Microrredes Eléctricas

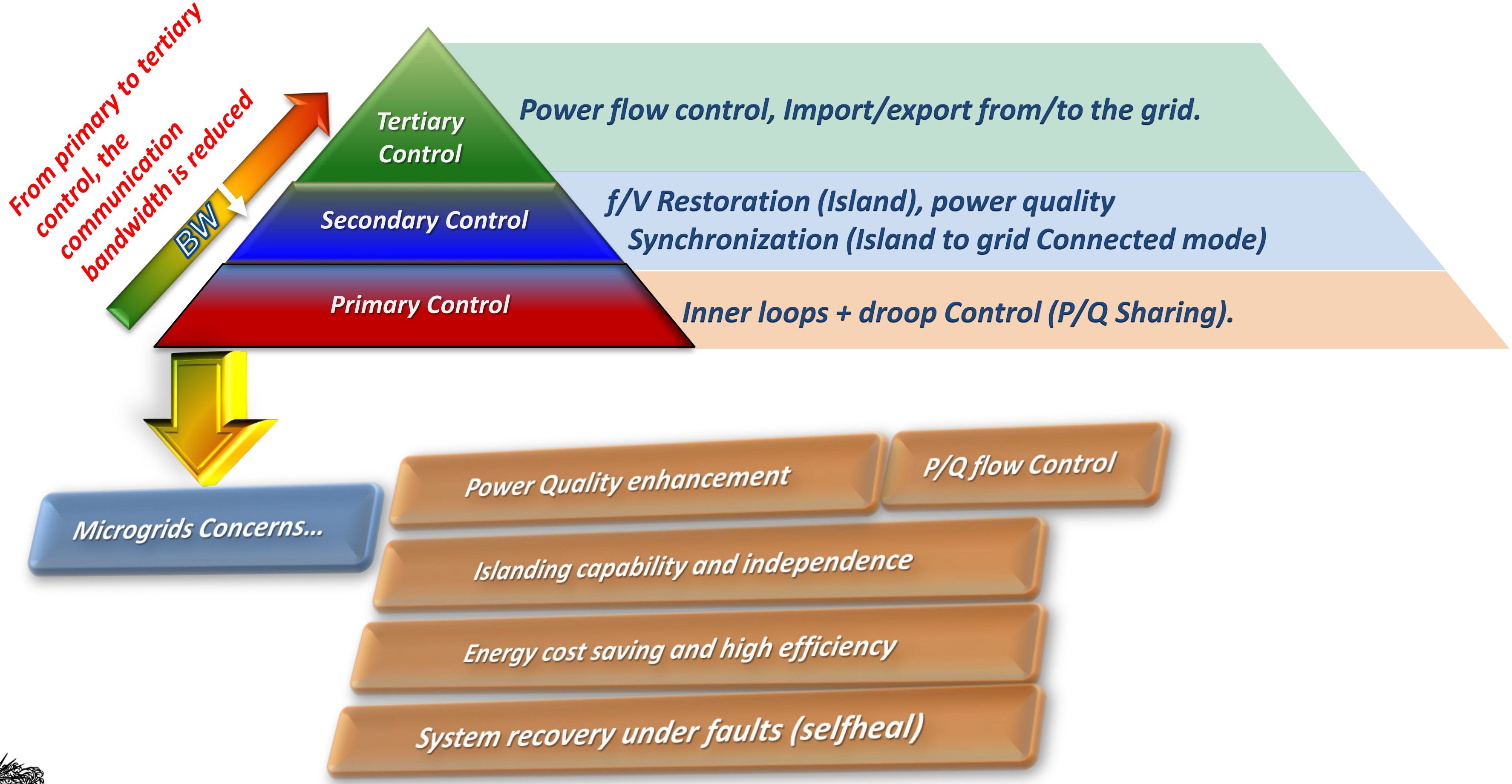
Tema 4
Hierarchical Control

1. Hierarchical Control Review.
2. Primary Control.
    1. AC Microgrids.
    2. DC Microgrids.

1. Hierarchical Control

1. Hierarchical Control

Clasic Approach (Hierarchical Control Scheme)



From primary to tertiary control, the communication bandwidth is reduced

Tertiary Control — *Power flow control, Import/export from/to the grid.*

Secondary Control — *f/V Restoration (Island), power quality Synchronization (Island to grid Connected mode)*

Primary Control — *Inner loops + droop Control (P/Q Sharing).*

Microgrids Concerns…

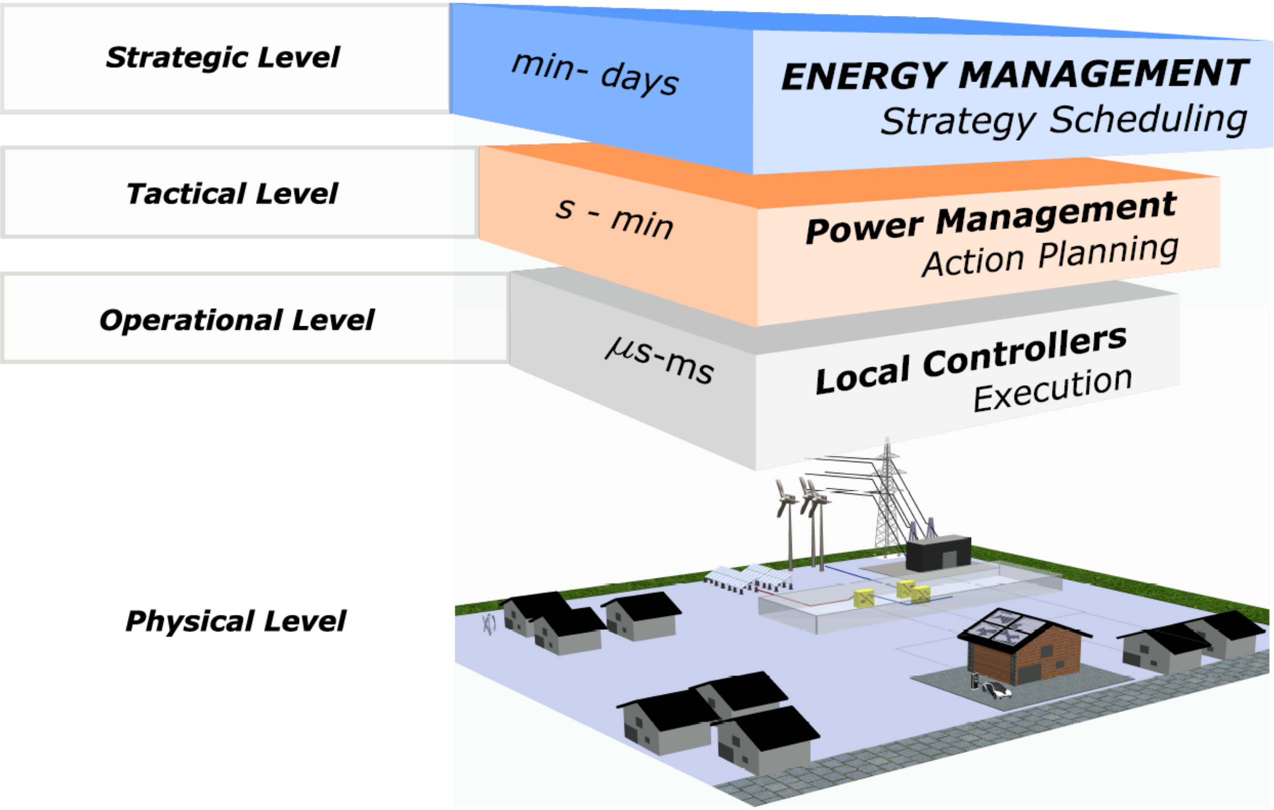
- *Power Quality enhancement*
- *P/Q flow Control*
- *Islanding capability and independence*
- *Energy cost saving and high efficiency*
- *System recovery under faults (selfheal)*

1. Hierarchical Control

Approach from Management Point of View

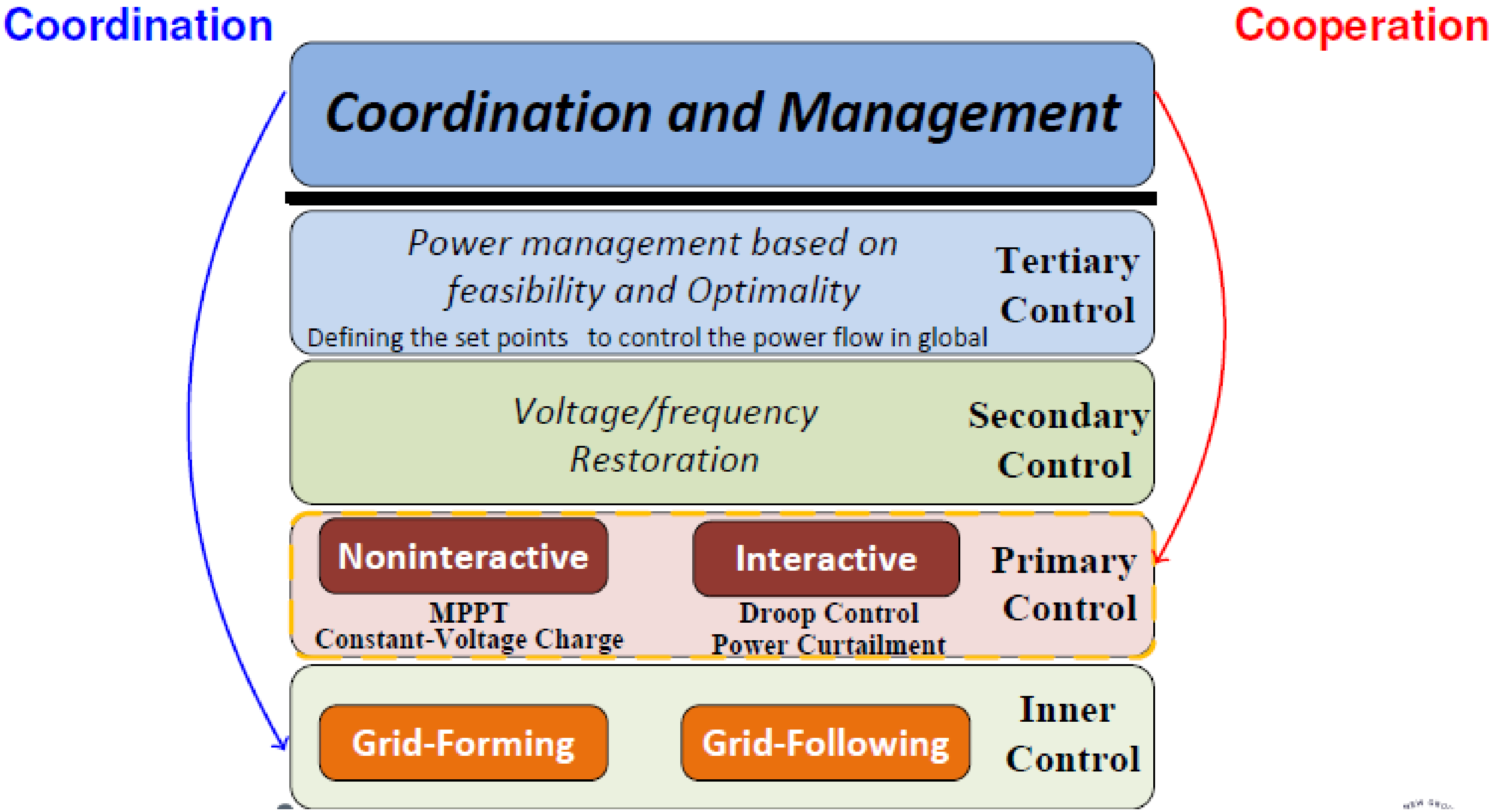
Classical Management Hierarchy

Hierarchy for Microgrids Management and Operation



1. Hierarchical Control

Approach from a Operative Point of View



Coordination

Cooperation

Coordination and Management

Power management based on feasibility and Optimality

Defining the set points to control the power flow in global

Tertiary Control

Voltage/frequency Restoration

Secondary Control

Noninteractive

MPPT
Constant-Voltage Charge

Interactive

Droop Control
Power Curtailment

Primary Control

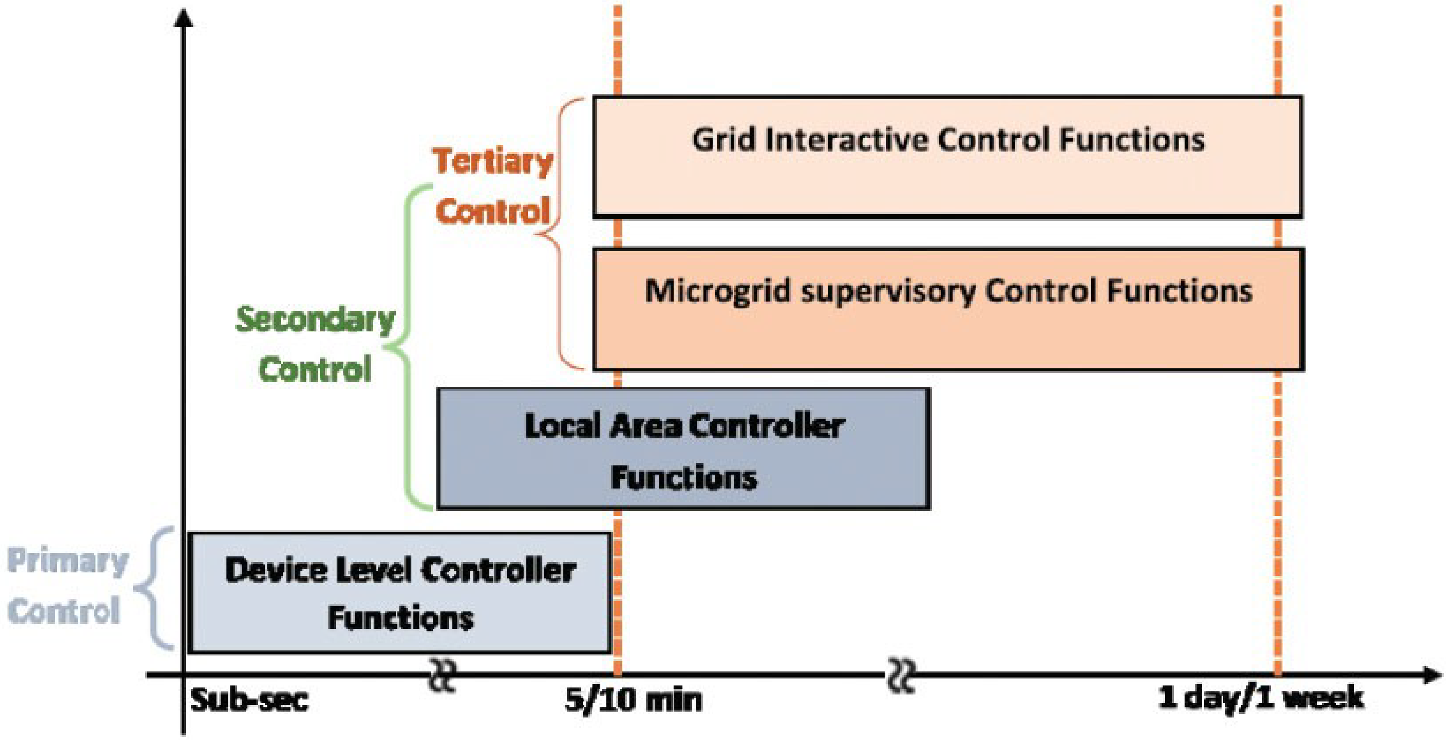
Grid-Forming

Grid-Following

Inner Control

1. Hierarchical Control

IEEE Std 2030.7-2017
IEEE Standard for the Specification of Microgrid Controllers



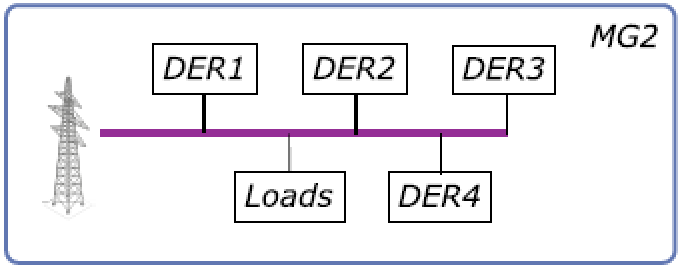
Inner Control Loops

1. Hierarchical Control

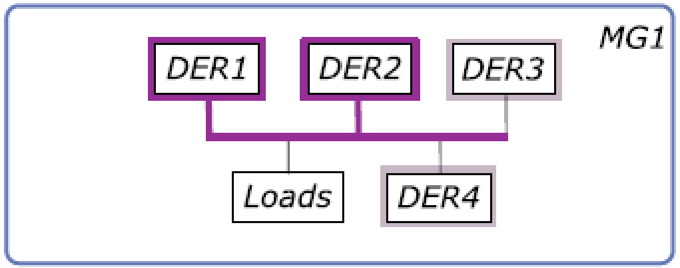
Inner Control Loops

- Grid-Forming. Assumed by DERs with enough capacity.
- Grid-Following. Aligned to a formed grid.

