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

Contributors:

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

DISCLAIMER

Technical Report (Arial 10 pt Bold)
Publication Number
Month Year (Arial 10 pt)

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 also like to acknowledge the Western Electricity Coordinating Council (WECC) Modeling and Validation Subcommittee (MVS) for supporting this model development work.

1 Introduction

This report describes a generic virtual synchronous machine (VSM) grid-forming inverter (GFM) model—REGFM_B1. The initial model specification was proposed by Pacific Northwest National Laboratory (PNNL), General Electric (GE), and Electric Power Research Institute (EPRI). Siemens Gamesa Renewable Energy (SGRE) also provided inputs to the specification. The model specification has been revised multiple times based on the discussions between all the contributors listed in this report. This work was funded by the Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium.

This generic model is developed to help the utility industry understand the concept of VSM GFMs. 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, generic 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 VSM GFM Model (REGFM_B1)

The main circuit of a VSM GFM can be represented as a voltage source behind impedance as shown in Figure 1.

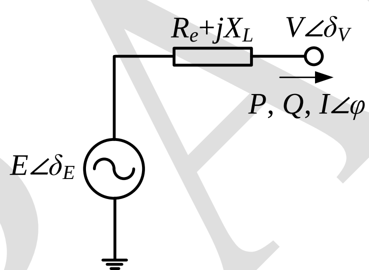


Figure 1 Voltage source representation of a grid-forming inverter

Figure 2 shows the virtual synchronous machine control block. In (1) and (2), P and I_d are per unit values on the system base, and P_{inv} and I_{dinv} are per unit values on the inverter rating base.

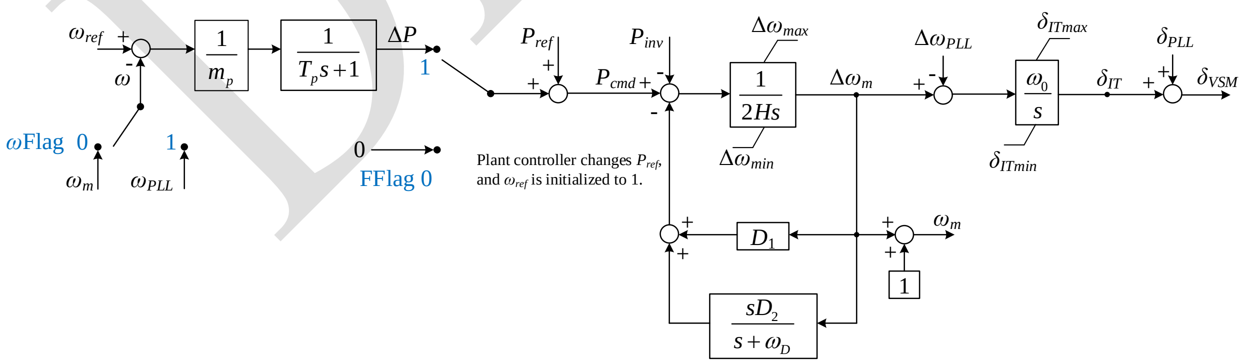


Figure 2 Virtual synchronous machine control

$$P_{inv} = \frac{1}{1+T_{Pf}s} P \frac{S_{base}}{M_{base}} \tag{1}$$

$$I_{dinv} = \frac{1}{1+T_{If}s} I_d \frac{S_{base}}{M_{base}} \tag{2}$$

Figure 3 shows the voltage control block. In (3) and (5), Q and I_q are per unit values on the system base, and Q_{inv} and I_{qinv} are per unit values on the inverter rating base.

