Primary and secondary controllers for islanded Microgrids

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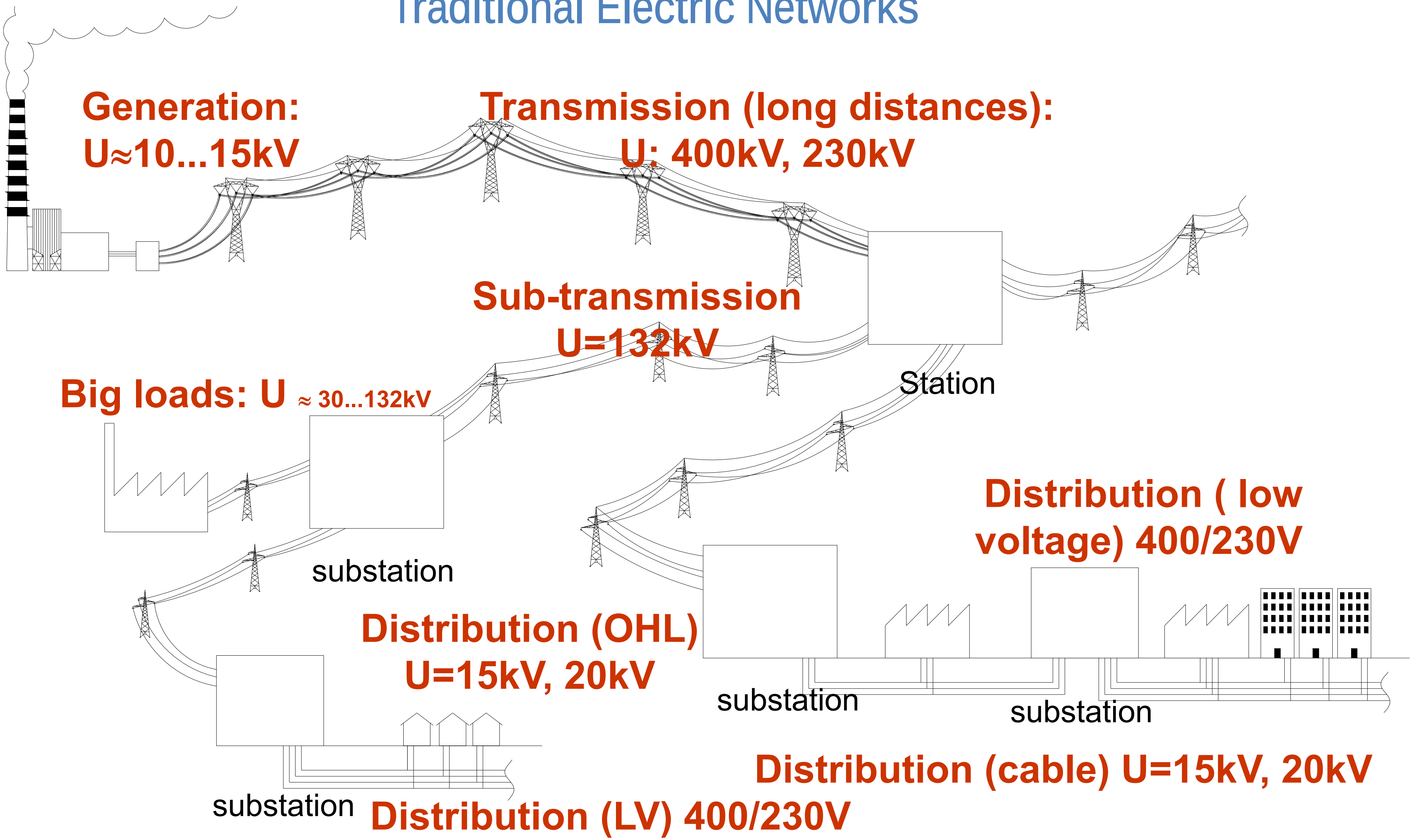
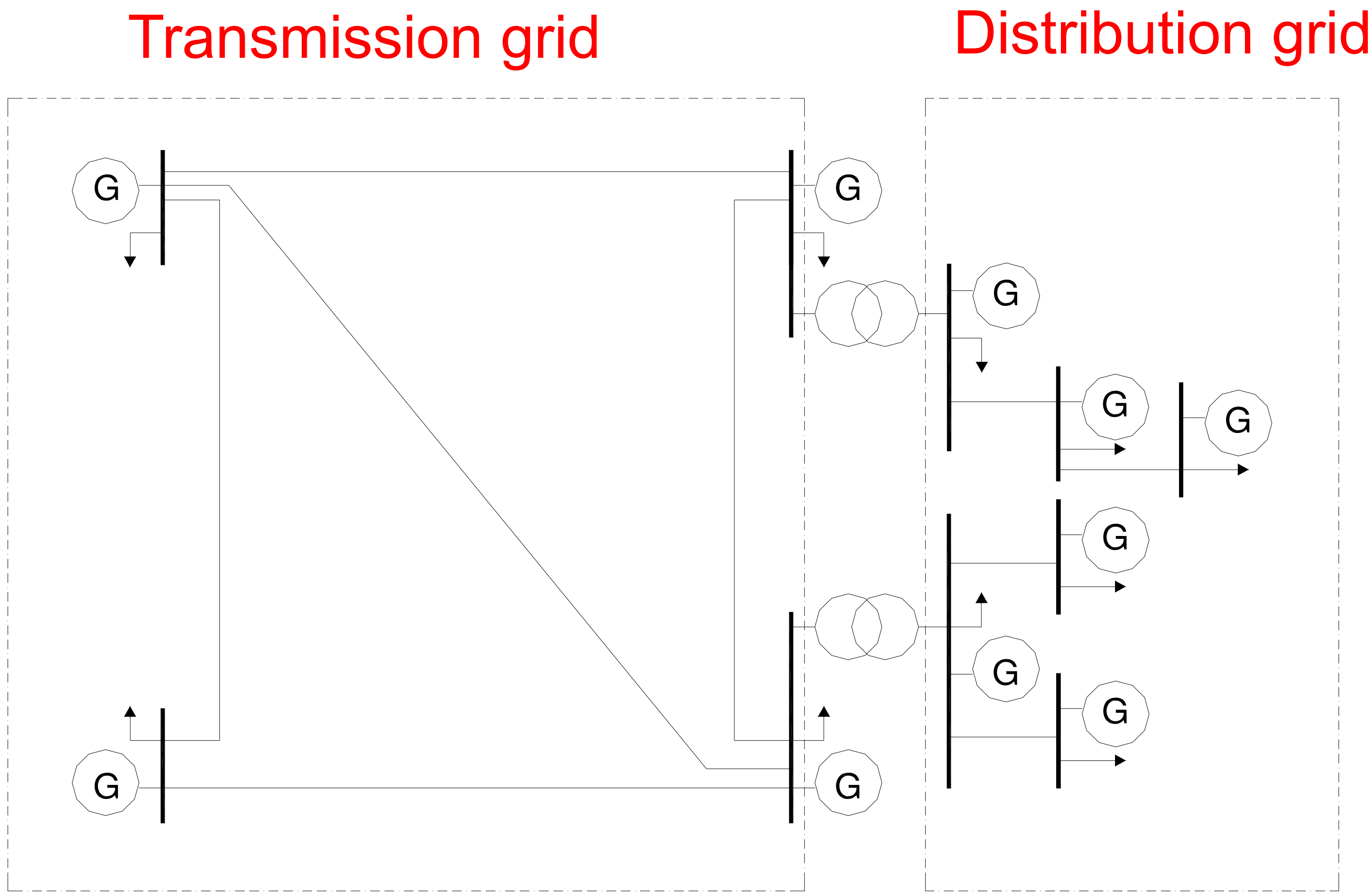
Traditional Electric Networks