Seguidores de Red (Grid-following)



Formadores de Red (Grid-forming)



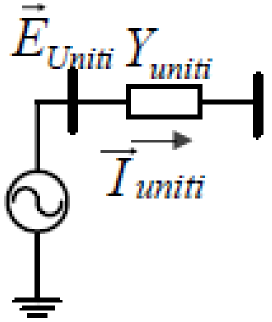
➢ **Grid Forming Controls:**
- Voltage. (VCM).
- Frequency.
- Power Sharing.

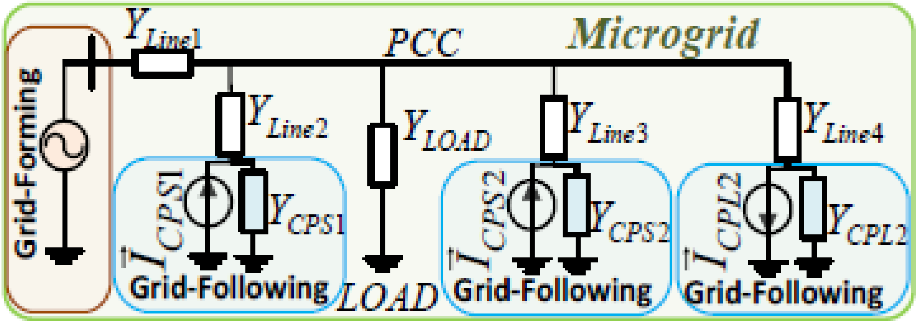
➢ **Grid-Following Controls:**
- Power Export.
- Power Dispatch.
- Reactive power support

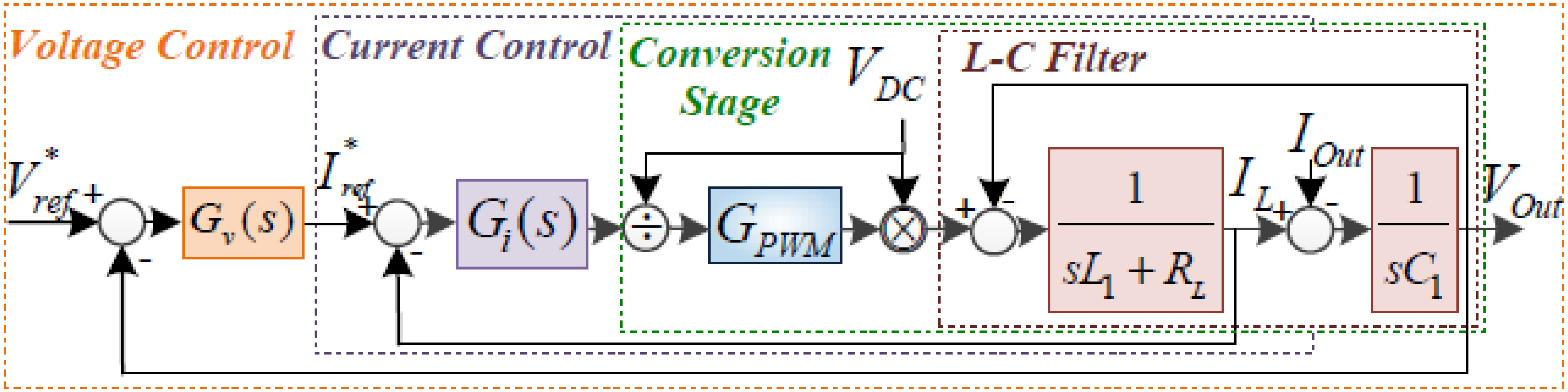
1. Hierarchical Control

Grid-Forming

Grid-Forming





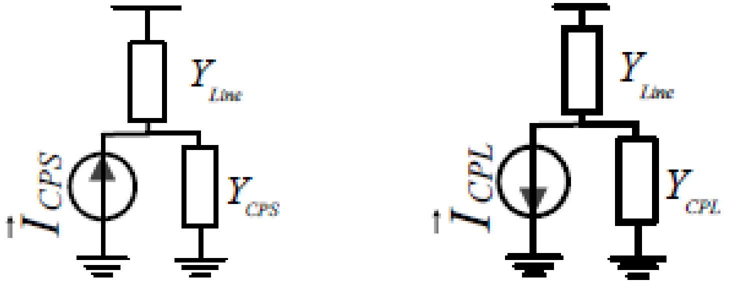


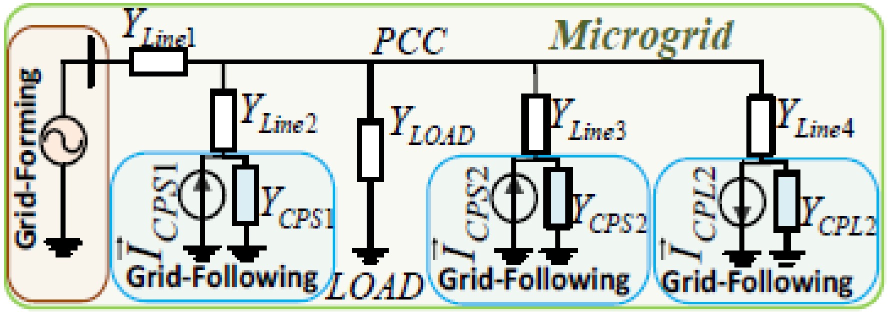
Voltage Control Mode (VCM)

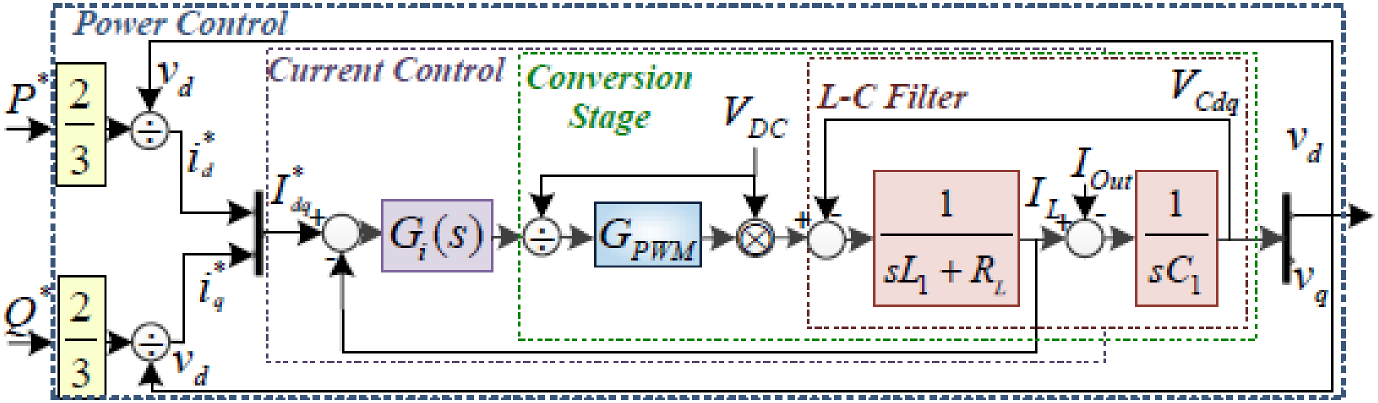
1. Hierarchical Control

Grid-Following

Grid-Following





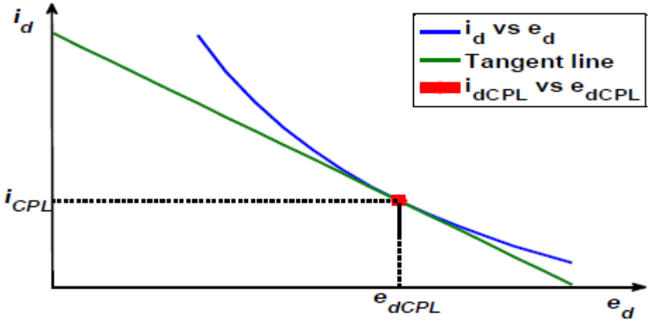


Current Control Mode (CCM)

Grid-Following

The i-v curve for CPS or CPL can be approximated by a straight line tangent to the curve at the operating point.

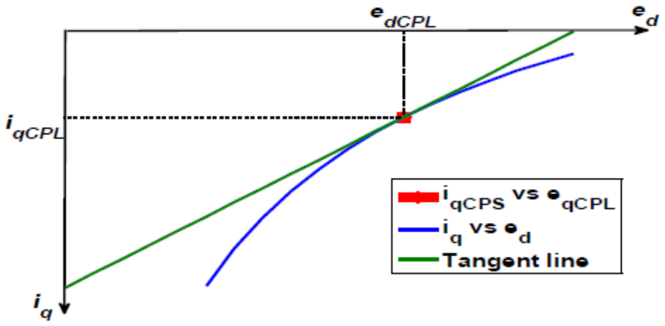
CPL (P)



$$i_{dCPXi} = \frac{2}{3}\frac{P_{CPX}}{e_{dCPXi}}$$

$$\hat{i}_{dCPXi} = -\frac{2}{3}\frac{P_{CPX}}{e^2_{dCPXi}}\hat{e}_{dCPXi} + 2\frac{2}{3}\frac{P_{CPX}}{e_{dCPXi}}$$

CPL (Q)



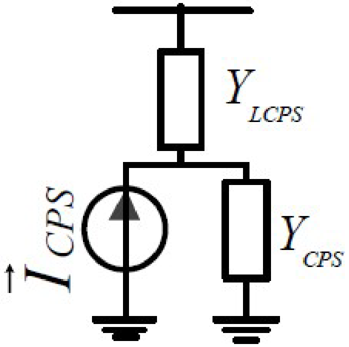
$$i_{qCPXi} = \frac{2}{3}\frac{Q_{CPX}}{e_{dCPXi}}$$

$$\hat{i}_{qCPXi} = -\frac{2}{3}\frac{Q_{CPX}}{e^2_{dCPXi}}\hat{e}_{dCPXi} + 2\frac{2}{3}\frac{Q_{CPX}}{e_{dCPXi}}$$

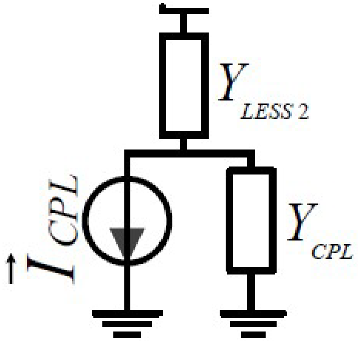
Grid-Following

- CPS and CPL can be approximated by an admittance in parallel with a constant current source.
- Reversed sign of (P) will yield to opposite signs in currents and admittance.

CPS



CPL



$$Y_{CPXi} = \frac{1}{-\frac{3}{2}\frac{e^2_{dCPXi}}{P_{CPX}} - j\frac{3}{2}\frac{e^2_{dCPXi}}{Q_{CPX}}}$$

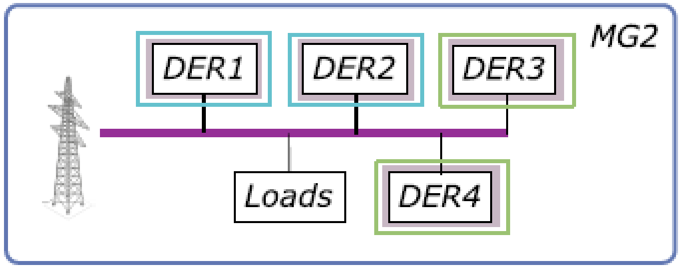
$$\vec{I}_{CPXi} = 2\frac{2}{3}\frac{P_{CPX}}{e_{dCPXi}} + j2\frac{2}{3}\frac{Q_{CPX}}{e_{dCPXi}}$$

1. Hierarchical Control

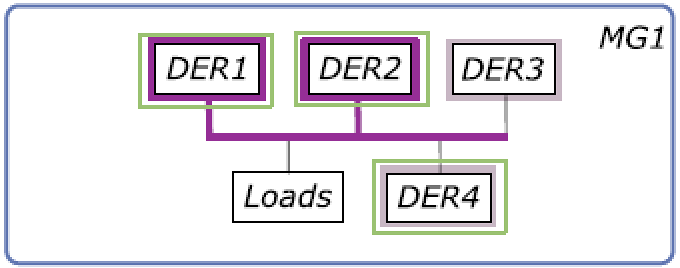
Primary Control

- Grid-interactive. Droop Control and Power Dispatch
- Grid-noninteractive. MPPT and Constant-Voltage Charge

Grid-noninteractive



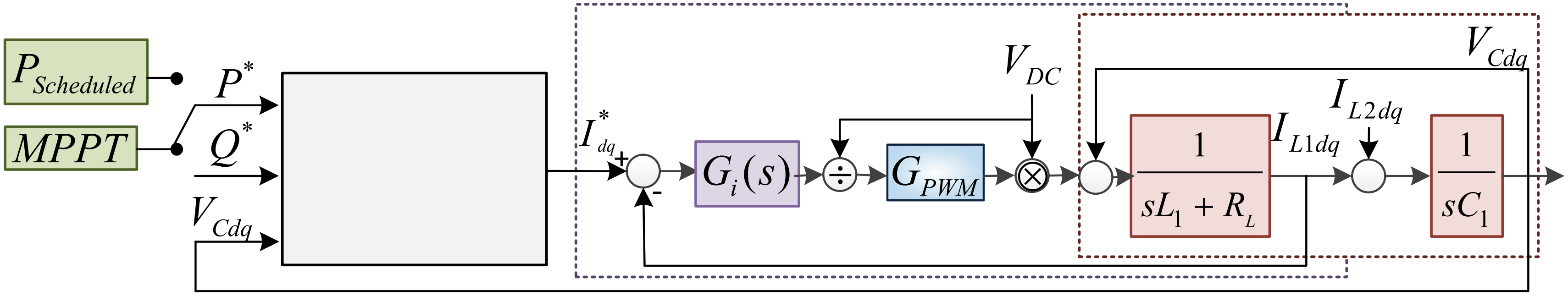
Grid-Interactive



- **Grid-noninteractive:**
  - Power Export.
  - MPPT.
  - Constant Battery Charge.
  - Voltage. (VCM).
  - Frequency.
- **Grid Interactive:**
  - Power Sharing.
  - Power Dispatch.
  - Reactive power Support
  - Power Curtailment.

1. Hierarchical Control

Example



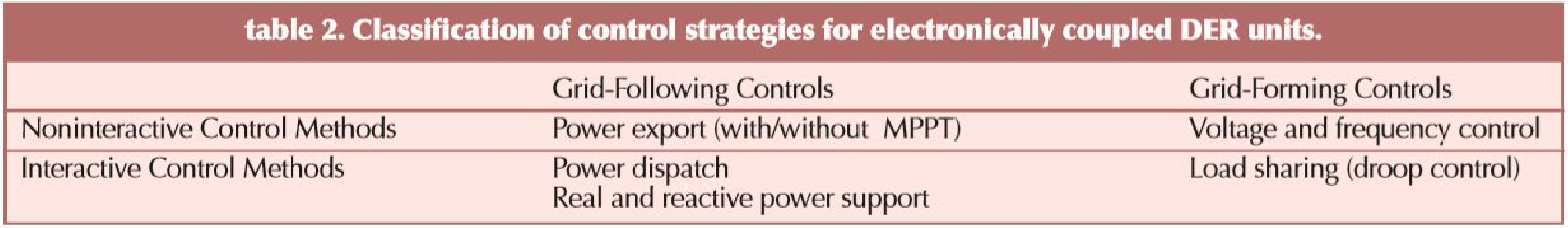


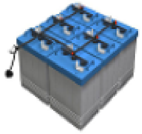
table 2. Classification of control strategies for electronically coupled DER units.

