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Model Specification of Droop-Controlled, Grid-Forming Inverters (GFMDRP_A)

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1.0 Objective

This document describes a positive-sequence phasor model of droop-controlled, grid-forming (GFM) inverter-based resources (IBRs). It can be considered as an initial model for evaluating the impacts of GFM IBRs on the transients and dynamics of transmission systems.

2.0 Grid-Forming Inverter Concept

A grid-forming inverter behaves as a controllable voltage source behind a coupling reactance as shown in Fig. 1. The internal voltage magnitude E and angular frequency ω are controlled by the droop controller.

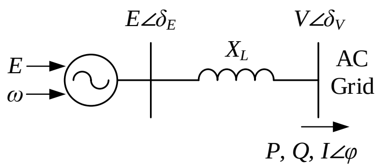


Fig. 1 Basic model of grid-forming inverter.

The coupling reactance, X_L, is important for the droop controller design. By properly sizing X_L, for example, between 0.05 and 0.15 pu on an inverter rating base, the inverter output active power, P, and reactive power, Q, can be approximately decoupled. As shown by (1) to (3), P is approximately linear with the phase angle difference δ_P, and Q is approximately linear with E. The well-developed droop control is based on this decoupling characteristic.

$$\delta_p = \delta_E - \delta_V \tag{1}$$

$$P = \frac{EV}{X_L}\sin\delta_p \approx \frac{EV}{X_L}\delta_p \tag{2}$$

$$Q = \frac{E^2 - EV\cos\delta_p}{X_L} \approx \frac{E(E-V)}{X_L} \tag{3}$$

3.0 Positive-Sequence Phasor Model of Droop-Controlled, Grid-Forming Inverters

This section will introduce the positive-sequence phasor model of droop-controlled, grid-forming inverters, including the inverter main circuit representation, the droop control, and the fault current limiting function. This model applies to energy storage systems and photovoltaic (PV) systems.

3.1 Inverter Main Circuit Representation

The inverter main circuit is modeled as a voltage source behind the coupling reactance X_L, as shown in Fig. 2 (a). The grid-forming controller will adjust the internal voltage magnitude E and phase angle δ_E. When interfacing with the network solver, the voltage source will be converted to its Norton equivalent current source, as shown in Fig. 2 (b).

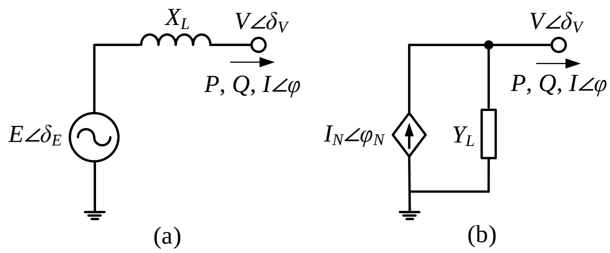


Fig. 2 Inverter equivalent circuits. (a) Inverter internal voltage source and the coupling reactance. (b) Norton equivalent current source.