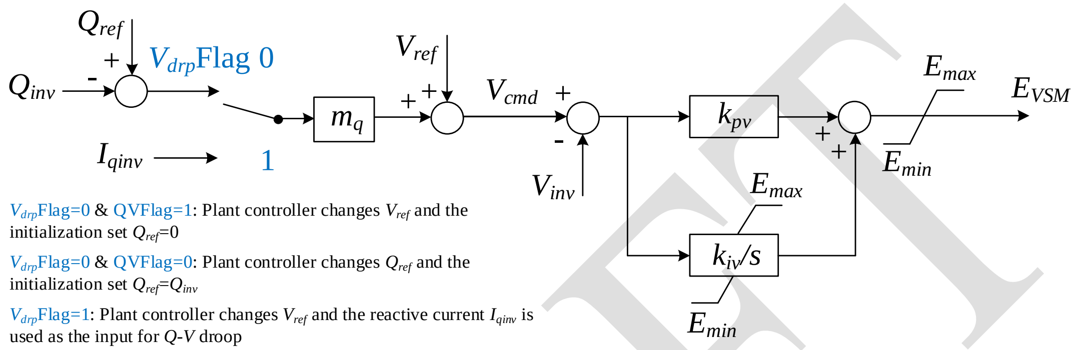


Figure 3 Voltage control

$$Q_{inv} = \frac{1}{1+T_{Qf}s} Q \frac{S_{base}}{M_{base}} \tag{3}$$

$$V_{inv} = \frac{1}{1+T_{Vf}s} V \tag{4}$$

$$I_{qinv} = \frac{1}{1+T_{If}s} I_q \frac{S_{base}}{M_{base}} \tag{5}$$

Figure 4 shows the PLL control block, and the voltages and currents in the *dq* frame can be calculated using (6)–(9).

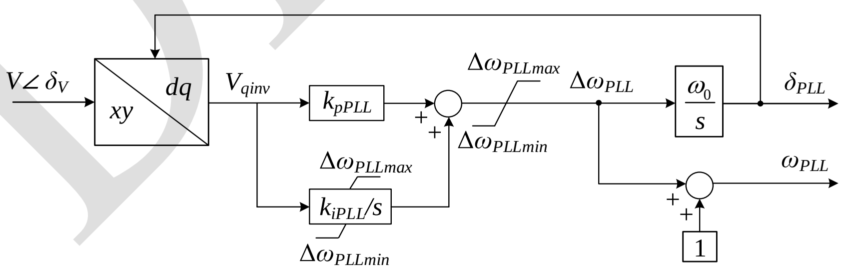


Figure 4 PLL block

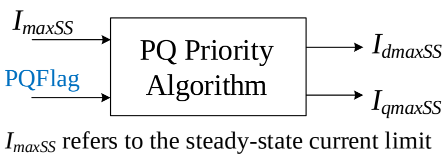
$$I_d = I_x \cos\delta_{PLL} + I_y \sin\delta_{PLL} \tag{6}$$

$$I_q = -I_x \sin\delta_{PLL} + I_y \cos\delta_{PLL} \tag{7}$$

$$V_d = V_x \cos\delta_{PLL} + V_y \sin\delta_{PLL} \tag{8}$$

$$V_q = -V_x \sin\delta_{PLL} + V_y \cos\delta_{PLL} \tag{9}$$

The PQ priority algorithm can be used to determine the steady-state active current limit I_{dmaxSS} and reactive current limit I_{qmaxSS}, as shown in Figure 5.



PQ Priority Algorithm

Q Priority (PQFlag=0)	P Priority (PQFlag=1)
$I_{q\max SS} = k_f I_{\max SS}$	$I_{d\max SS} = k_f I_{\max SS}$
$I_{d\max SS} = \sqrt{I_{\max SS}^2 - I_{qinv}^2}$	$I_{q\max SS} = \sqrt{I_{\max SS}^2 - I_{dinv}^2}$

Figure 5 PQ priority algorithm to determine the steady-state maximum active and reactive currents

The steady-state reactive current I_{qinv} can be limited by reducing the internal voltage magnitude E using the algorithm described in (10) and (11).

$$E_{\min} = \sqrt{(V_{inv} - I_{q\max SS} X_L)^2 + (I_{dinv} X_L)^2} \quad (10)$$

$$E_{\max} = \sqrt{(V_{inv} + I_{q\max SS} X_L)^2 + (I_{dinv} X_L)^2} \quad (11)$$

The steady-state active current I_{dinv} can be limited by using the control block described in Figure 6. (12) describes how to calculate δ_{max}.