	Grid-Following Controls	Grid-Forming Controls
Noninteractive Control Methods	Power export (with/without MPPT)	Voltage and frequency control
Interactive Control Methods	Power dispatch Real and reactive power support	Load sharing (droop control)

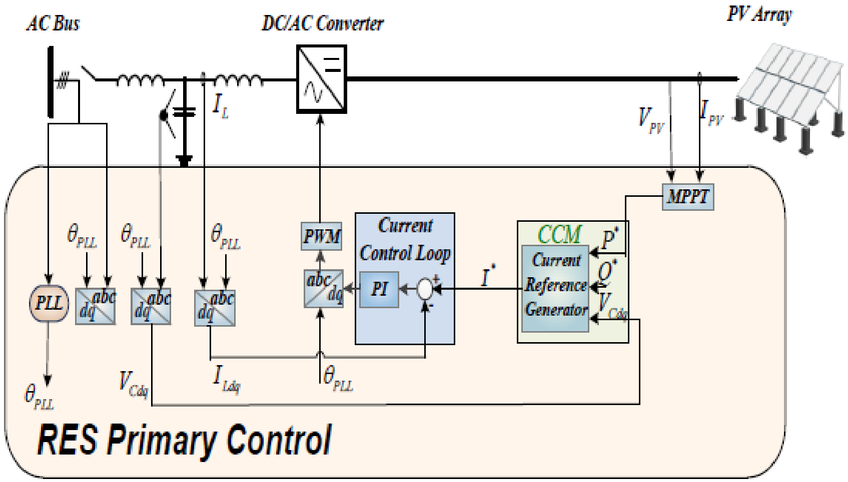
6 Katiraei, F.; Iravani, R.; Hatziargyriou, N. & Dimeas, A. “Microgrids management”, IEEE Power and Energy Magazine, 2008

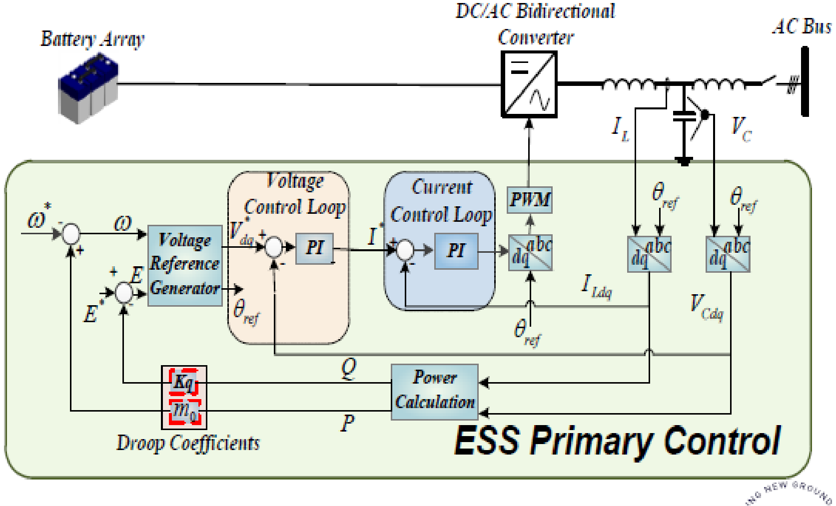
1. Hierarchical Control

- RES are more likely to operate under MPPT algorithms.
- Grid-following, Current control mode (CCM).



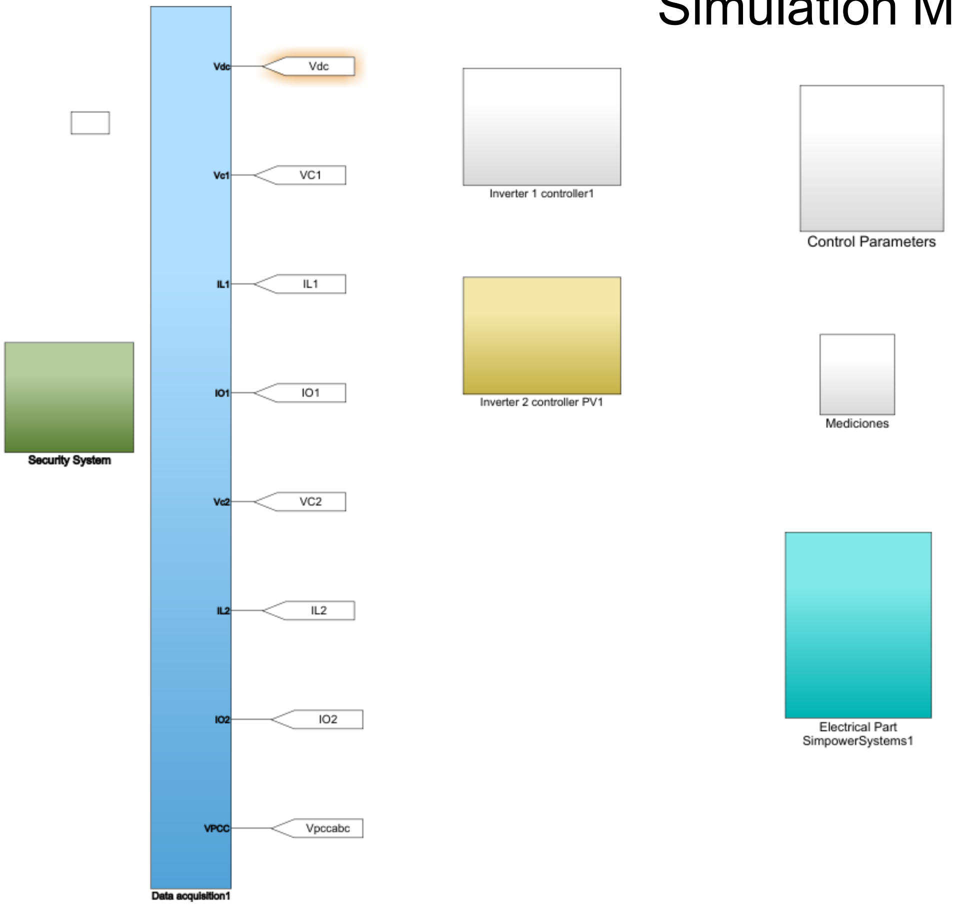
- Commonly, ESS are the Grid-forming units.
- ESSs are responsible of power balance and common bus regulation.

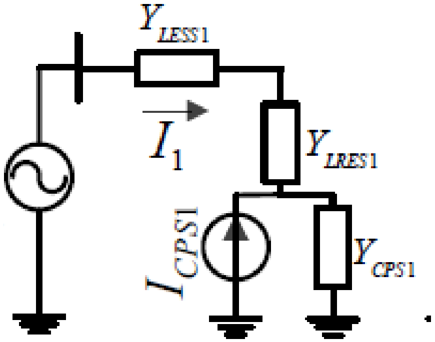




Simulation 1

Simulation Model

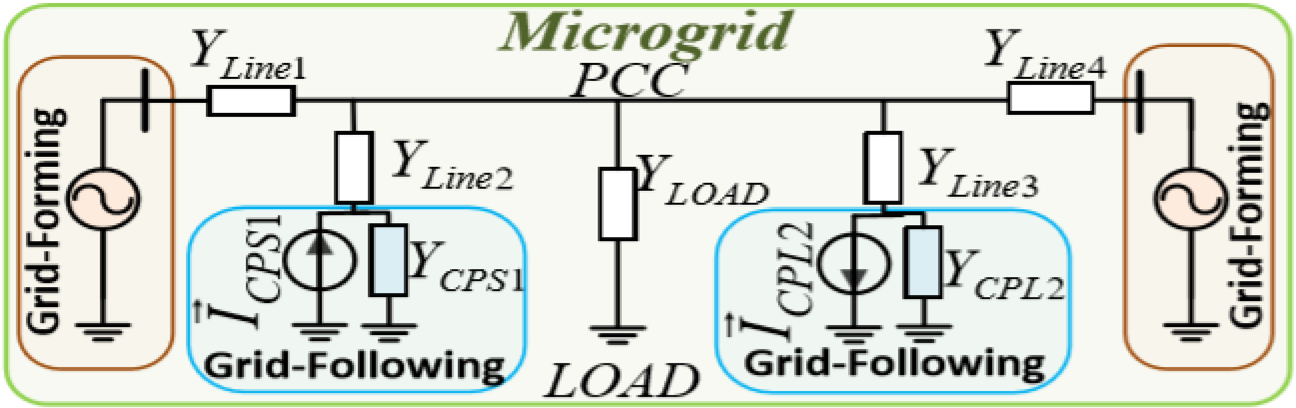




Primary Control

2. Primary Control

Two or more grid-forming units may operate simultaneously in an islanded microgrid.



Distributed grid-forming units can share the load demand and concurrently respond to variations in the microgrid load. Commonly, droop control loops are used to share power between distributed units in VCM.

3.2 Power Sharing methods between Grid forming Units.

Active Methods (power/current) :

- ✓ Centralized
- ✓ Master-Slave
- ✓ Circular Chain Control (3C)
- ✓ Average load Sharing

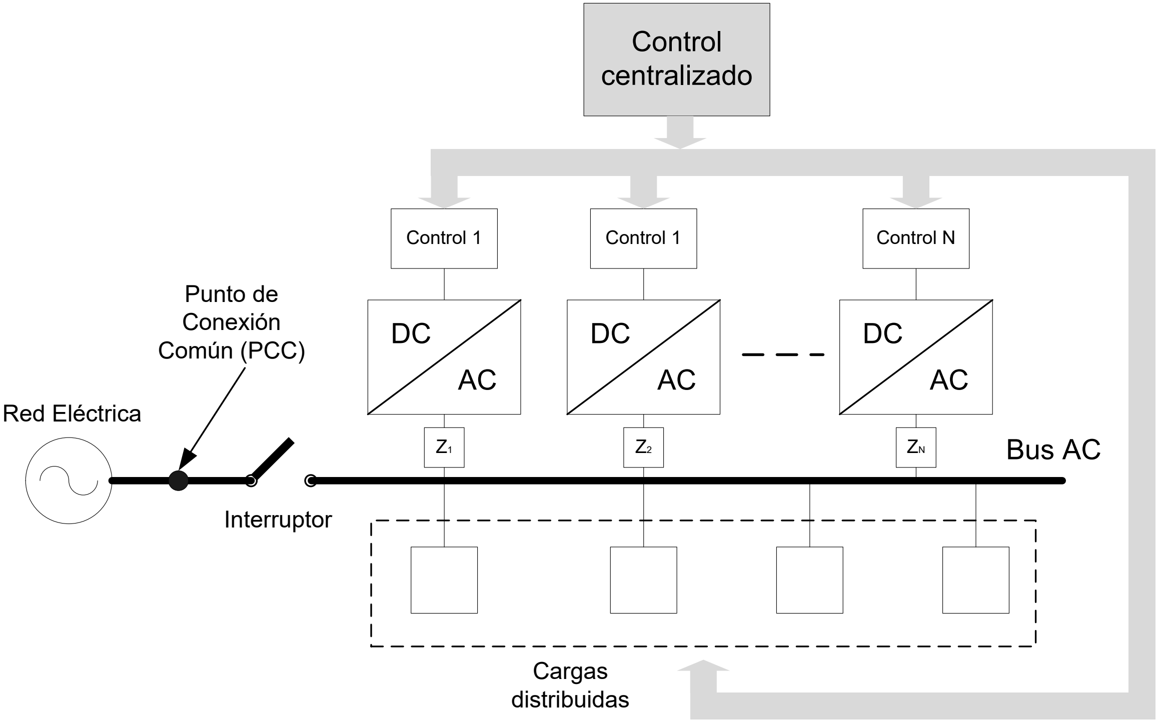
Wireless Methods:

- ✓ High Frequency signals by PLC
- ✓ Droop Control.

2. Primary Control

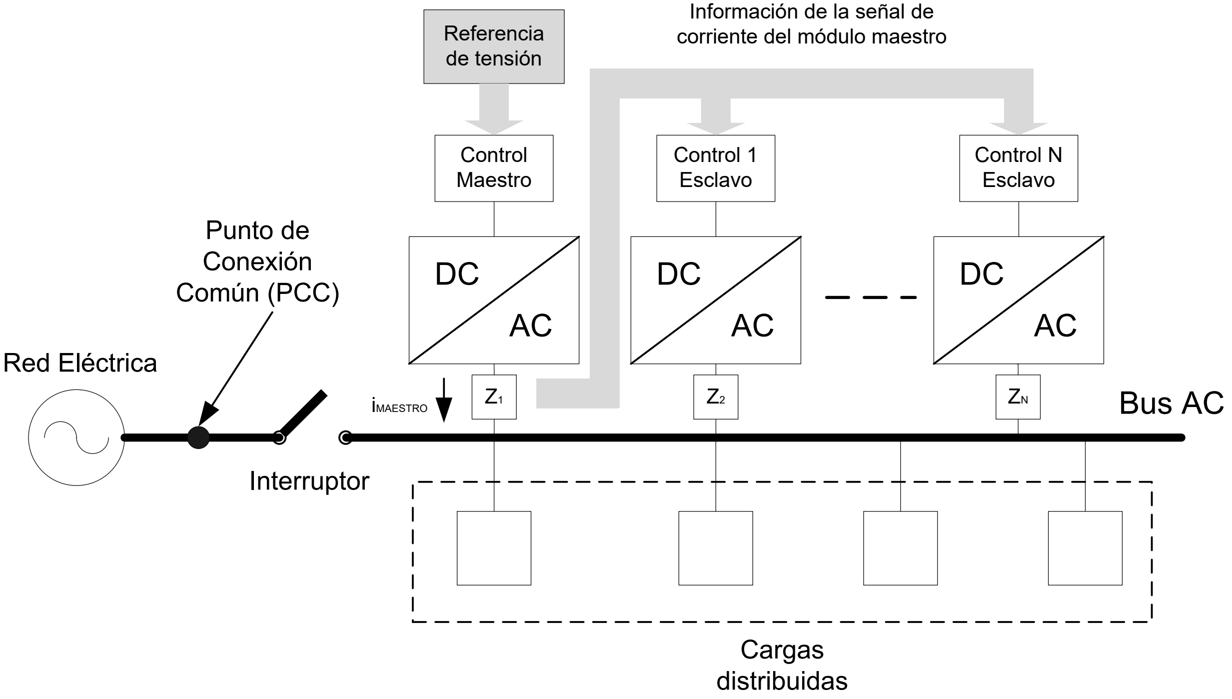
Active Methods (power/current) :