3.2 Grid-Forming Droop Control Model

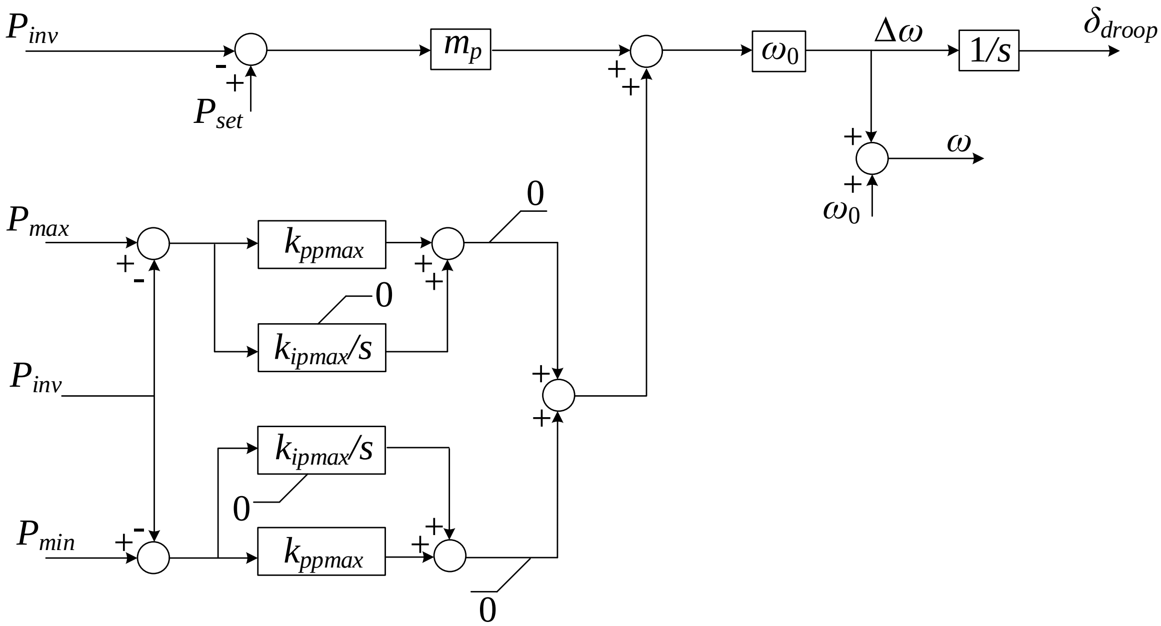
Fig. 3 (a) and (b) show the *P-f* droop control and *Q-V* droop control, which regulate the inverter internal voltage magnitude and phase angle during normal operations. Table 1 shows the inverter and controller parameters.

Table 1 Parameters of the Droop-Controlled, Grid-Forming Inverters on the Inverter Rating Base

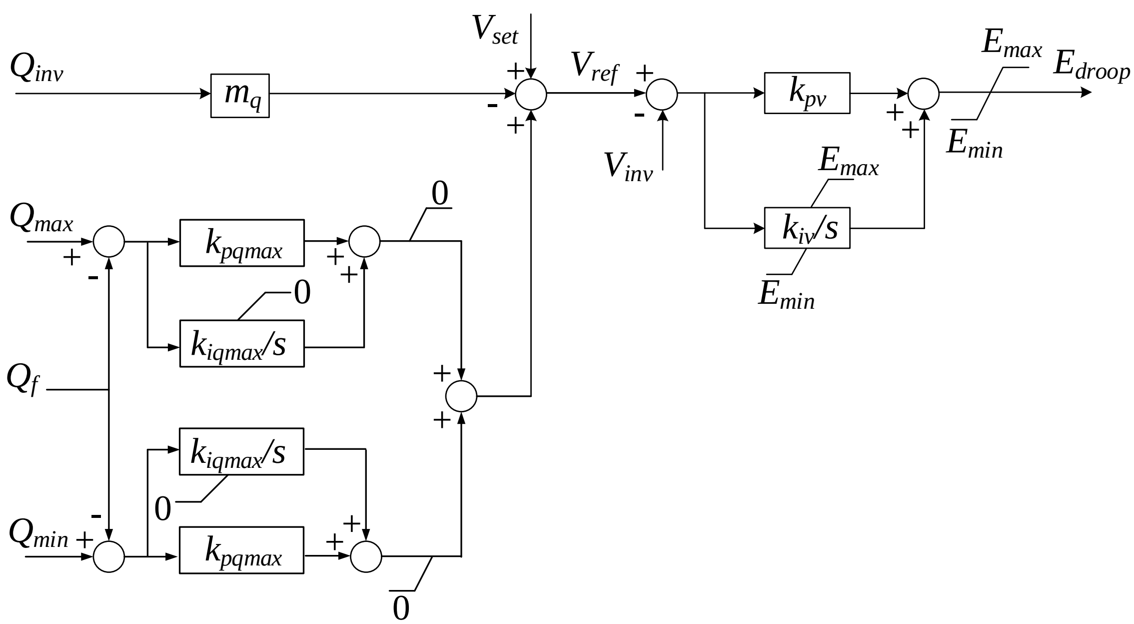
Symbol	Description	Typical Value	Normal Range
X_L	Inverter coupling reactance	0.15 pu	0.05 pu–0.25 pu
m_q	*Q-V* droop gain	0.05 pu	0.02 pu–0.10pu
V_{set}	Voltage set point	Initialized by power flow	NA
k_{pv}	Proportional gain of the voltage controller	0 pu	0 pu–0.01pu
k_{iv}	Integral gain of the voltage controller	5.86 pu/s	3 pu/s–15 pu/s
E_{max}	Upper limit of the output of the voltage loop	1.2 pu	1 pu–1.5 pu
E_{min}	Lower limit of the output of the voltage loop	0 pu	0 pu
m_p	*P-f* droop gain	0.01 pu	0.005 pu–0.05 pu
P_{set}	Power set point	Initialized by power flow	NA
