub>VSM</sub> equals to the inverter terminal voltage V
- $V_{ref}$  equals to the terminal voltage V
- $I_{qref_{GFM}}$  is a variable and its default value is 0

#### 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.

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

#### Figure 5 PQ Priority Current Limiting Algorithm.

$$\operatorname{Re}(I_{GFL} \angle \varphi_{GFL}) = I_{p \ GFL} \cos \delta_{V} + I_{a \ GFL} \sin \delta_{V}$$
<sup>(4)</sup>

$$\operatorname{Im}(I_{GFL} \angle \varphi_{GFL}) = I_{p_{-}GFL} \sin \delta_{V} - I_{q_{-}GFL} \cos \delta_{V}$$
(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:

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

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

$$I_{total} \angle \varphi_{total} = I_{VSM} \angle \varphi_{VSM} + I_{GFL} \angle \varphi_{GFL}$$
<sup>(7)</sup>

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:

$$k = \frac{I_{total}}{I_{max}}$$
(8)

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

$$I_{\max} \angle \varphi_{total} = \frac{I_{VSM} \angle \varphi_{VSM}}{k} + \frac{I_{GFL} \angle \varphi_{GFL}}{k}$$
(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.

$$\frac{E_{VSM} \angle \delta_{VSM}}{k} (R_s + jX_s) + V \angle \delta_V \xrightarrow{I_{total} < I_{max}} \underbrace{E \angle \delta_E}_{M}$$

Figure 6 Current limiting algorithm for the GFM branch.



Figure 7 Current limiting algorithm for the GFL branch.

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
VFlag	A flag to determine whether the $I_q$ -V droop is enabled (VFlag=1) or disabled (VFlag=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 $\leq R_s \leq \frac{1}{4}X_s$ )	pu	0.05
$X_s$	Virtual reactance. (0.04 pu $\leq X_s \leq 0.4$ pu)	pu	0.2
$m_q$	Q-V droop gain of the GFM branch.	pu	0.4
$k_{pE}$	Proportional gain of the voltage PI loop of the GFM branch.	pu	0.333
k <sub>iE</sub>	Integral gain of the voltage PI loop of the GFM branch.	pu/s	3.333
$\Delta E_{max}$	Upper limit of the volage PI loop of the GFM branch.	pu	0.2083
$\Delta E_{min}$	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 <sub>VSM</sub>	Time constant of low-pass filter of the GFM branch.	S	0.3183
Tvf	Time constant of low-pass filter of the GFM branch.	s	0.02
	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 nu	90
	Angular frequency of the washout block of the GFM branch.	pu	3.14
$m_{p}$	<i>P-f</i> droop gain of the GFM branch.	pu nu	0.041667
$\Delta P_{GFM max}$	Upper limit of the VSM droop output	pu nu	1.36
$\Delta P_{GFM}$ max	Lower limit of the VSM droop output	pu	-1.36
$\Delta P_{D}$ max	Upper limit of the VSM damping output	pu	1.5
$\Delta P_{D min}$	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
$\Delta \phi_{min}$	Lower limit of the VSM integrator of the GFM branch	pu	-0.3333
	Time constant of low-pass filter of the GFM branch.	s s	0.025
Tom	Time constant of low-pass filter of the GFM branch.	s	0.3183
	Time constant of low-pass filter of the GFM branch.	s	0.02
Pend GEL max	Upper limit of the active power reference for the GFL branch	pu	0.8
Period GFL min	Lower limit of the active power reference for the GFL branch	pu	-0.8
Ocmd GEL max	Upper limit of the reactive power reference for the GFL branch	pu	0.6
Ocmd GEL min	Lower limit of the reactive power reference for the GFL branch	pu	-0.6
Vmin	Lower voltage limit of the GFL branch.	pu	0.88
Vraf	Voltage reference of the GFL branch.	pu	1.0
kw	Voltage control factor of the GFL branch.	pu	2
dbyri	Lower threshold of the deadband of the GFL branch.	pu	-0.12
dbyH1	Upper threshold of the deadband of the GFL branch.	pu	0.12
k <sub>f</sub>	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	Maximum output current	nu	1.2
$\omega_0$	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

Table 1 Model Main Circuit and Controller Parameters

### References

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



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