- ✓ **Centralized Control**



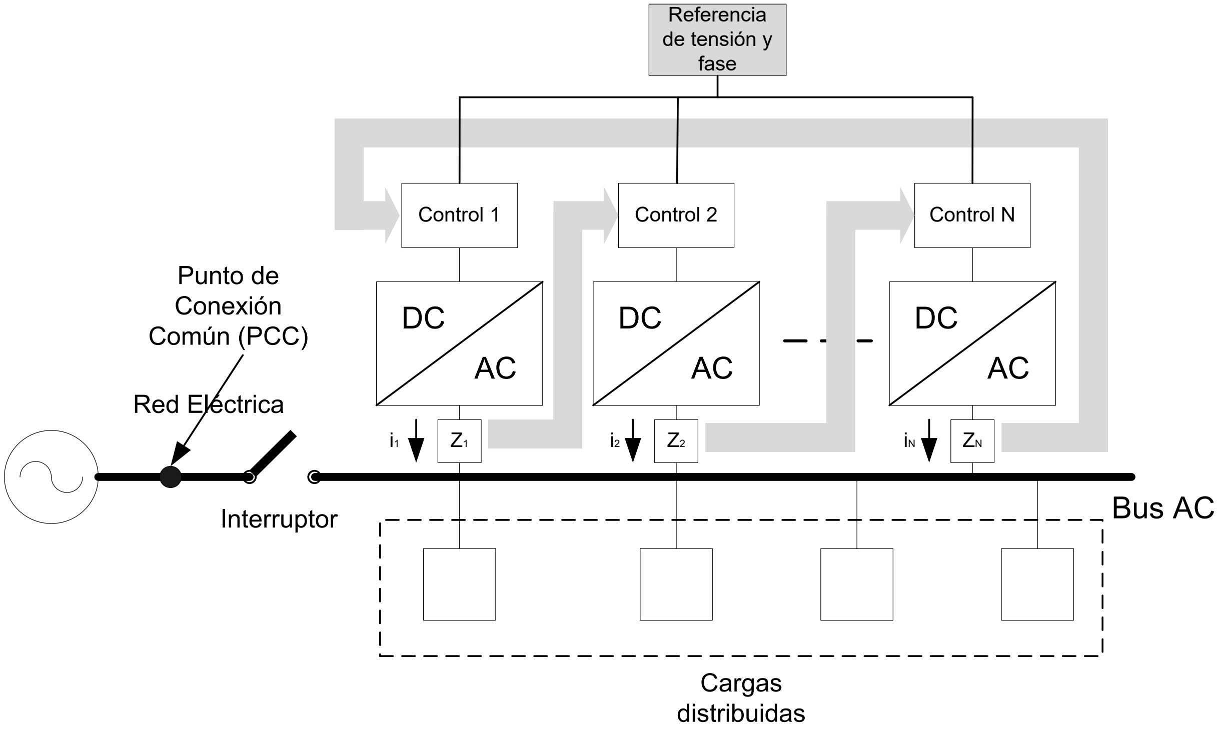
2. Primary Control

- ✓ **Master-Slave**



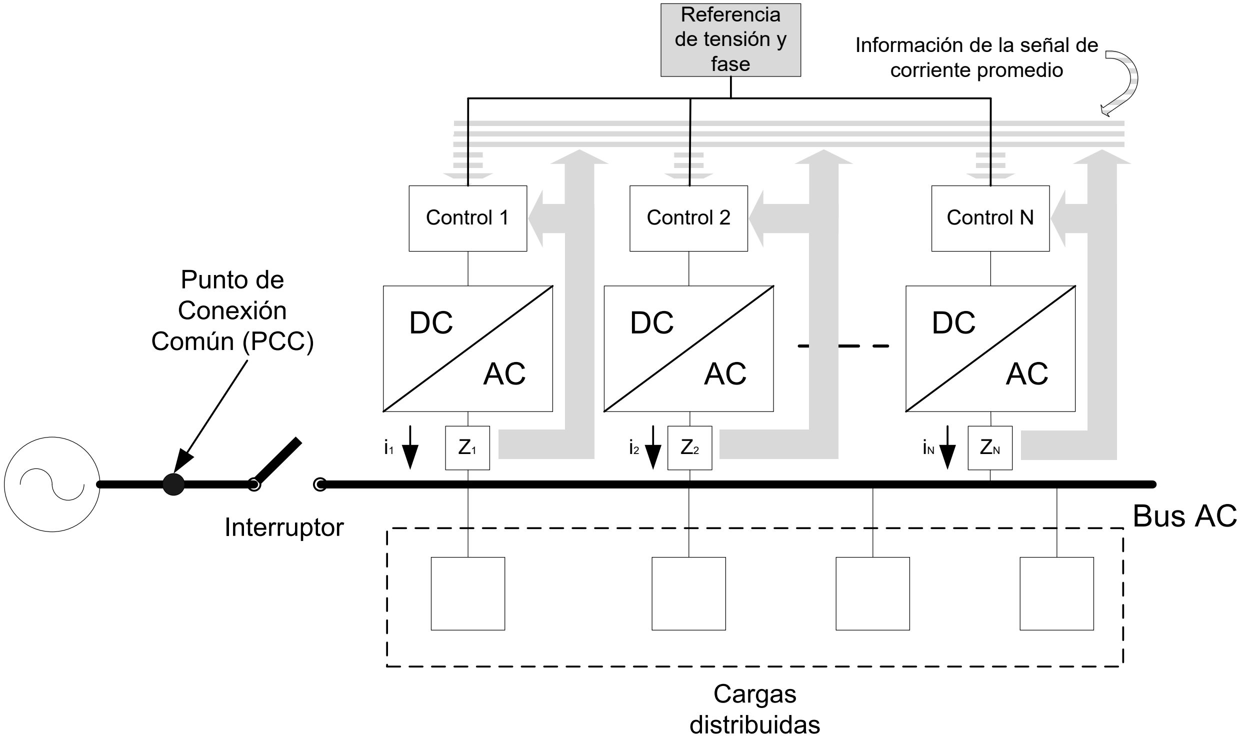
2. Primary Control

✓ Circular Chain Control (3C)



2. Primary Control

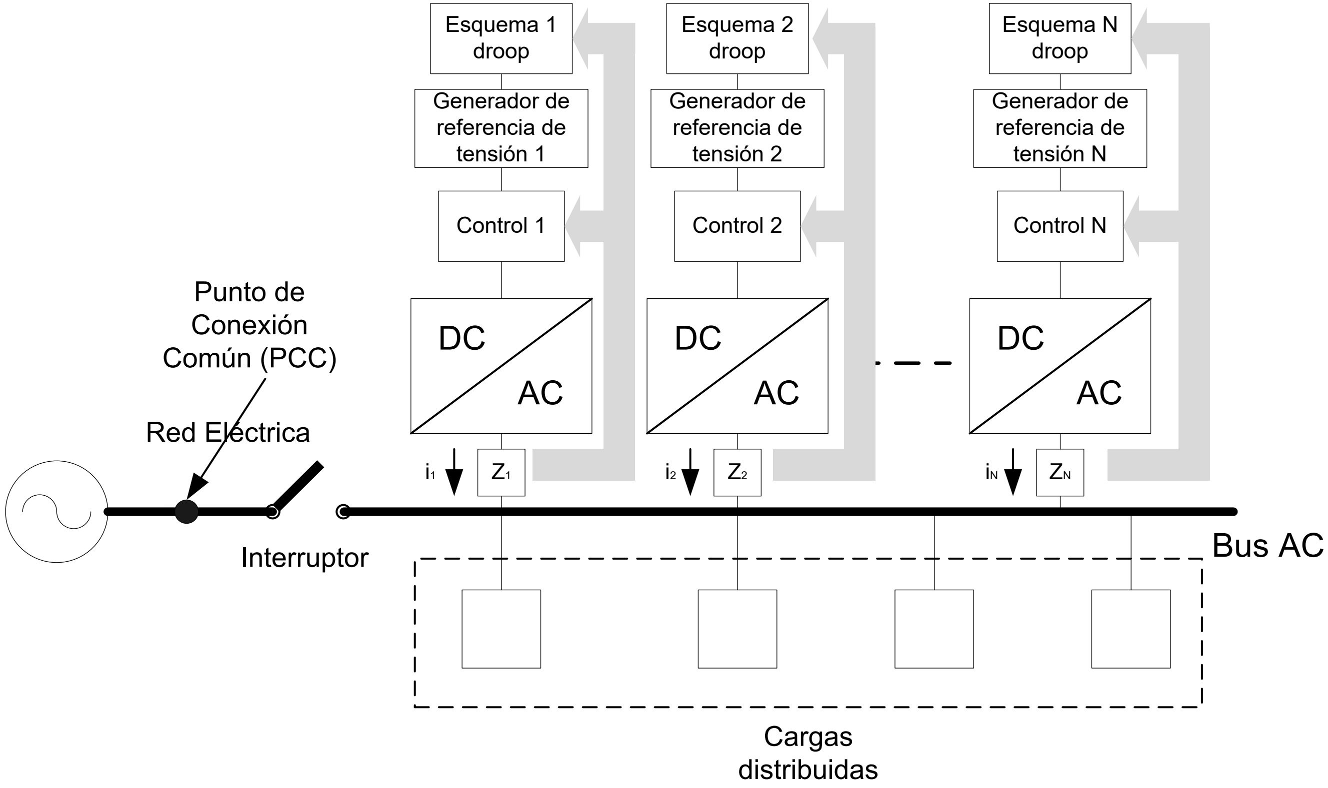
- ✓ **Average load Sharing**



2. Primary Control

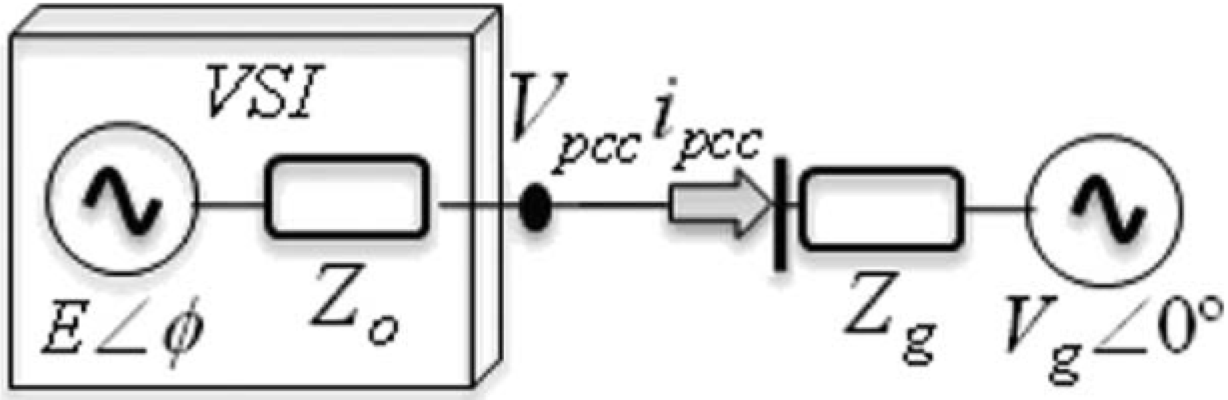
Wireless Methods:

- ✓ **Droop Control**



2. Primary Control

Power Flow Analysis

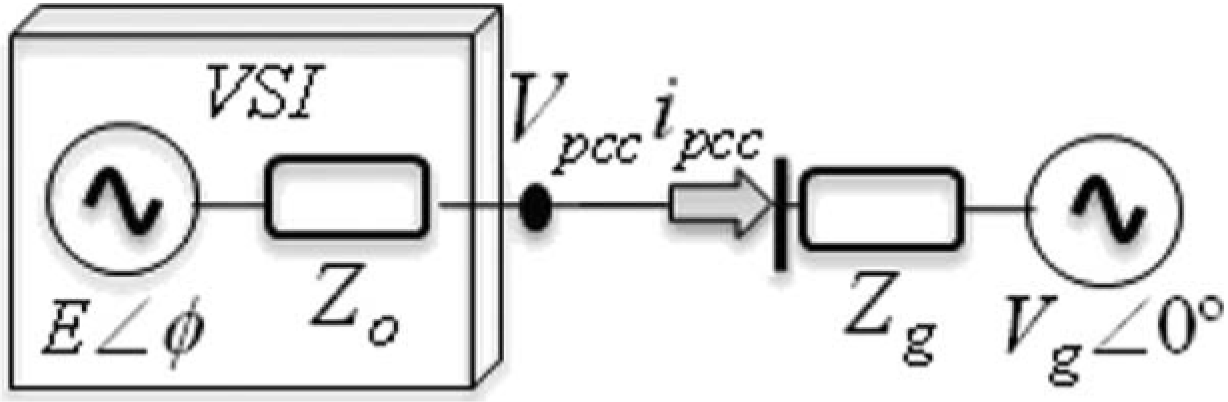


$$P = \frac{1}{Z_g}\left[\left(EV_g\cos\phi - V_g^2\right)\cos\theta_g + EV_g\sin\phi\sin\theta_g\right]$$

$$Q = \frac{1}{Z_g}\left[\left(EV_g\cos\phi - V_g^2\right)\sin\theta_g - EV_g\sin\phi\cos\theta_g\right]$$

2. Primary Control

For Inductive Lines



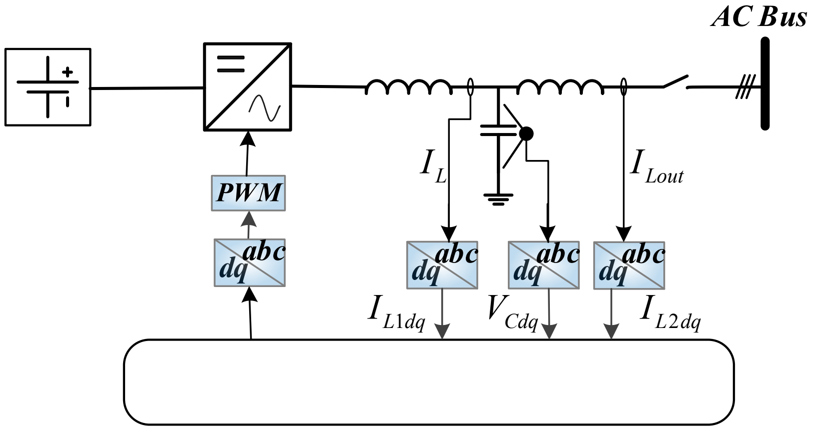
$$P = \frac{EV_g}{Z_g}\sin(\emptyset)$$

$$Q = \frac{EV_g cos(\emptyset) - V_g^2}{Z_g}$$

J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodriguez and R. Teodorescu, "Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes," in *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4088-4096, Oct. 2009.

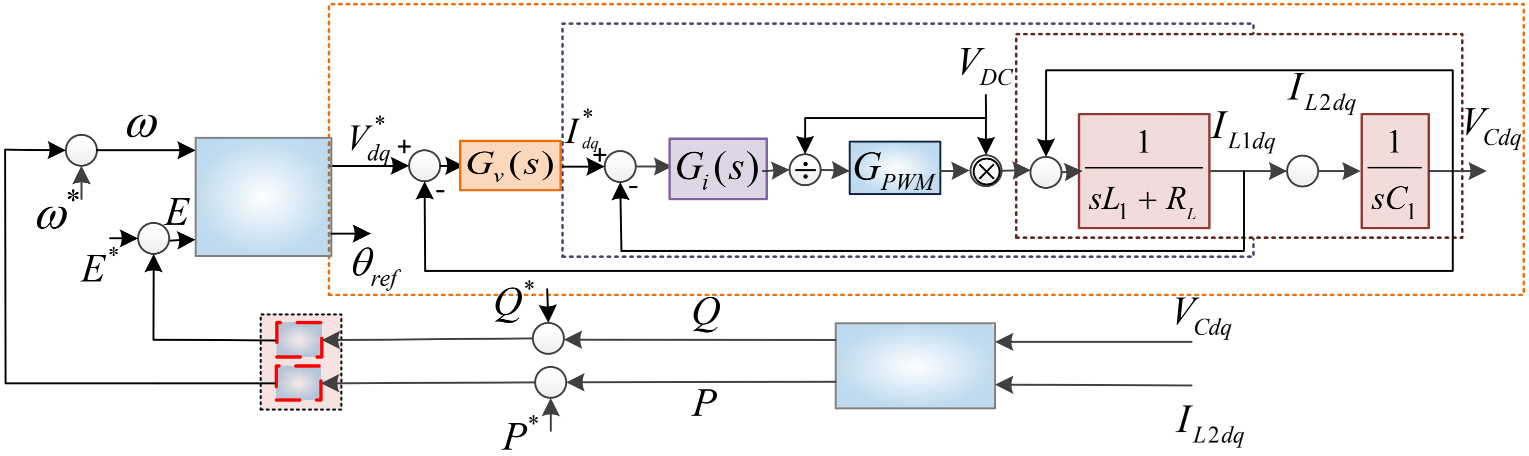
1. Droop Control

The conventional voltage control loop incorporates a external power loop based on droop Characteristics



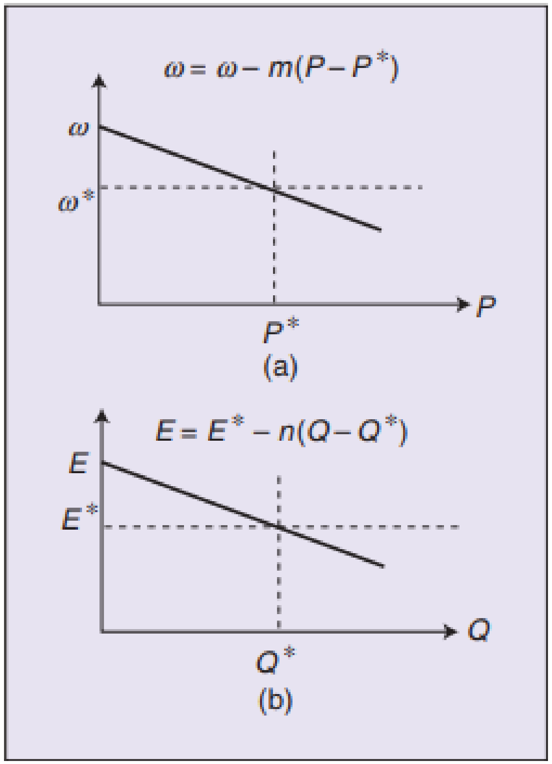
$$\omega = \omega^* - m(P - P^*)$$

$$E = E^* - n(Q - Q^*),$$



1. Droop Control

Droop Characteristics



$$\omega = \omega^{*} - m(P - P^{*})$$

$$E = E^{*} - n(Q - Q^{*}),$$

Apply only for Inductive Lines

J. C. Vasquez, J. M. Guerrero, J. Miret, M. Castilla and L. Garcia de Vicuna, "Hierarchical Control of Intelligent Microgrids," in *IEEE Industrial Electronics Magazine*, vol. 4, no. 4, pp. 23-29, Dec. 2010.