P_{max}	Upper limit of the inverter active power output	1 pu	1 pu–1.5 pu
P_{min}	Lower limit of the inverter active power output	0 pu	Should be negative when representing energy storage systems.
k_{ppmax}	Proportional gain of the overload mitigation controller	0.01 pu	0.005 pu–0.05 pu
k_{ipmax}	Integral gain of the overload mitigation controller	0.1 pu/s	0.05 pu/s–0.2 pu/s
ω_0	Rated angular frequency	376.99 rad/s	NA
T_{Pf}	Time constant of the low-pass filter for P measurement	0.01 s	0.01 s–0.1 s
T_{Qf}	Time constant of the low-pass filter for Q measurement	0.01 s	0.01 s–0.1 s
T_{Vf}	Time constant of the low-pass filter for V measurement	0.01 s	0.01 s–0.1 s
Q_{max}	Upper limit of the inverter reactive power output	1 pu	0.5 pu–1 pu
Q_{min}	Lower limit of the inverter reactive power output	-1 pu	-0.5 pu– -1 pu
k_{pqmax}	Proportional gain of the Q_{max} and Q_{min} controller	3 pu	1 pu – 5 pu
K_{iqmax}	Integral gain of the Q_{max} and Q_{min} controller	20 pu/s	3 pu/s – 30 pu/s
I_{max}	Inverter maximum output current	2 pu	1.5 pu–3 pu