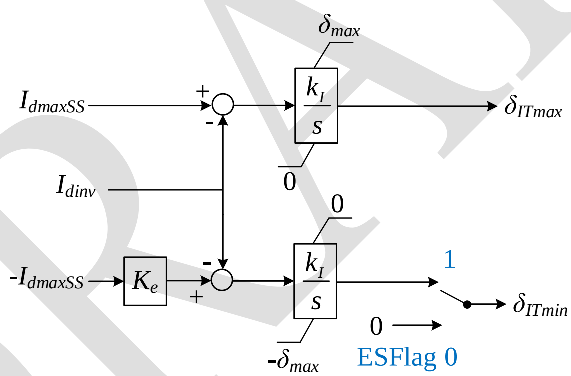


Figure 6 Active current limiting block

$$\delta_{\max} = \sin^{-1}(X_L I_{\max SS}) \quad (12)$$

Equation (13) and Figure 7 describe the transient current limiting function. When the transient current limiting is activated, the output current is limited algebraically by the network solution. Note that I_{maxF} should be set larger than I_{maxSS}.

$$I\angle\varphi = \frac{E_{VSM}\angle\delta_{VSM} - V\angle\delta_V}{R_e + jX_L} \quad (13)$$

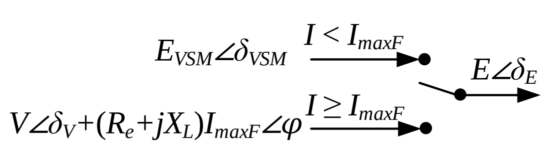


Figure 7 Transient current limiting function

Table 1 Model Main Circuit and Controller Parameters

Symbol	Description	Unit	Example Value
ωFlag	A flag to select whether to use the measured frequency from PLL as the input for the P-f droop.	NA	0
V_{drp}Flag	A flag to select whether to use Q or I_q as the input of the Q-V droop control.	NA	0
QVFlag	A flag to determine whether Q_{ref} or V_{ref} should be used to interact with the plant controller.	NA	1
PQFlag	A flag to determine whether P priority (PQFlag=1) or Q priority (PQFlag=0) should be selected.	NA	0
FFlag	A flag to determine whether the power-frequency droop is enabled (FFlag=1) or disabled (FFlag=0).	NA	1
ESFlag	A flag to determine if the model represents a battery source (ESFlag=1) or a non-battery source (ESFlag=0).	NA	1
R_e	Inverter coupling resistance. (0 pu ≤ R_e ≤ ¼X_L)	pu	0
X_L	Inverter coupling reactance. (0.04 pu ≤X_L≤0.4 pu)	pu	0.1
m_q	Q-V droop gain. When $V_{drpflag}$=1, m_q represents a per unit virtual impedance.	pu	0.05
k_{pv}	Proportional gain of the voltage controller	pu	0
k_{iv}	Integral gain of the voltage controller	pu/s	5
m_p	P-f droop gain	pu	0.02
$\Delta\omega_{max}$	Upper limit of $\Delta\omega_m$	pu	0.05
$\Delta\omega_{min}$	Lower limit of $\Delta\omega_m$	pu	-0.05
k_{pPLL}	Proportional gain of PLL	pu	0.265
k_{iPLL}	Integral gain of PLL	pu/s	2.65
$\Delta\omega_{PLLmax}$	Upper limit of the PLL output	pu	0.2
$\Delta\omega_{PLLmin}$	Lower limit of the PLL output	pu	-0.2
T_p	Time constant of the low-pass filter in the VSM control block. (T_p≥0)	s	0
H	Inertia time constant	s	0.5
D_1	Damping	pu	0
D_2	Transient damping	pu	100
ω_D	Angular frequency of the washout block	pu	50
I_{maxSS}	Steady-state current limit. (I_{maxSS}≤0 is treated as 1/X_L) (I_{maxSS}≤1/X_L) (I_{maxSS}≤I_{maxF})	pu	1
k_f	A factor to determine I_{qmax} (PQFlag=0) or I_{dmax} (PQFlag=1). If k_f=0, the software should reset it to be 1 and generate a warning message.	NA	0.9
k_I	Integral gain for the active current limiting loop	pu/s	2
I_{maxF}	Transient current limit	pu	1.5
T_{pf}	Time constant of the low-pass filter for active power measurement	s	0.02 s
T_{Qf}	Time constant of the low-pass filter for reactive power measurement	s	0.02 s
T_{Vf}	Time constant of the low-pass filter for voltage measurement	s	0.02 s
T_{If}	Time constant of the low-pass filter for current measurement	s	0.02 s
K_e	Scalar on I_{dmax} for negative active steady-state current limitation (0 <= K_e <= 1.0)	NA	1
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

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.

For more information, visit:

sites.google.com/view/unifi-consortium

www.energy.gov/eere/solar/unifi-consortium