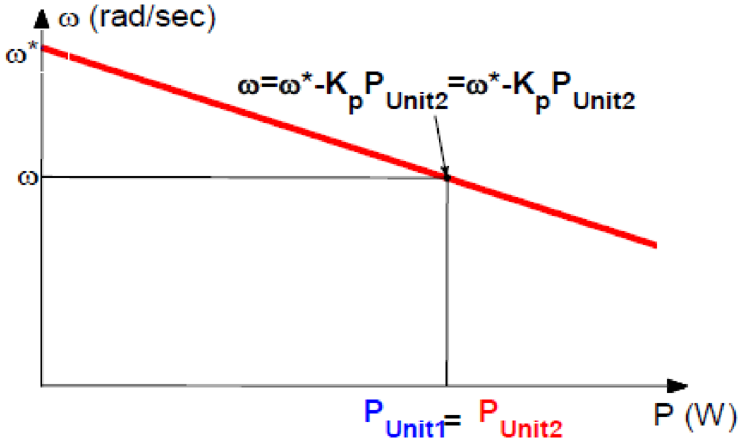
1. Droop Control

Droop Characteristics

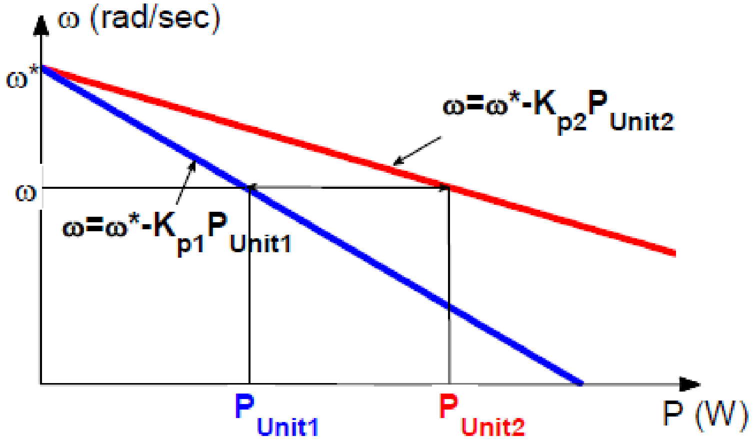
$$\omega_{ref} = \omega^* - K_p \cdot P_{Uniti}$$

$$E_{ref} = E^* - K_q \cdot Q_{Uniti}$$

Active power can be equally shared between units



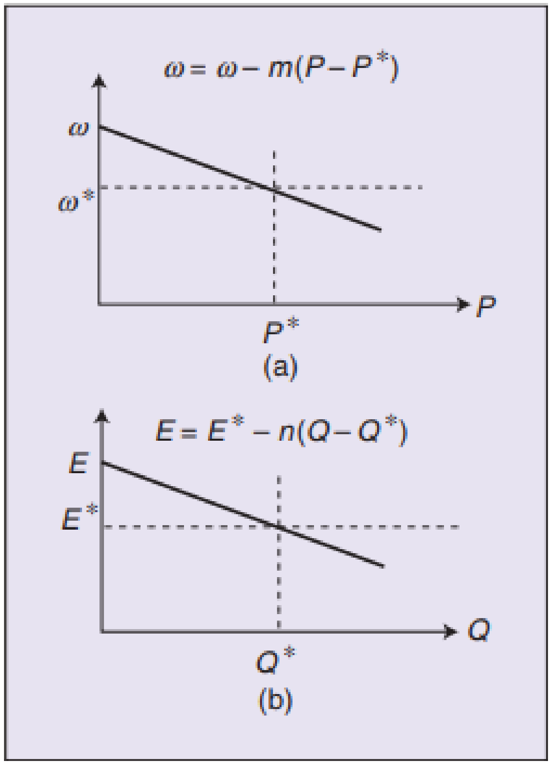
Power sharing can be adjusted with different K_p



The droop characteristic determines the proportion of shared power and the contribution level of each DER.

1. Droop Control

Droop Calculations



$$m_P = \frac{f_i - f_{\min}}{P_i - P_{i,\max}}$$

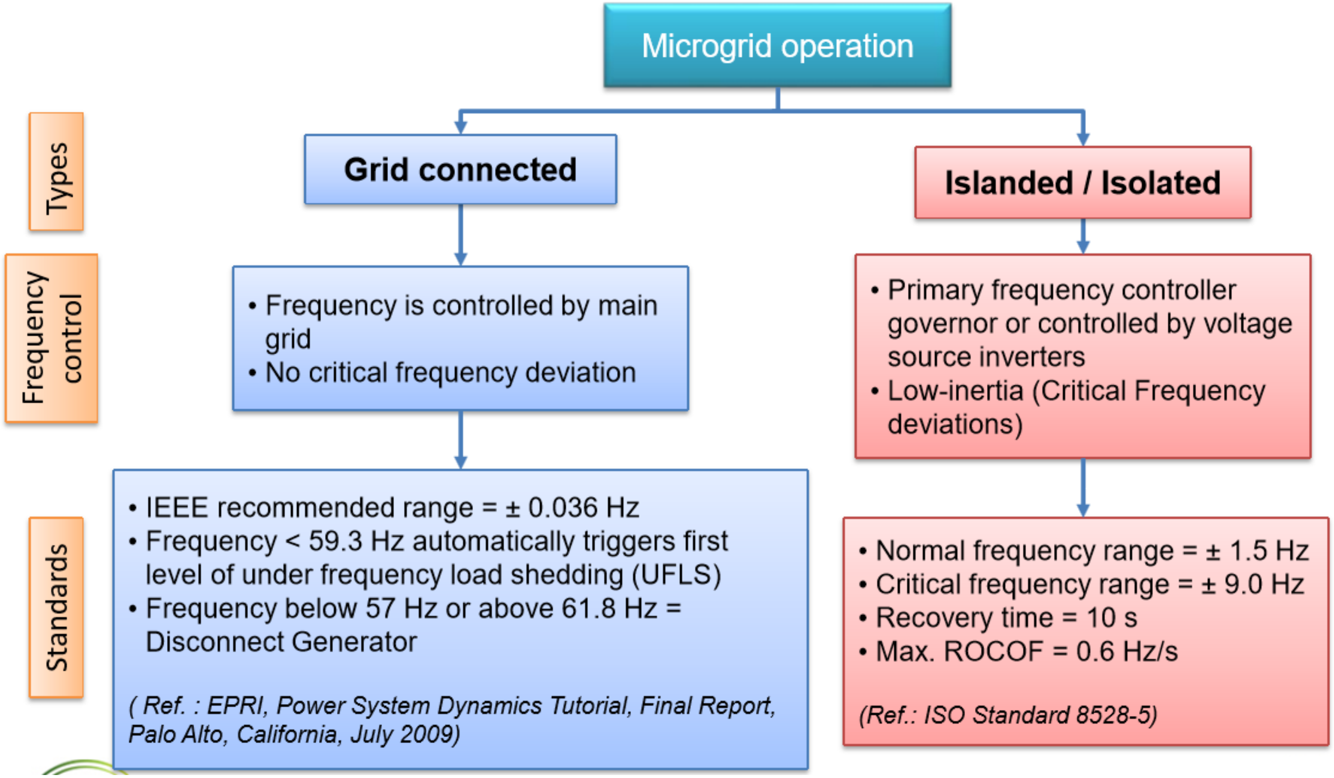
$$n_Q = \frac{E_{i,\max} - E_{i,\min}}{Q_{i,\min} - Q_{i,\max}}.$$

However it my compromise the stability of the system

J. C. Vasquez, J. M. Guerrero, J. Miret, M. Castilla and L. Garcia de Vicuna, "Hierarchical Control of Intelligent Microgrids," in *IEEE Industrial Electronics Magazine*, vol. 4, no. 4, pp. 23-29, Dec. 2010.

1. Droop Control

There is a trade-off between power sharing and Frequency Regulation



Microgrid operation

Types

Grid connected

Islanded / Isolated

Frequency control

- Frequency is controlled by main grid
- No critical frequency deviation

- Primary frequency controller governor or controlled by voltage source inverters
- Low-inertia (Critical Frequency deviations)

Standards

- IEEE recommended range = ± 0.036 Hz
- Frequency < 59.3 Hz automatically triggers first level of under frequency load shedding (UFLS)
- Frequency below 57 Hz or above 61.8 Hz = Disconnect Generator

(Ref. : EPRI, Power System Dynamics Tutorial, Final Report, Palo Alto, California, July 2009)

- Normal frequency range = ± 1.5 Hz
- Critical frequency range = ± 9.0 Hz
- Recovery time = 10 s
- Max. ROCOF = 0.6 Hz/s

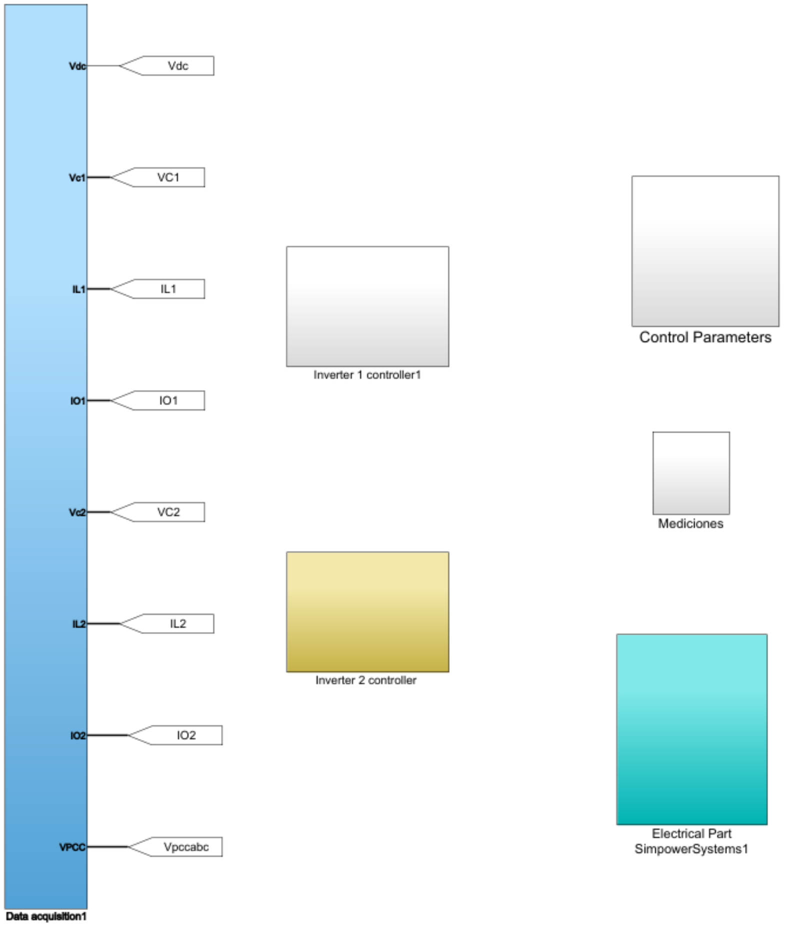
(Ref.: ISO Standard 8528-5)

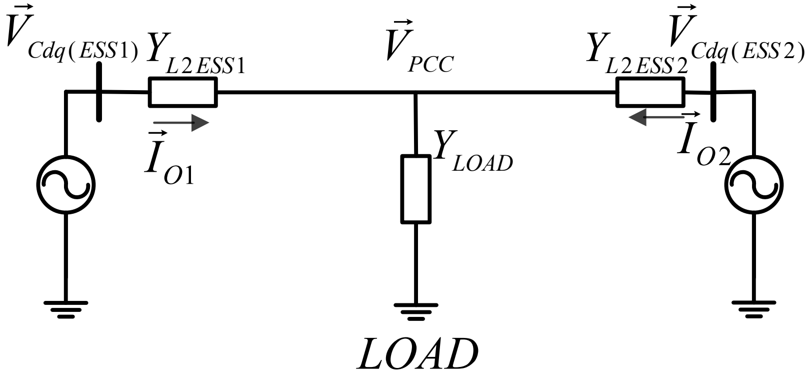
$\Delta\omega_{max} = 2\%$ EN 50160 $\Delta E_{max} = 5\%$

J. C. Vasquez, J. M. Guerrero, J. Miret, M. Castilla and L. Garcia de Vicuna, "Hierarchical Control of Intelligent Microgrids," in *IEEE Industrial Electronics Magazine*, vol. 4, no. 4, pp. 23-29, Dec. 2010.

2. Droop Control

Simulation Exercise





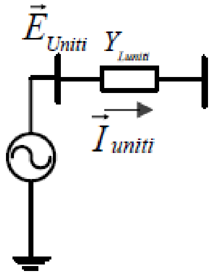
$$m_P = \frac{f_i - f_{\min}}{P_i - P_{i,\max}}$$

$$n_Q = \frac{E_{i,\max} - E_{i,\min}}{Q_{i,\min} - Q_{i,\max}}.$$

2. Stability Analysis

- The small signal model of a single distributed generator operating as grid-forming unit is defined as:

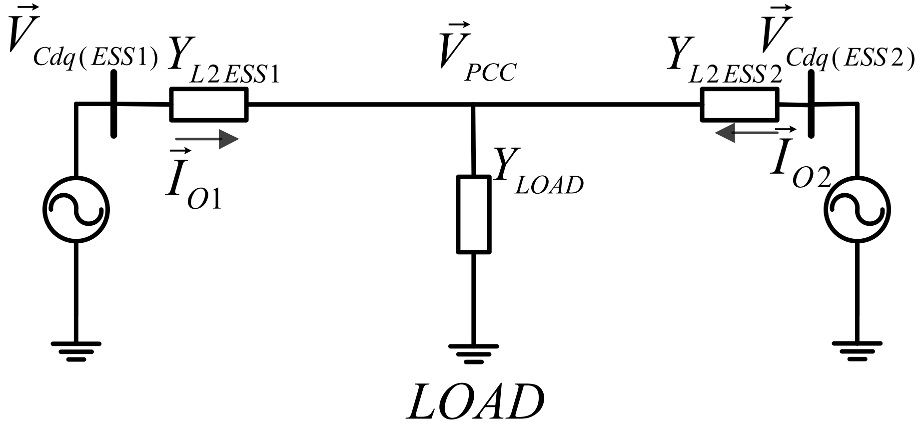
$$\begin{bmatrix} \Delta\dot{\omega}_i \\ \Delta\dot{e}_{di} \\ \Delta\dot{e}_{qi} \end{bmatrix} = [M_i] \begin{bmatrix} \Delta\omega_i \\ \Delta e_{di} \\ \Delta e_{qi} \end{bmatrix} + [C_i] \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}$$



$$\vec{E} = e_d + je_q$$

$$[C_i] = \begin{bmatrix} -K_p\omega_f & 0 \\ 0 & \dfrac{K_q m_q\omega_f}{m_d n_q - m_q n_d} \\ 0 & \dfrac{K_q m_d\omega_f}{m_q n_d - m_d n_q} \end{bmatrix}$$

2. Stability Analysis



$$\begin{bmatrix} \vec{I}_1 \\ \vec{I}_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & -Y_{12} \\ -Y_{21} & Y_{22} \end{bmatrix} \times \begin{bmatrix} \vec{E}_{ESS1} \\ \vec{E}_{ESS2} \end{bmatrix}$$

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$
2.

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \end{bmatrix} = \frac{3}{2} \begin{bmatrix} i_{d1} & i_{q1} & 0 & 0 \\ i_{q1} & -i_{d1} & 0 & 0 \\ 0 & 0 & i_{d2} & i_{q2} \\ 0 & 0 & i_{q2} & -i_{d2} \end{bmatrix} \times \begin{bmatrix} \Delta e_{d1} \\ \Delta e_{q1} \\ \Delta e_{d2} \\ \Delta e_{q2} \end{bmatrix}$$

$$+ \frac{3}{2} \begin{bmatrix} e_{d1} & e_{q1} & 0 & 0 \\ -e_{q1} & e_{d1} & 0 & 0 \\ 0 & 0 & e_{d2} & e_{q2} \\ 0 & 0 & -e_{q2} & e_{d2} \end{bmatrix} \times \begin{bmatrix} \Delta i_{d1} \\ \Delta i_{q1} \\ \Delta i_{d2} \\ \Delta i_{q2} \end{bmatrix}$$

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$
3. $[\Delta S] = [Is][\Delta e] + [Es][\Delta i]$ Substituting 1 in 3.