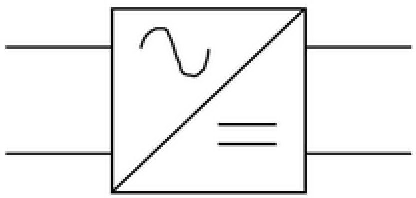


Traditional Electric Networks

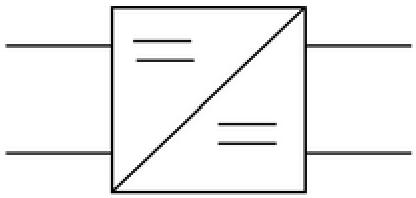


- Interconnected networks
- Working as AC 3 phase systems
- Few and “big” energy sources
- Power flows and bus voltages not controllable

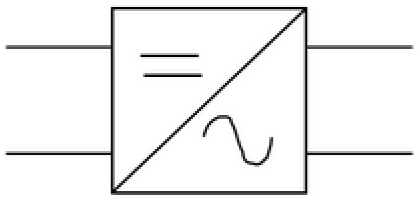
The first "revolution": Power electronics devices



AC-DC converters



DC-DC converters



DC-AC converters

What has changed?

- **Interconnected networks**
- **Working as ~~AC 3~~ phase systems**
- **Few and “big” energy sources**
- **Power flows and ~~bus~~ voltages not controllable**

The second “revolution”: Distributed Generation (DG)

PV units (RES: not dispatchable)

Wind turbines (RES: not dispatchable)

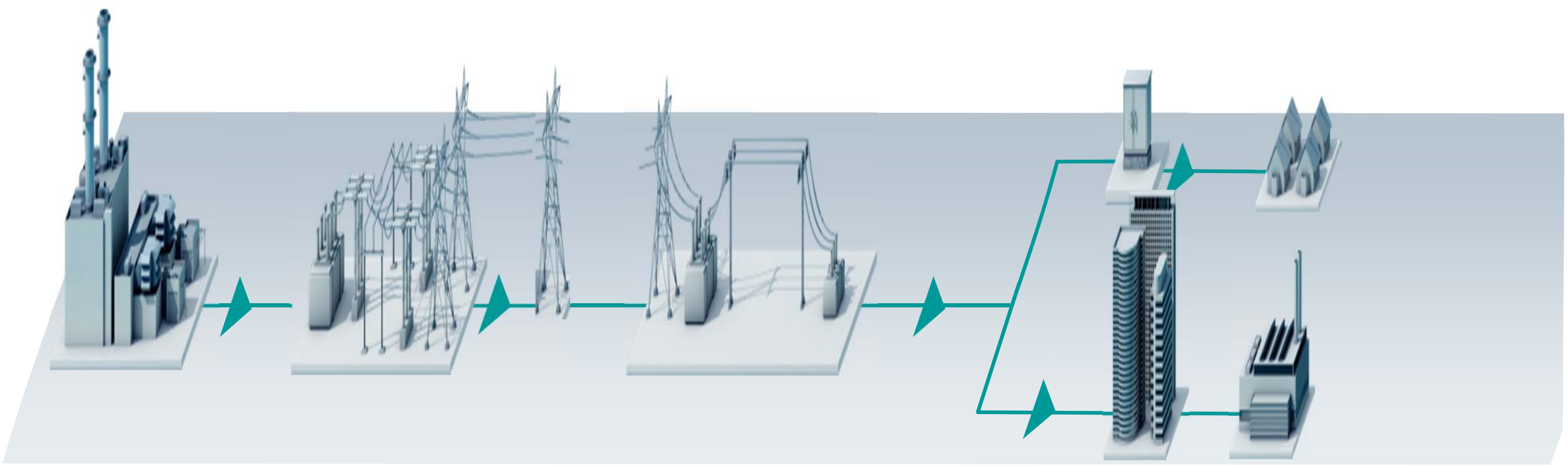
Microturbines (CHP units: dispatchable)

What has changed?

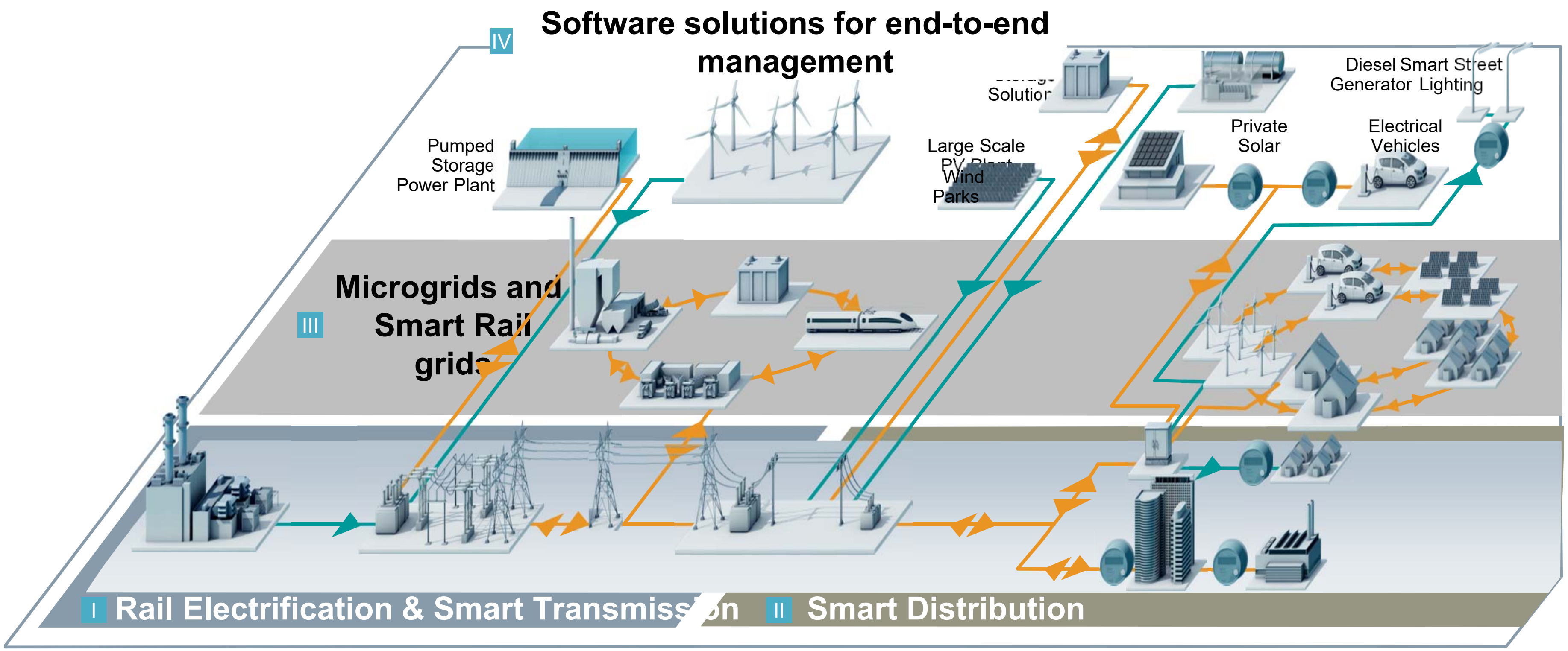
- Interconnected networks
- Working as AC 3 phase systems
- Few and “big” energy sources
- Power flows and bus voltages not controllable