The *P-f* droop control ensures that the phase angles of multiple grid-forming inverters are synchronized during normal operations. When two grid-forming inverters operate in parallel under *P-f* droop control, any disturbance causes an increase in the output power of one inverter. This, causes its *P-f* droop control to reduce the angular frequency ω of the internal voltage so that the phase angle, δ_{droop}, is reduced, preventing the inverter from further increasing its output power. This negative-feedback control mechanism guarantees the synchronization when multiple grid-forming inverters work in parallel. In addition, the controller shown in Fig. 3 (a) also prevents the output power of the inverter from exceeding P_{max} or dropping below P_{min}. The *P-f* droop control also achieves load sharing between grid-forming inverters.

The *Q-V* droop control prevents large circulating reactive power between grid-forming inverters. As shown in Fig. 3 (b), the *Q-V* droop control guarantees that the magnitude of grid-side voltage has a predefined *Q-V* droop characteristic by regulating E_{droop}, through a proportional-integral controller. In addition, there is also a Q_{max} and Q_{min} controller to prevent the inverter reactive power output from exceeding Q_{max} or dropping below Q_{min}.



(a)



(b)

Fig. 3 Droop control. (a) *P-f* droop control and overload mitigation control. (b) *Q-V* droop control.

When interacting with the transmission network solver, the per unit values of P, Q, V on the system rating base returned by the network solver need to be converted to the per unit values on the inverter rating base and pass through a low-pass filter as shown by (4) to (6), where S_{base} is the base value of the system rating, M_{base} is the base value of the inverter rating, and P_{inv}, Q_{inv}, and V_{inv} are the per unit values of inverter output active power, reactive power, and voltage magnitude on the inverter rating base. The outputs of the controller, E_{droop} and δ_{droop}, are used to determine the inverter internal voltage $E\angle\delta_E$.

$$P_{inv} = \frac{1}{1+T_{Pf}s} P \frac{S_{base}}{M_{base}} \quad (4)$$

$$Q_{inv} = \frac{1}{1+T_{Qf}s} Q \frac{S_{base}}{M_{base}} \quad (5)$$

$$V_{inv} = \frac{1}{1+T_{Vf}s} V \quad (6)$$

3.3 Fault Current Limiting Function

During normal operations, the droop control will control the inverter voltage magnitude and phase angle. However, during short circuit faults, the fault current limiting function will be activated to limit the output current of the inverter. Fig. 4 shows the fault current limiting function. The inverter works in the droop control mode during normal operations and keeps monitoring its output current $I\angle\varphi$. The output current $I\angle\varphi$ is calculated using (7) in each simulation step. When the magnitude of the output current I is smaller than the inverter maximum current limit I_{max}, the inverter internal voltage is governed by the droop control so that $E\angle\delta_E = E_{droop}\angle\delta_{droop}$. However, once I exceeds I_{max} because of severe faults, the inverter internal voltage $E\angle\delta_E$ will be calculated based on the inverter terminal voltage $V\angle\delta_V$, the coupling reactance X_L, and the new current phasor $I_{max}\angle\varphi$ as shown by Fig. 4. By doing so the magnitude of the inverter output current I will be limited at I_{max} during faults, but its phase angle φ will remain unchanged compared to the case without the fault current limiting function. Once the fault is cleared, the inverter output current will drop below I_{max} so that the operation mode will autonomously switch back to the droop control mode.

$$I\angle\varphi = \frac{E_{droop}\angle\delta_{droop} - V\angle\delta_V}{jX_L} \quad (7)$$

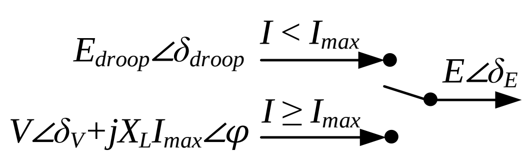


Fig. 4 Fault current limiting function.

4.0 Interface with the Transmission Network Solver

When interfacing with the transmission network solver, the inverter internal voltage source needs to be converted to its Norton equivalent circuit for the network solution, as shown in Fig. 2 (a) and (b). Equation (8) and (9) are used for the conversion.

$$I_N \angle \varphi_N = \frac{E \angle \delta_E}{jX_L} \quad (8)$$

$$Y_L = \frac{1}{X_L} \quad (9)$$

The flowchart in Fig. 5 shows the process of how the developed positive-sequence phasor model interacts with the transmission network solver.

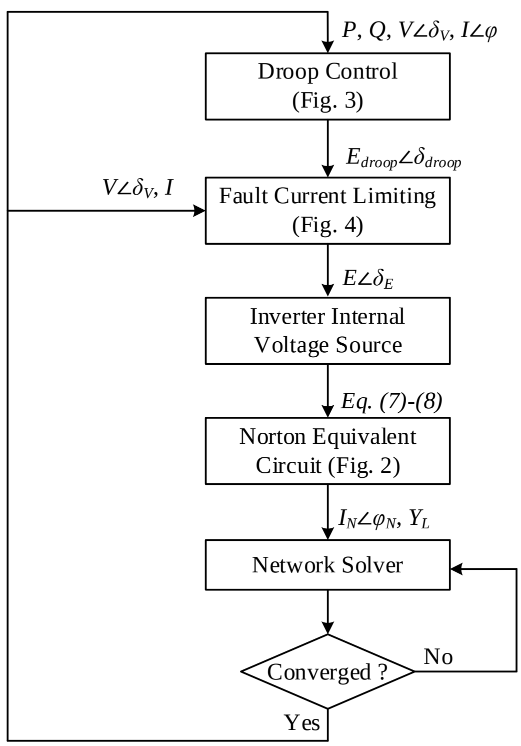


Fig. 5 Interaction between the grid-forming inverter model and the transmission network solver.

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