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$
3. $[\Delta S] = [Is][\Delta e] + [Es][\Delta i]$ Substituting 1 in 3.
4. $[\Delta S] = ([Is] + [Es][Ys])[\Delta e]$

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$
3. $[\Delta S] = [Is][\Delta e] + [Es][\Delta i]$ Substituting 1 in 3.
4. $[\Delta S] = ([Is] + [Es][Ys])[\Delta e]$
5. $\begin{bmatrix} \Delta\dot{\omega}_1 \\ \Delta\dot{e}_{d1} \\ \Delta\dot{e}_{q1} \\ \Delta\dot{\omega}_2 \\ \Delta\dot{e}_{d2} \\ \Delta\dot{e}_{q2} \end{bmatrix} = \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \times \begin{bmatrix} \Delta\omega_1 \\ \Delta e_{d1} \\ \Delta e_{q1} \\ \Delta\omega_2 \\ \Delta e_{d2} \\ \Delta e_{q2} \end{bmatrix} + \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \times \begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \end{bmatrix}$

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$
3. $[\Delta S] = [Is][\Delta e] + [Es][\Delta i]$ Substituting 1 in 3.
4. $[\Delta S] = ([Is] + [Es][Ys])[\Delta e]$

6. $[\Delta \dot{X}] = [Ms][\Delta X] + [Cs][\Delta S]$

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$
3. $[\Delta S] = [Is][\Delta e] + [Es][\Delta i]$ Substituting 1 in 3.
4. $[\Delta S] = ([Is] + [Es][Ys])[\Delta e]$

6. $[\Delta \dot{X}] = [Ms][\Delta X] + [Cs][\Delta S]$
7. $[\Delta \dot{X}] = [Ms][\Delta X] + [Cs]([Is] + [Es][Ys])[\Delta e]$

2. Stability Analysis

1. $[\Delta i] = [Ys][\Delta e]$
3. $[\Delta S] = [Is][\Delta e] + [Es][\Delta i]$ Substituting 1 in 3.
4. $[\Delta S] = ([Is] + [Es][Ys])[\Delta e]$

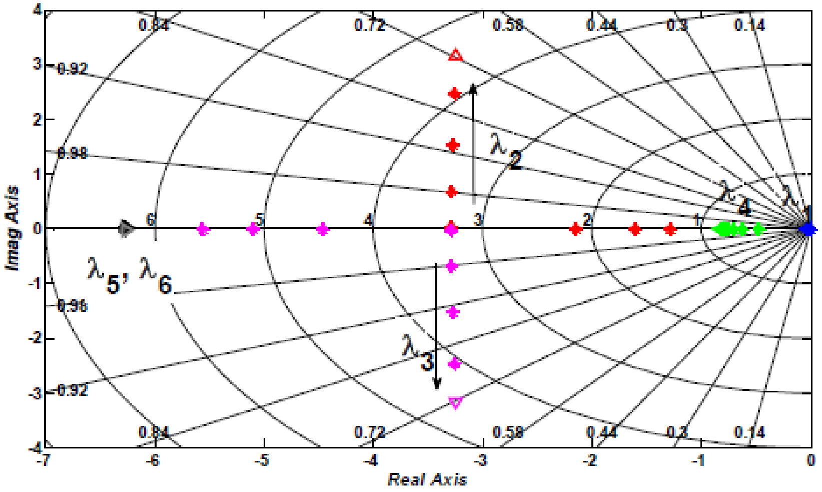
6. $[\Delta \dot{X}] = [Ms][\Delta X] + [Cs][\Delta S]$
7. $[\Delta \dot{X}] = [Ms][\Delta X] + [Cs]([Is] + [Es][Ys])[\Delta e]$

- It is obtained a linear model for the Isolated Microgrid
- $[\Delta \dot{X}] = [A1][\Delta X]$

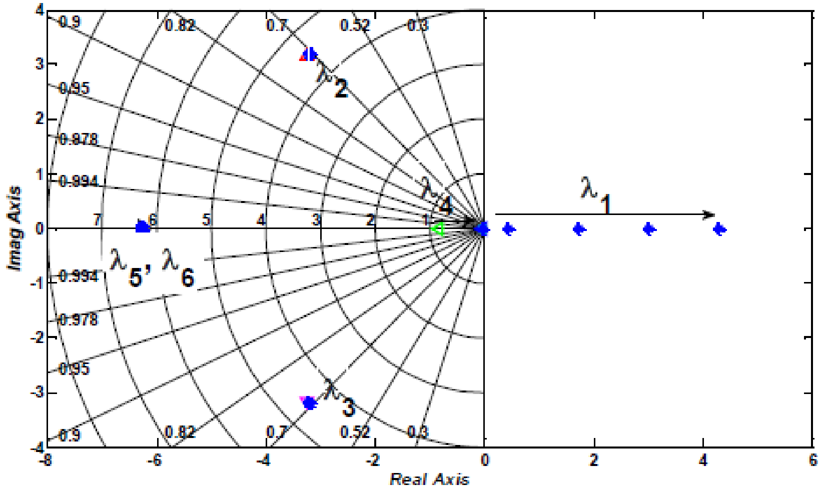
2. Stability Analysis

$$[\Delta \dot{X}] = [A1][\Delta X]$$

Root Locus plot for two Grid-Forming units varying $(P - \omega)$ droop coefficient K_p.

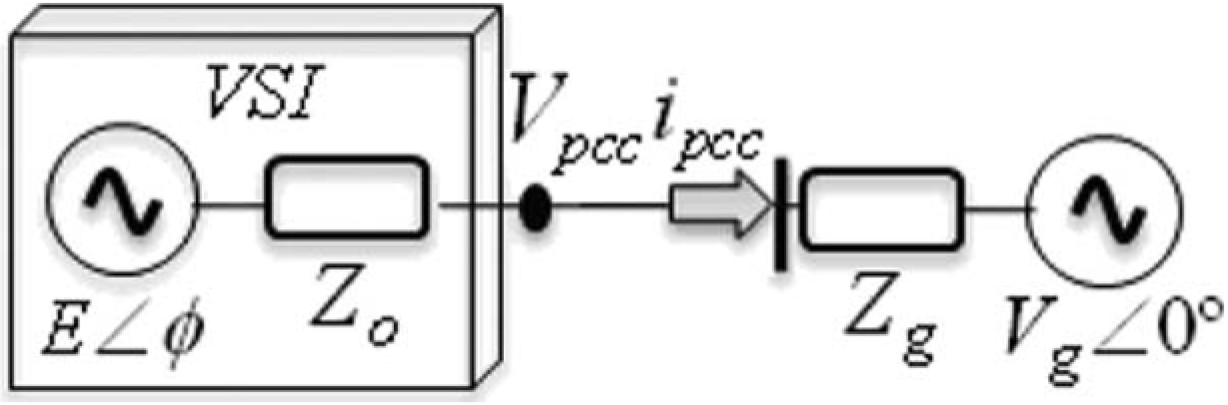


Root Locus plot for two Grid-Forming units varying $(Q - E)$ droop coefficient K_q.



2. Primary Control

For Resistive Lines

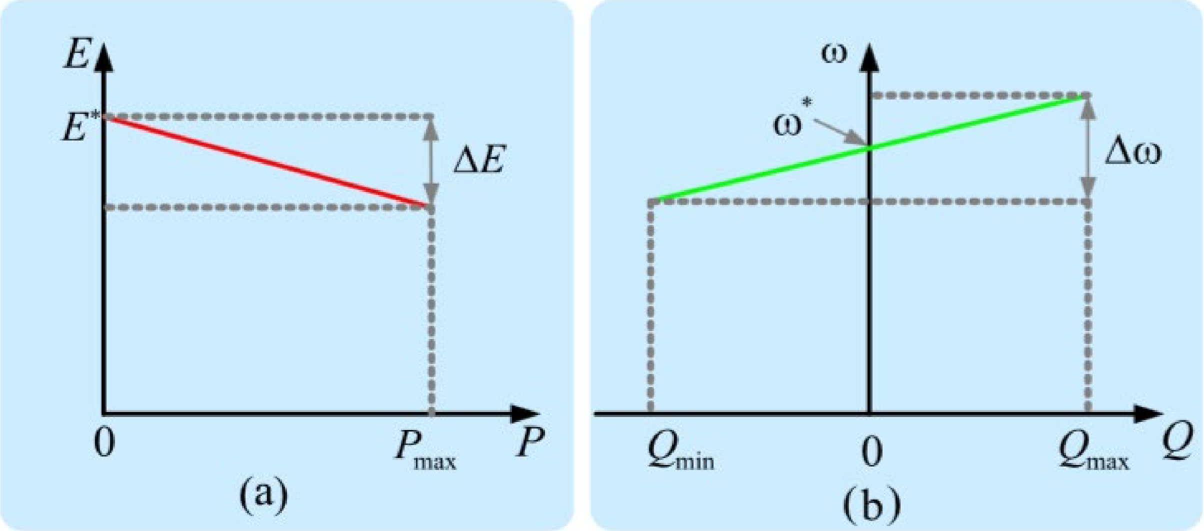


$$P = \frac{EV_g cos(\varnothing) - V_g^2}{Z_g}$$

$$Q = \frac{EV_g}{Z_g}\sin(\varnothing)$$

J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodriguez and R. Teodorescu, "Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes," in *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4088-4096, Oct. 2009.

Droop Characteristics Resistive line



$$\omega_i = \omega_{\text{rated}} + m_Q \cdot Q_i$$
$$E_i = E_{\text{rated}} - n_P \cdot P_i.$$

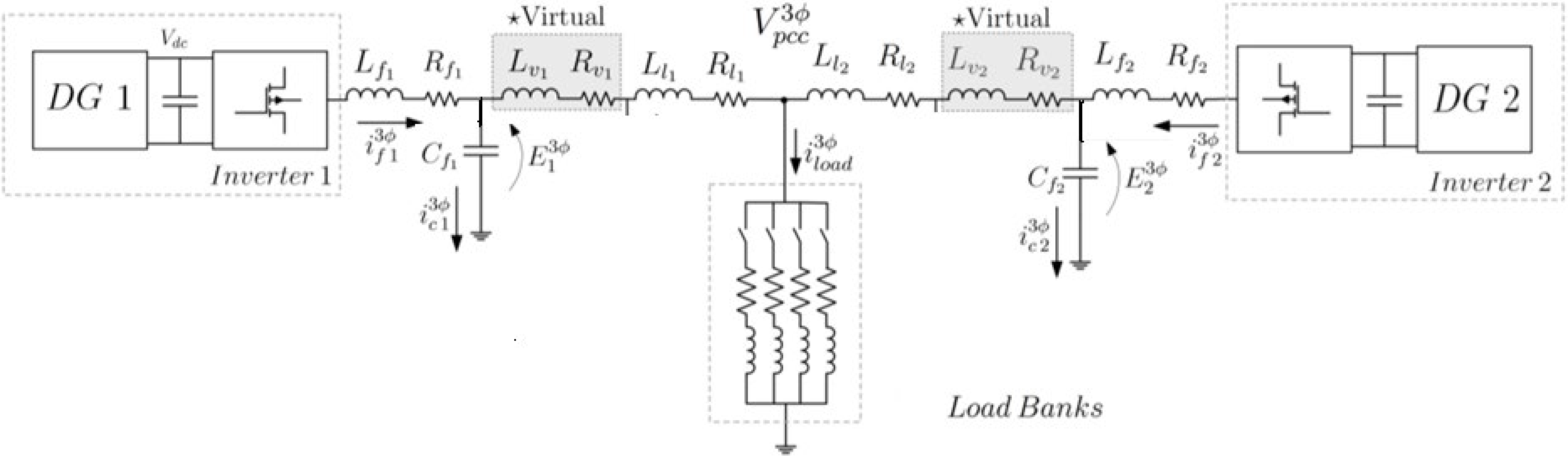
Apply only for Resistive Lines

H. Han, X. Hou, J. Yang, J. Wu, M. Su and J. M. Guerrero, "Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids," in IEEE Transactions on Smart Grid, vol. 7, no. 1, pp. 200-215, Jan. 2016.

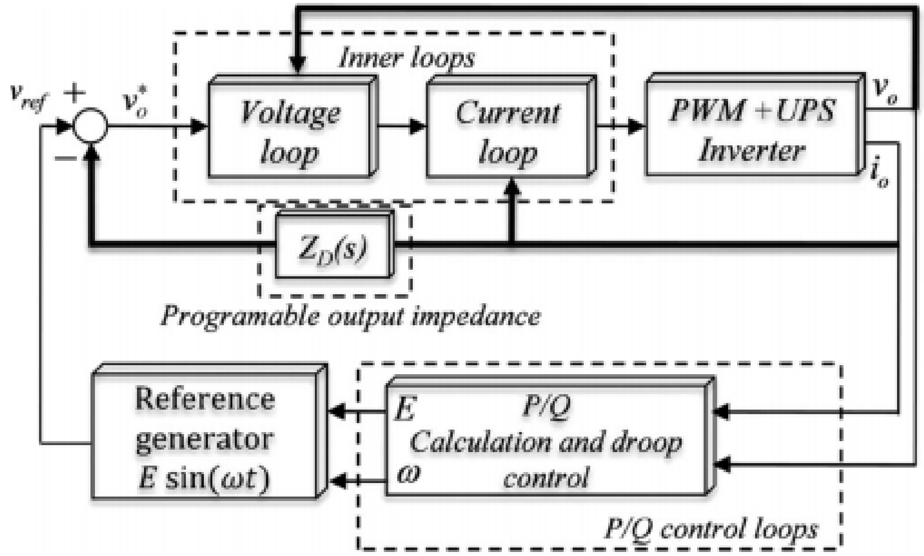
2. Droop Control

If the microgrids are basically small size power grids characterized by distributed energy resources located in a limited area (short distances). Then, is it possible to ensure inductive lines for droop control?

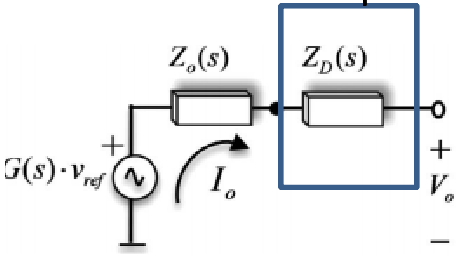
2. Virtual Impedance



2. Virtual Impedance



Virtual Impedance (VI)



J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodriguez and R. Teodorescu, "Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes," in *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4088-4096, Oct. 2009.

2. Virtual Impedance

$$V_{VI} = L\frac{di(t)}{dt} + Ri(t)$$

In dq

$$V_{VI} = L[P]\frac{d}{dt}\left([P]^{-1}\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix}\right) + Ri\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix}$$

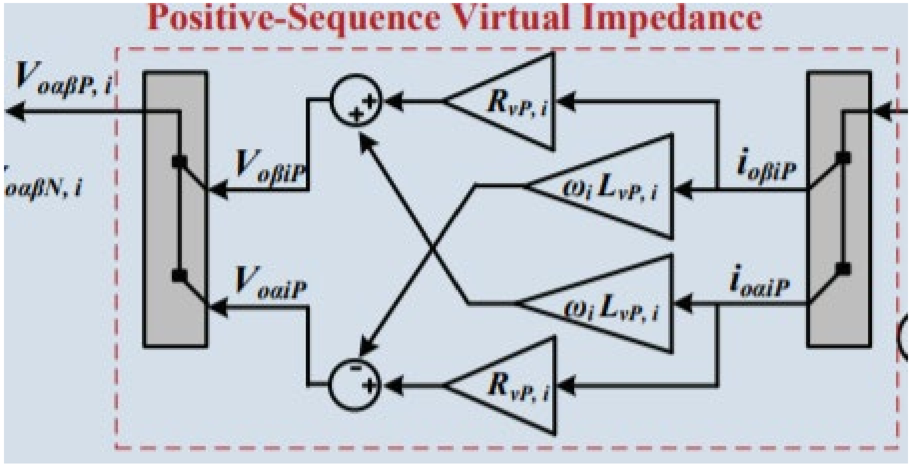
$$P\ is\ the\ Clrak - Park\ transformation\ Matrix$$

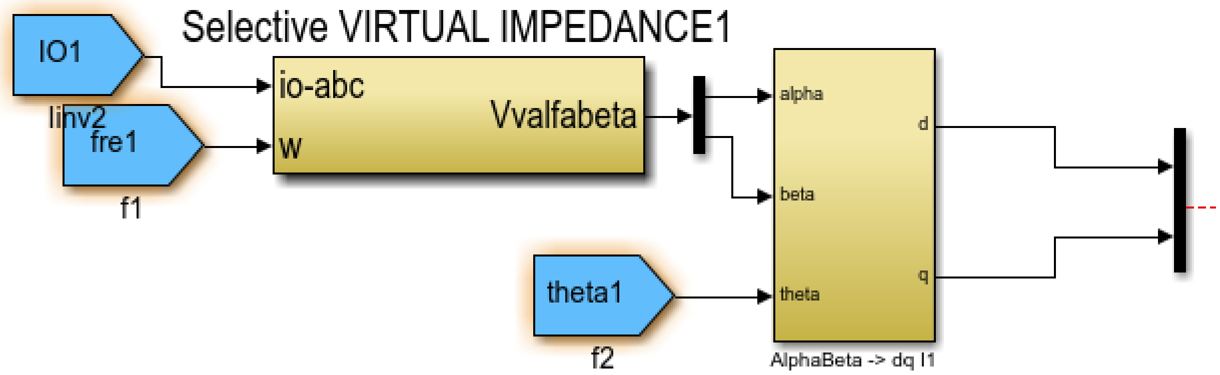
$$L[P]\frac{d}{dt}\left([P]^{-1}\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}\right) = L[P]\frac{d}{dt}([P]^{-1})\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$

$$L[P]\frac{d}{dt}\left([P]^{-1}\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}\right) = L\begin{bmatrix} 0 & -w & 0 \\ w & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$

$$V_{VI} = -L\frac{di(t)}{dt} = \begin{bmatrix} 0 & -w & 0 \\ w & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} + Ri\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix}$$

2. Virtual Impedance





2. Virtual Impedance

- **Advantage of the virtual Impedance:**
  - Provides to a microgrid with resistive line a inductive line behaviour.
  - More accurate active and reactive power sharing.
  - Increases the range of stability for the droop coefficients.