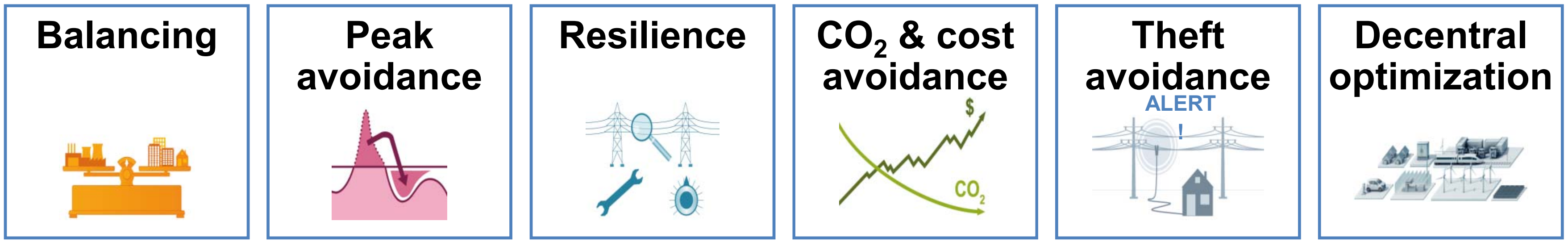
The third “revolution”: microgrids(DG)

From centralized, unidirectional Grid …



… to distributed energy and bidirectional





Definition

A cluster of loads and microsources operating as a single controllable system that provides both power and heat to its local area.

The microgrid study architecture consists of a group of radial feeders, which could be part of a distribution system.

There is a single point of connection to the utility called point of common coupling (PCC).

Microgrids kinds

• Microgrids normally operate in a **grid-connected** mode through the substation transformer.

• However, it is also expected to provide sufficient generation capacity, controls, and operational strategies to supply at least a portion of the load after being disconnected from the distribution system at the PCC and remain operational as an autonomous **(islanded)** entity.

•Microgrids can include conventional or rotary units that are interfaced to the main grid through rotating machines.

•Another kind consists of electronically coupled units that utilize power electronic converters to provide the coupling media with the host system (**no inertia Microgrids)**

Microgrids control

Energy management in microgrids is usually thought of as a three-level hierarchical control system.