- **Disadvantages:**
  - Larger voltage and frequency deviation.
  - Slower dynamic response.

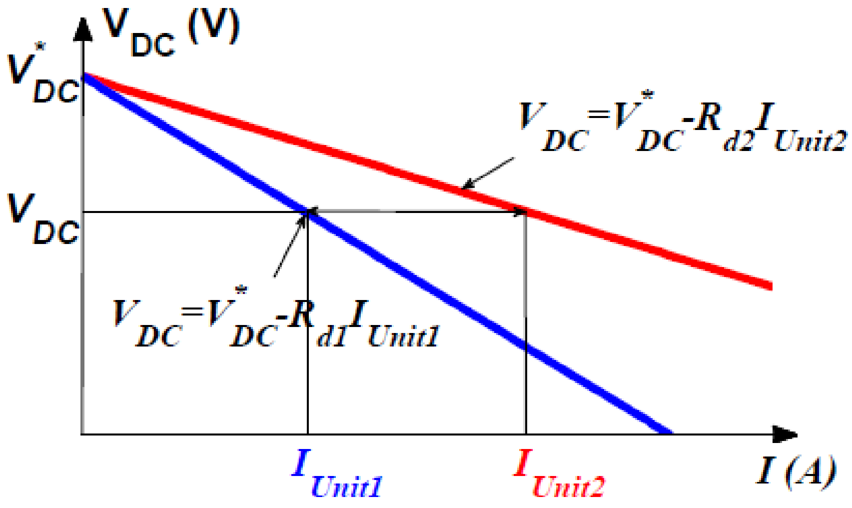
Doop in DC Microgrids

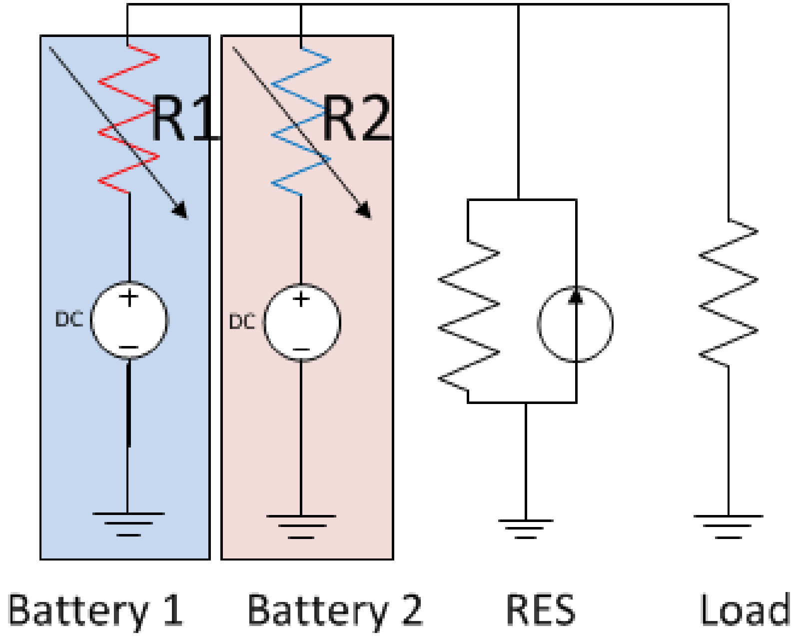
2. Droop for DC MG

Droop control loops in DC microgrids. (virtual resistance)

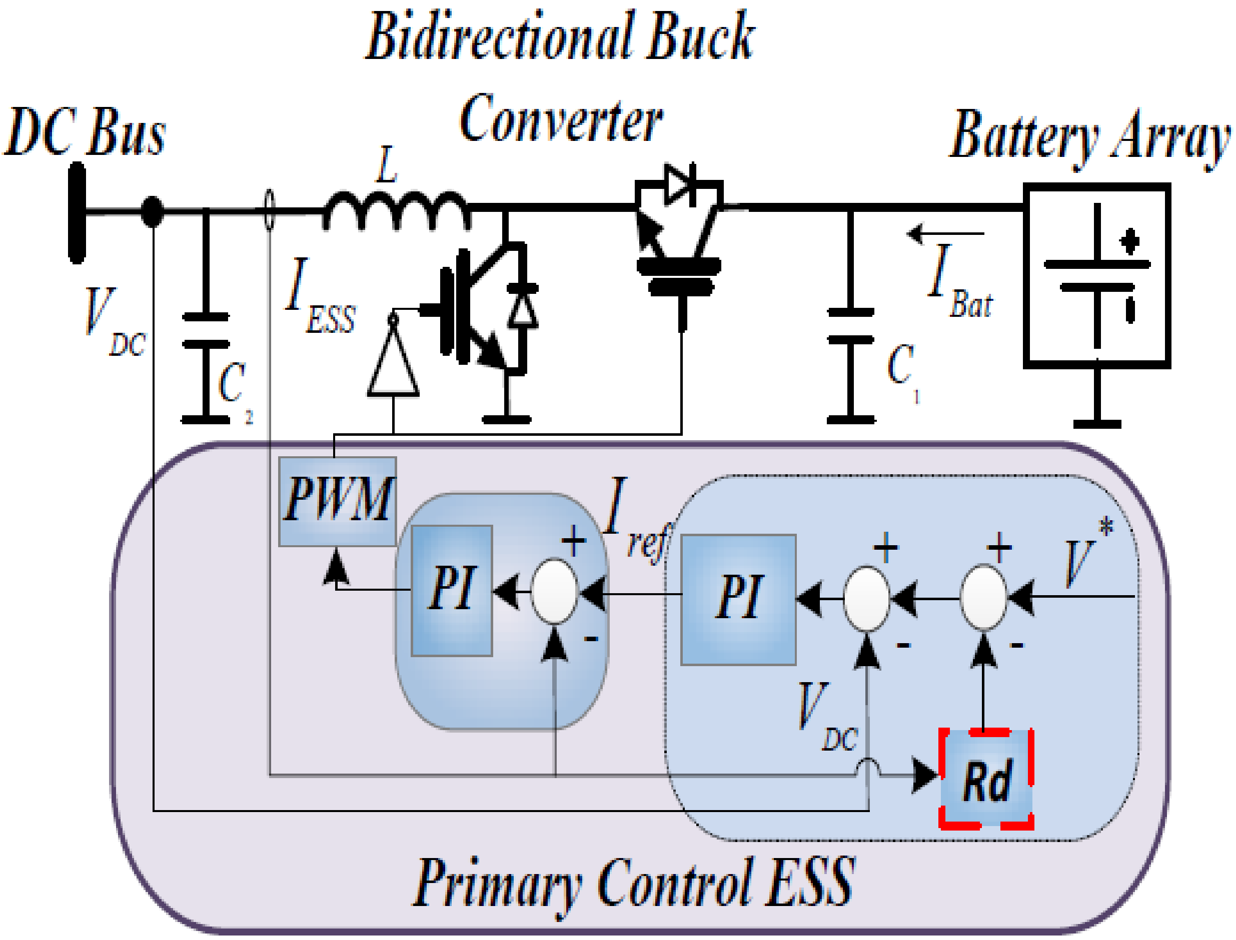
$$V_{ref} = V^{*} - R_d \cdot I_{Uniti}$$

Current sharing can be adjusted with different R_d



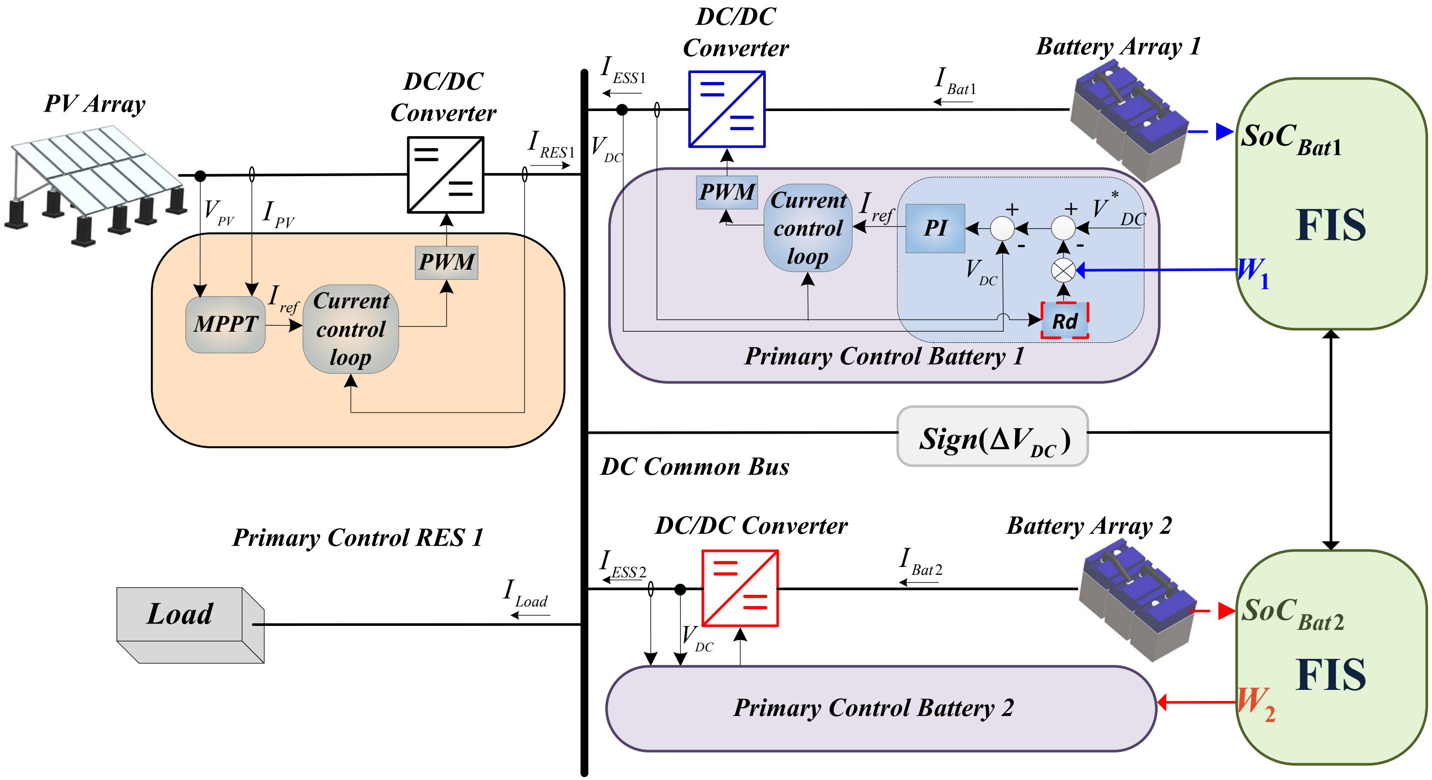


2. Droop for DC MG



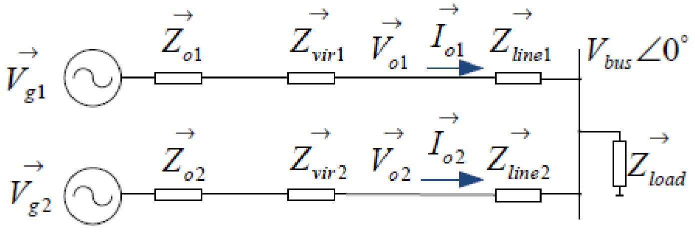
2. Droop for DC MG

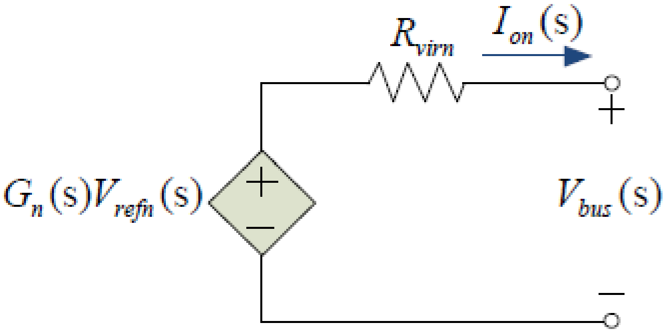
Simulation Exercise

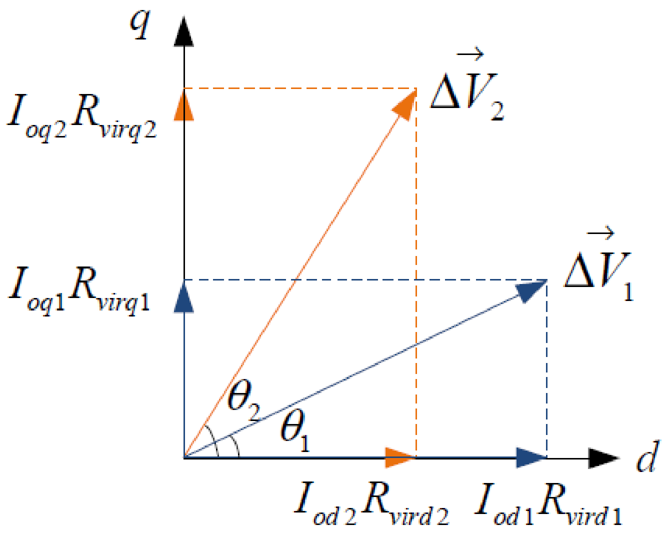


2. Power Sharing-AC

synchronous-reference-frame (SRF) virtual impedance loop







$$\vec{V}_{refn} - \vec{V}_{bus} = I_{odn}R_{virdn} + jI_{oqn}R_{virqn}$$

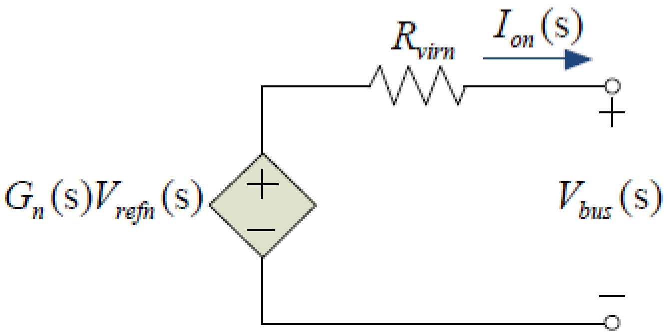
$$I_{od1}R_{vird1} = I_{od2}R_{vird2} = \ldots = I_{odN}R_{virdN}$$
$$I_{oq1}R_{virq1} = I_{oq2}R_{virq2} = \ldots = I_{oqN}R_{virqN}$$

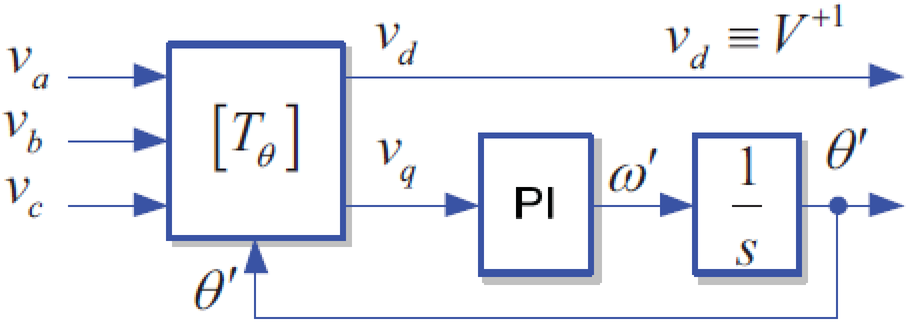
$$P_{o1}R_{vird1} = P_{o2}R_{vird2} = \ldots = P_{oN}R_{virdN}$$
$$Q_{o1}R_{virq1} = Q_{o2}R_{virq2} = \ldots = Q_{oN}R_{virqN}$$

Y. Guan, J. M. Guerrero, X. Zhao, J. C. Vasquez and X. Guo, "A New Way of Controlling Parallel-Connected Inverters by Using Synchronous-Reference-Frame Virtual Impedance Loop—Part I: Control Principle," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4576-4593, June 2016.