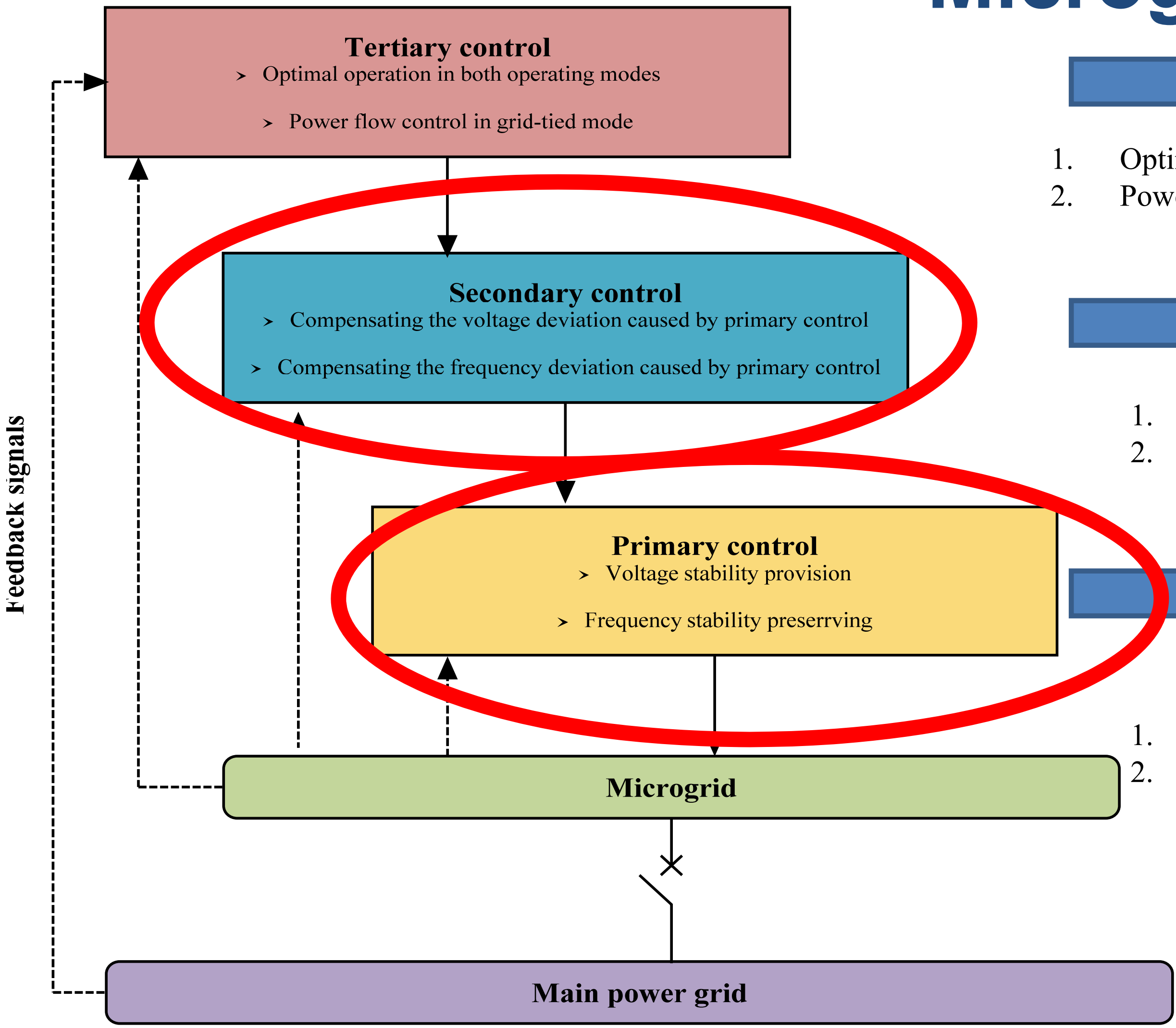
- The first control level, often called “**primary**” or “autonomous” control, consists of a number of local, autonomous controllers. Each controller governs a power electronics converter and is responsible to interface generators, storage devices, and loads with the microgrid. These controllers are the fastest, as they operate in the millisecond range, employing a droop control in islanded mode.

Microgrids control

- A **secondary** control level employs a low-bandwidth communication to fix the frequency and amplitude of the microgrid's units, restoring their nominal values.

- Finally, the **tertiary** control level is related to the control of active and reactive power flow. This level of control is related to EMS and to the optimization of the microgrid resources

Microgrids control



1. Optimal operation (grid connected and islanding mode)
2. Power flow control

1. Compensating frequency deviation
2. Compensating voltage deviation

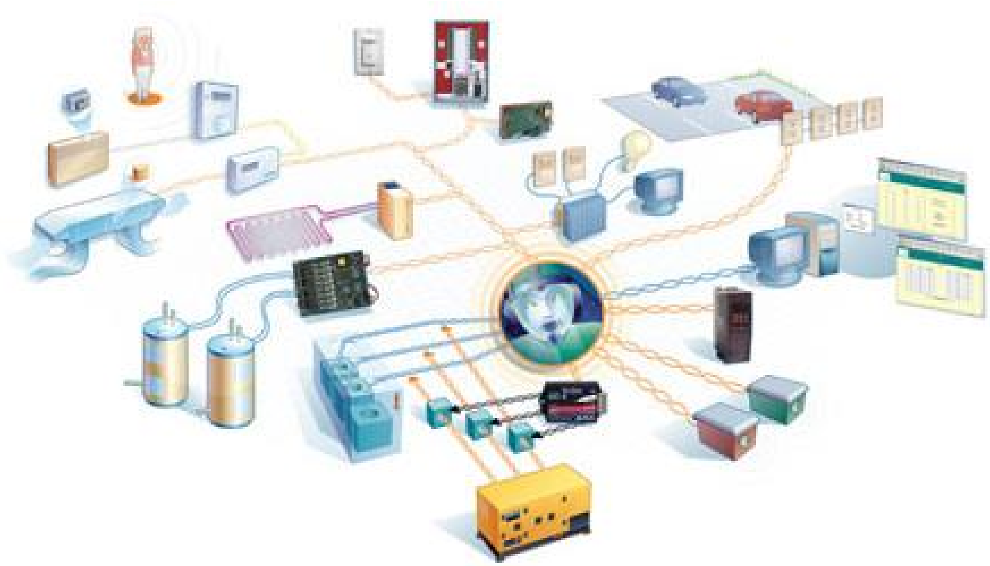
1. Stabilize voltage and frequency
2. Active and reactive power sharing

Energy Management System (EMS)

The **Energy Management System** provides the intelligence and sustainability metrics that manages the devices controllers and **minimizes the operation costs**.

INPUT:

- Generation forecasting
- Electrical and thermal load forecasting



OUTPUT:

Power profile of each unit

Optimization problem

AIM: Find out the time-profile of all unit connected to the grid which minimize (maximize) a specific objective function over time range

REQUIREMENT: a complete model of each unit connected to the grid

FORMULATION: refer to linear/piecewise linear/quadratic relation between the decisional variables for using **Mixed Integer Linear Programming** (MILP) or **Mixed Integer Quadratic Programming** (MIQP) procedures.

Decisional (free) variables

- reactive powers of all the devices connected to the grid by means of converters
- active powers of electrical and thermal generation (cogen) units (CU)
- active powers of electrical generation units (GU)
- active power exchanged by the storage batteries (SU)
- thermal power of the heat units (HU)
- Voltage/phase at each node and current at each branch

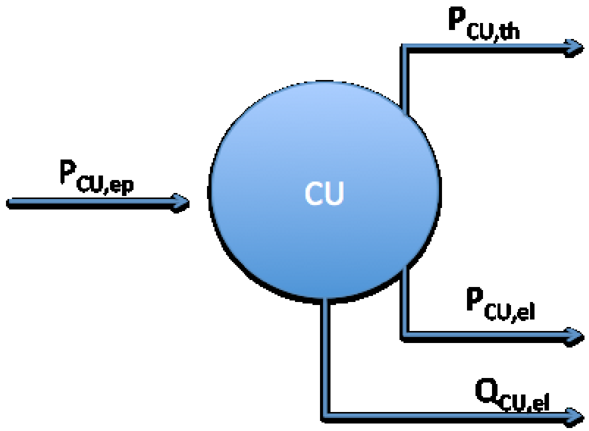
Variables supposed to be known

- Renewable electrical power profile (REN)
- Electrical Load profiles (EL)
- Thermal energy request (TL)

Model of cogen units (CU)

The model for a cogenerative unit involves:

- the injected active power **(free)** $P_{CU,el}$
- the exchanged reactive power **(free)** $Q_{CU,el}$
- the thermal power **(dependent)** $P_{CU,th}$
- The primary energy **(dependent)** $P_{CU,ep}$



linear constraints

$P_{CU,th}$ and $P_{CU,ep}$ inked to $P_{CU,el}$ by means of **suitable** piecewise linear function

quadratic constraints (capability)

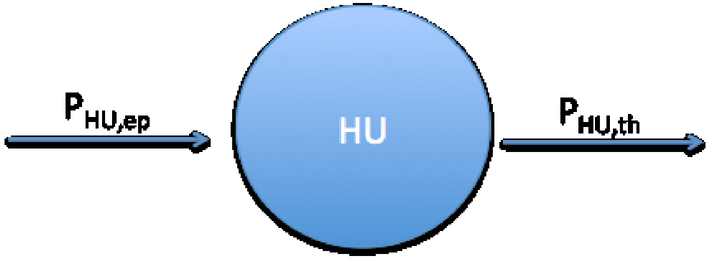
$$\left(P_{CU,el}\right)^2 + \left(Q_{CU,el}\right)^2 \le \left(A_{CU}\right)^2$$

inverter rating

Model of heat unit (HU)

The model for a heat unit involves:

- The primary per unit time energy **(dependent)** $P_{HU,ep}$
- the thermal power **(free)** $P_{HU,th}$