2. Power Sharing-AC

synchronous-reference-frame (SRF) virtual impedance loop

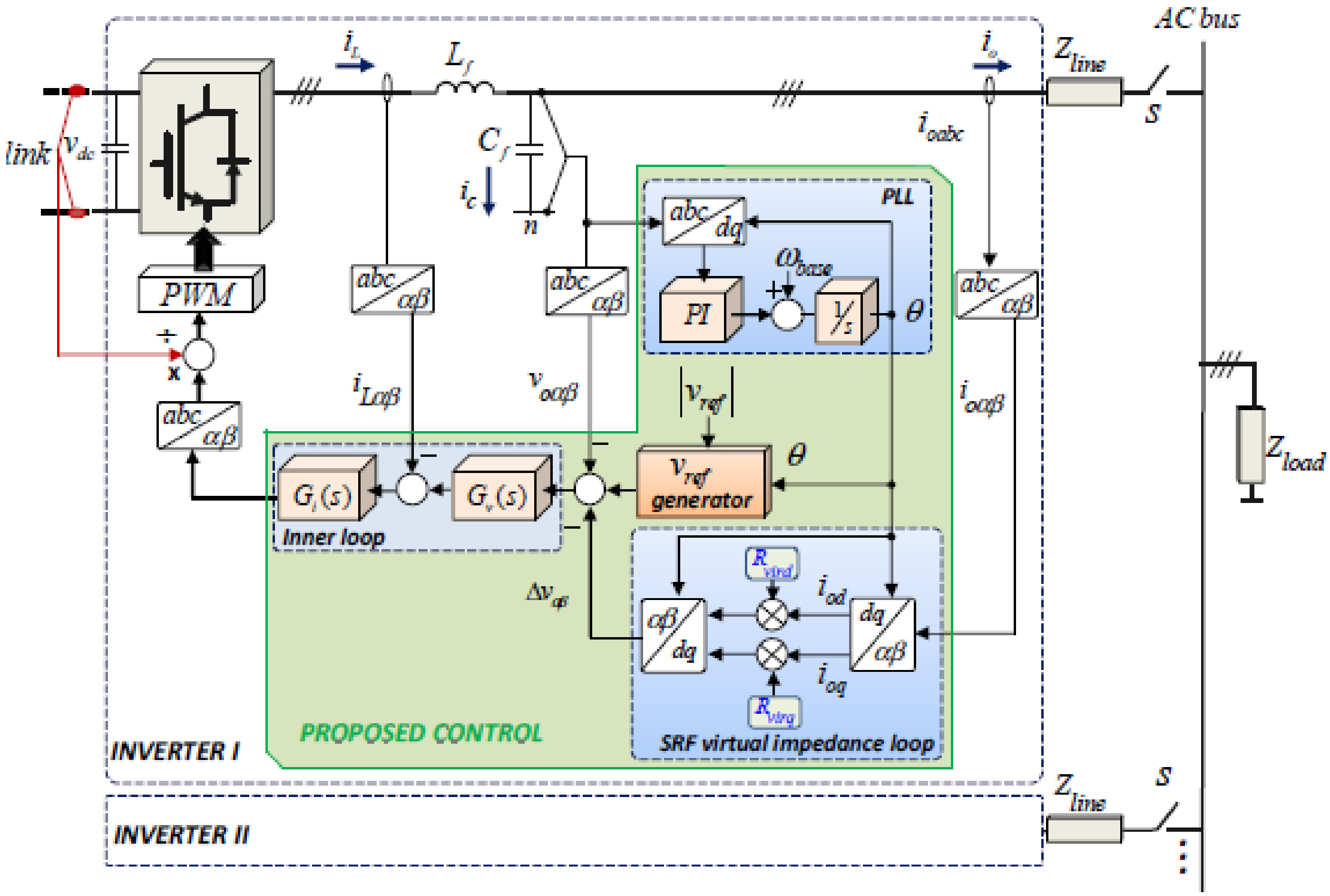




Y. Guan, J. M. Guerrero, X. Zhao, J. C. Vasquez and X. Guo, "A New Way of Controlling Parallel-Connected Inverters by Using Synchronous-Reference-Frame Virtual Impedance Loop—Part I: Control Principle," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4576-4593, June 2016.

2. Power Sharing-AC

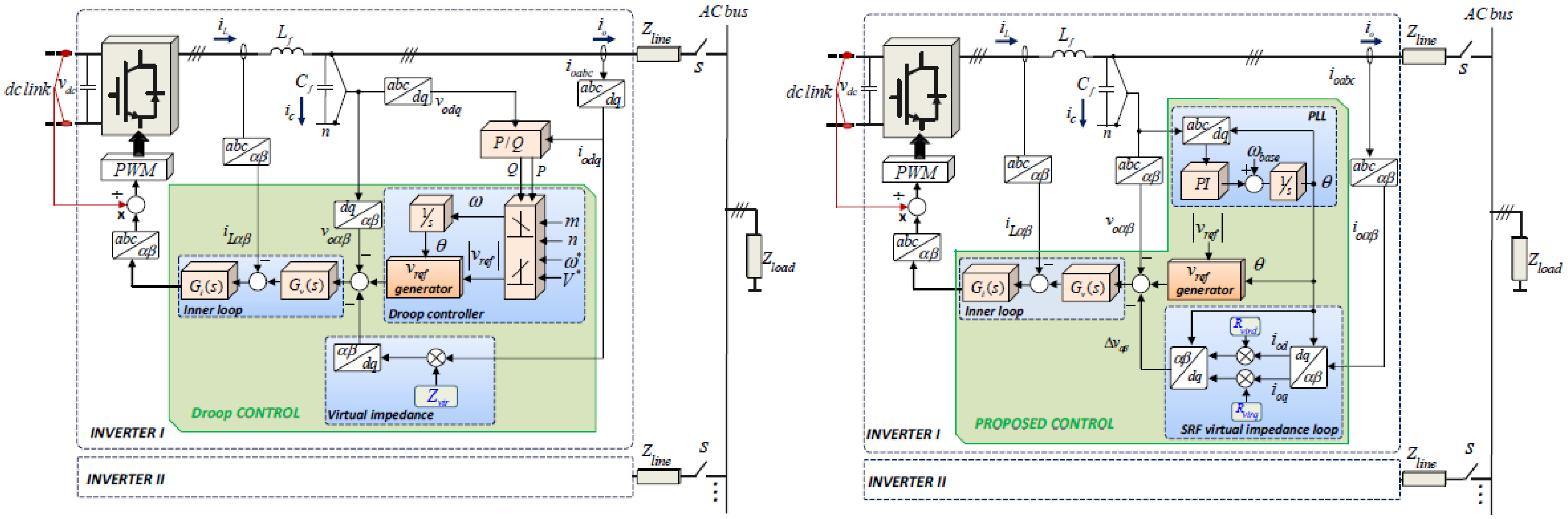
synchronous-reference-frame (SRF) virtual impedance loop



Y. Guan, J. M. Guerrero, X. Zhao, J. C. Vasquez and X. Guo, "A New Way of Controlling Parallel-Connected Inverters by Using Synchronous-Reference-Frame Virtual Impedance Loop—Part I: Control Principle," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4576-4593, June 2016.

2. Power Sharing-AC

synchronous-reference-frame (SRF) virtual impedance loop



Y. Guan, J. M. Guerrero, X. Zhao, J. C. Vasquez and X. Guo, "A New Way of Controlling Parallel-Connected Inverters by Using Synchronous-Reference-Frame Virtual Impedance Loop—Part I: Control Principle," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4576-4593, June 2016.

2. Power Sharing-AC

synchronous-reference-frame (SRF) virtual impedance loop

$$I_{oq} - \omega$$

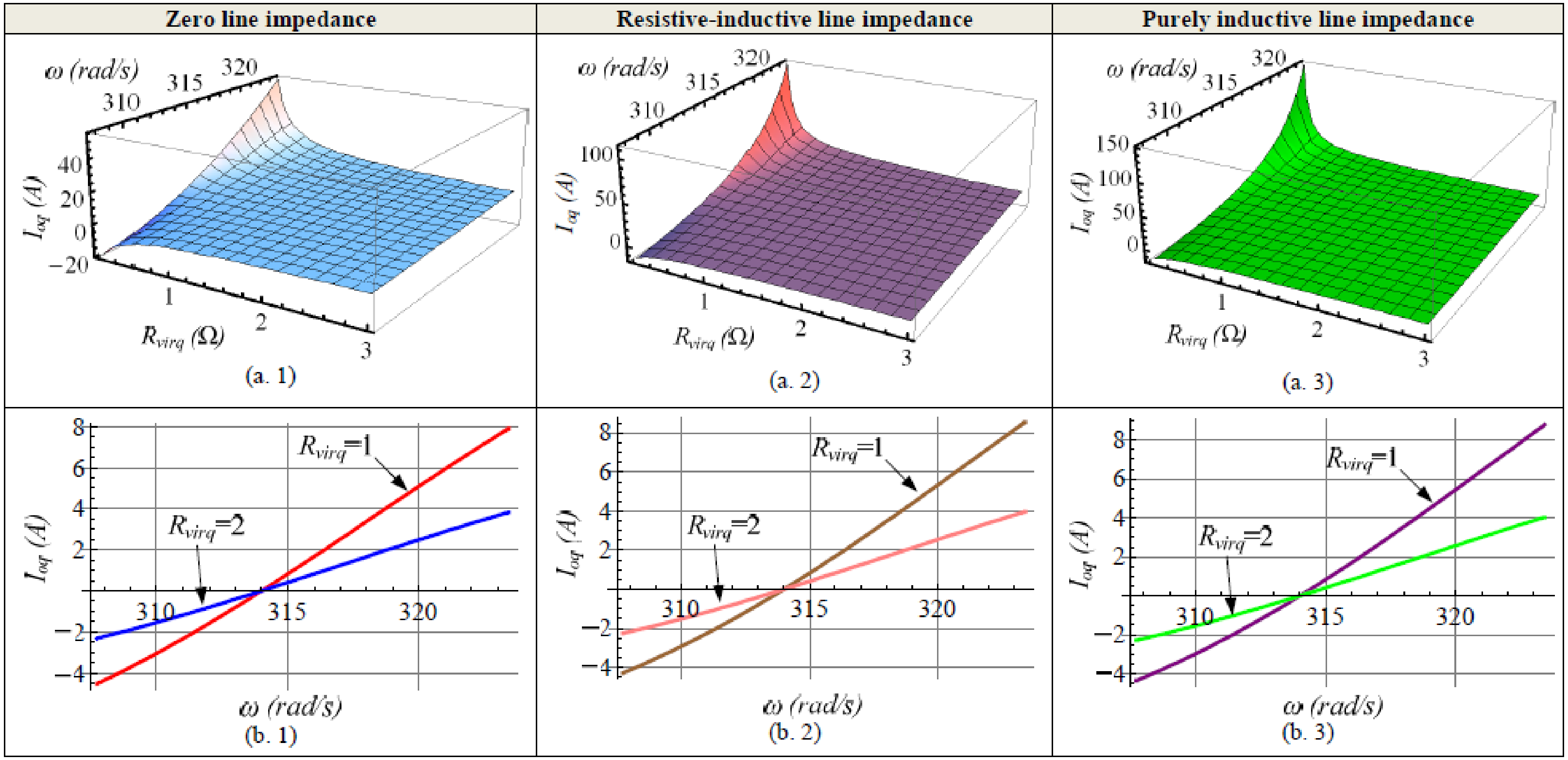


Fig. 8. The relationship of R_{virq}, I_{oq} and ω with different line impedances. (a) The relationship of R_{virq}, I_{oq} and ω with different line impedances, (b) The relationship of I_{oq} and ω when R_{virq}=1Ω/2Ω with different line impedances.

Y. Guan, J. M. Guerrero, X. Zhao, J. C. Vasquez and X. Guo, "A New Way of Controlling Parallel-Connected Inverters by Using Synchronous-Reference-Frame Virtual Impedance Loop—Part I: Control Principle," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4576-4593, June 2016.

2. Power Sharing-AC

synchronous-reference-frame (SRF) virtual impedance loop

$$I_{od} - V$$

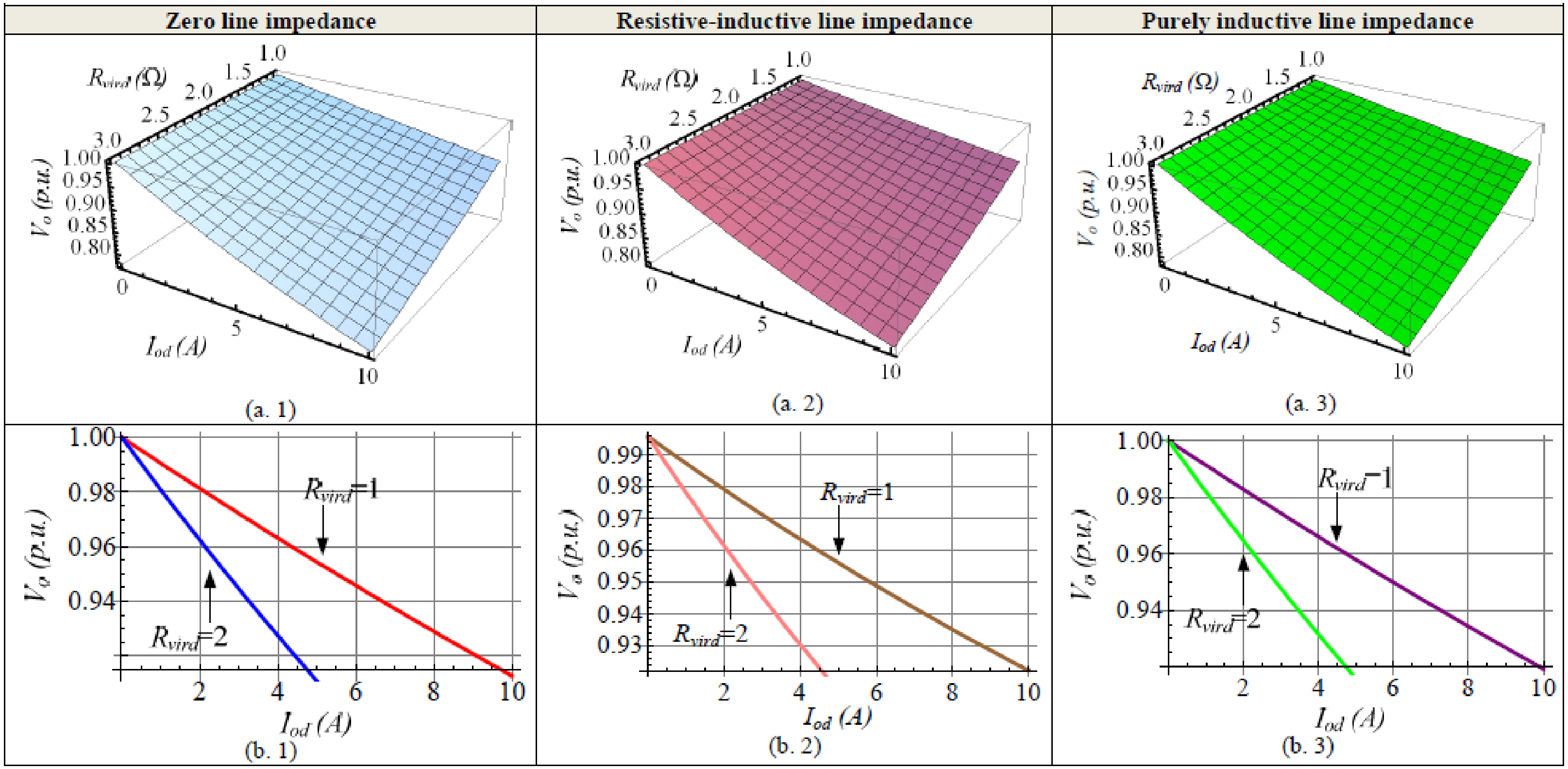


Fig. 10. The relationship of R_{vird}, I_{od} and V_o with different line impedances. (a) The relationship of R_{vird}, I_{od} and V_o with different line impedances, (b) The relationship of I_{od} and V_o when R_{vird}=1Ω/2Ω with different line impedances respectively.

Y. Guan, J. M. Guerrero, X. Zhao, J. C. Vasquez and X. Guo, "A New Way of Controlling Parallel-Connected Inverters by Using Synchronous-Reference-Frame Virtual Impedance Loop—Part I: Control Principle," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4576-4593, June 2016.