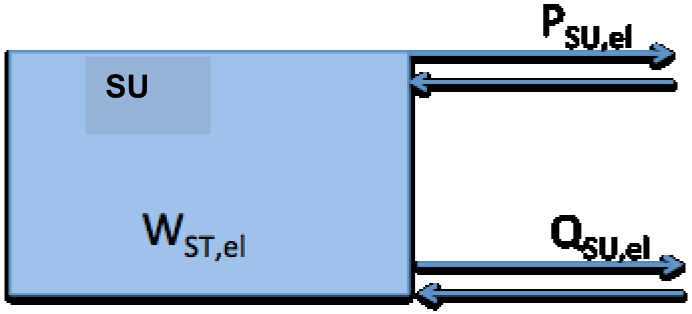
linear constraint

$P_{HU,ep}$ linked to $P_{HU,th}$ by means of **suitable** piecewise linear function

Model of electrical storage unit (SU)

The model for an electrical storage unit involves:

- the injected active power **(dependent)** $P_{SU,el}$
- the exchanged reactive power **(free)** $Q_{SU,el}$
- the storage energy content **(free)** $W_{SU,el}$



linear constraint

$P_{SU,el}$ linked to $W_{SU,el}$ by means of:

- the continuity equation
- a **suitable** piecewise linear function modelling charging and discharging efficiencies

$$P_{SU,el} = \begin{cases} \dfrac{1}{\eta_{ST}^{in}} \dfrac{dW_{SU,el}}{dt}, \text{ if charging} \\ \eta_{ST}^{out} \dfrac{dW_{SU,el}}{dt}, \text{ if discharging} \end{cases}$$

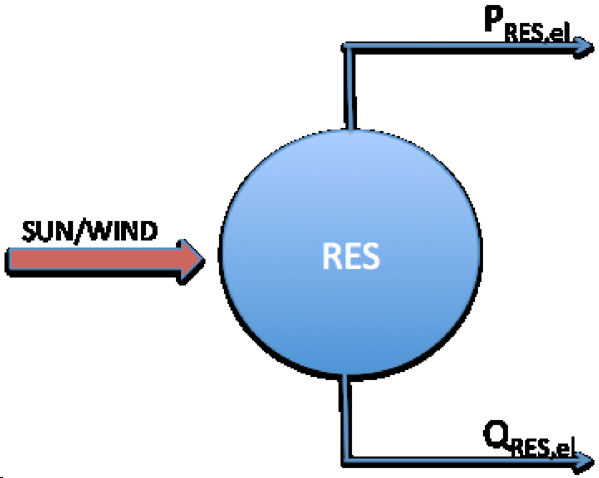
quadratic constraint (capability)

$$\left(P_{SU,el}\right)^2 + \left(Q_{SU,el}\right)^2 \le \left(A_{SU}\right)^2$$

Model of the renewable energy sources (RES)

The model for a RES involves:

- the injected active power **(known)** $P_{RES,el}$
- the exchanged reactive power **(free)** $Q_{RES,el}$



linear constraint (capability)

$$-\sqrt{\left(A_{RES}\right)^2-\left(P_{RES,el}\right)^2} \leq Q_{RES,el} \leq \sqrt{\left(A_{RES}\right)^2-\left(P_{RES,el}\right)^2}$$

inverter rating

Model of Electrical and Thermal Loads

The EL involves:

- the injected active power **(known)** $P_{EL,el}$
- the exchanged reactive power **(known)** $Q_{EL,el}$

The TL involves:

- the thermal power request **(known)** $P_{TL,th}$

linear constraint (thermal balance)

$$P_{HU,th} + P_{CU,th} \geq P_{TL,th}$$

Model of Electrical Network

The E-NET involves:

- the voltage at each node **(free)** V_k
- the phase at each node **(free)** δ_k
- the current at each branch **(free)** I_n
- active power injected at each node (dependent) P_h
- reactive power injected at each node (dependent) Q_h

- voltage and current feasibility range

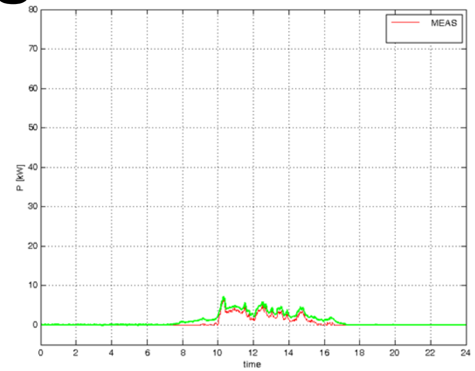
$$V_{\min} \le V_k \le V_{\max} \quad \text{and} \quad 0 \le I_h \le I_{\max}$$

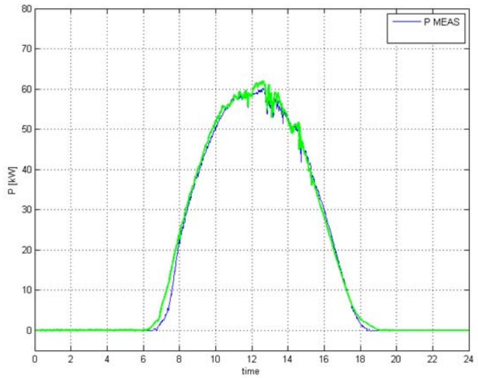
- load flow equations

$$P_{h,t} + jQ_{h,t} = V_{h,t} \sum_{k=1}^{6} Y^*_{hk} V_{k,t} \exp(-j\delta_{k,t}),$$

Generation Forecasting

CSP model / PV model





Electrical and Thermal Forecasting

Electrical Load Forecasting

Historical Database of
Electrical and Thermal Load
and
Weather Forecasting

+

Statistical Based Approach
(regression models,
neural network
approach)

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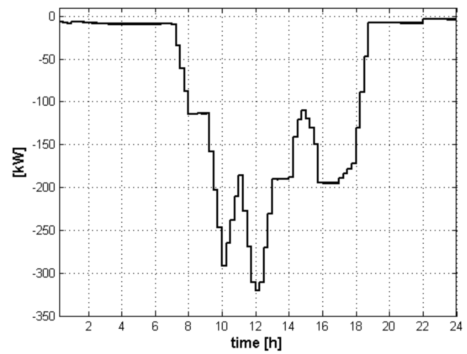
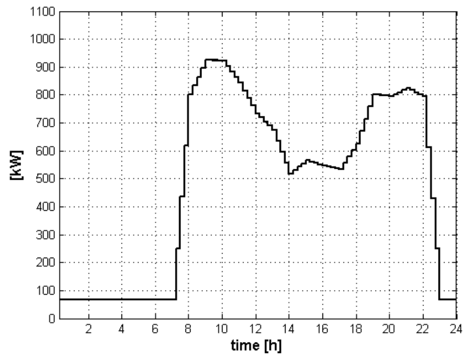




Forecasting Update

$$P^{fc}_{RES,s|t} = P^{fc}_{RES,s|t-1} + \left[P^{me}_{RES,t} - P^{fc}_{RES,t|t-1} \right]$$

$$P^{fc}_{EL,s|t} = P^{fc}_{EL,s|t-1} + \left[P^{me}_{EL,t} - P^{fc}_{EL,t|t-1} \right]$$

$$P^{fc}_{TL,s|t} = P^{fc}_{TL,s|t-1} + \left[P^{me}_{TL,t} - P^{fc}_{TL,t|t-1} \right]$$

Limited by the inverter rating

The problem: minimize

$$C = \left(C_{CU} + C_{HU} + C_{NET} \right)$$

Cogenenerative units Cost

Heat Unit Cost

Exchanging NET Cost

Hard task from a numerical point of v
C weakly depends on reactive power generation

Split the problem into two subproblems!

First problem: Economic Dispatch (ED)

Minimize

$$C = \left(C_{CU} + C_{HU} + C_{NET} \right)$$

Subjected to

$$P^{th}_{CHP,1,t+i} + P^{th}_{CHP,2,t+i} + P^{th}_{BO,t+i} \geq P^{fc}_{TL,t+i|t}$$

Thermal power balance

$$P^{el}_{CHP,1,t+i} + P^{el}_{CHP,2,t+i} + P_{ST,t+i} + P_{net,t+i} + \\ + P^{fc}_{EL,t+i|t} + P^{fc}_{RES,t+i|t} = 0$$

Electric power balance

$$P_{ST,t} = \begin{cases} \dfrac{1}{\eta^{in}_{ST}} \dfrac{W_{ST,t-1} - W_{ST,t}}{\Delta t} & W_{ST,t-1} < W_{ST,t} \\ \eta^{out}_{ST} \dfrac{W_{ST,t-1} - W_{ST,t}}{\Delta t} & W_{ST,t-1} \geq W_{ST,t} \end{cases}$$

Storage model

Finds out the thermal and the electric active power production of the units over the whole time horizon

MILP problem

Second problem: Power Quality (PQ)

Minimize $\left|Q_{\mathrm{QEG},t}\right|$

Subjected to

$$P_{h,t} + \mathrm{j}Q_{h,t} = V_{h,t}\sum_{k=1}^{6} Y^{*}{}_{hk}V_{k,t}\exp(-\mathrm{j}\delta_{k,t}),$$

Load flow equation

$$V_{\min} \le V_k \le V_{\max}$$

$$0 \le I_h \le I_{\max}$$

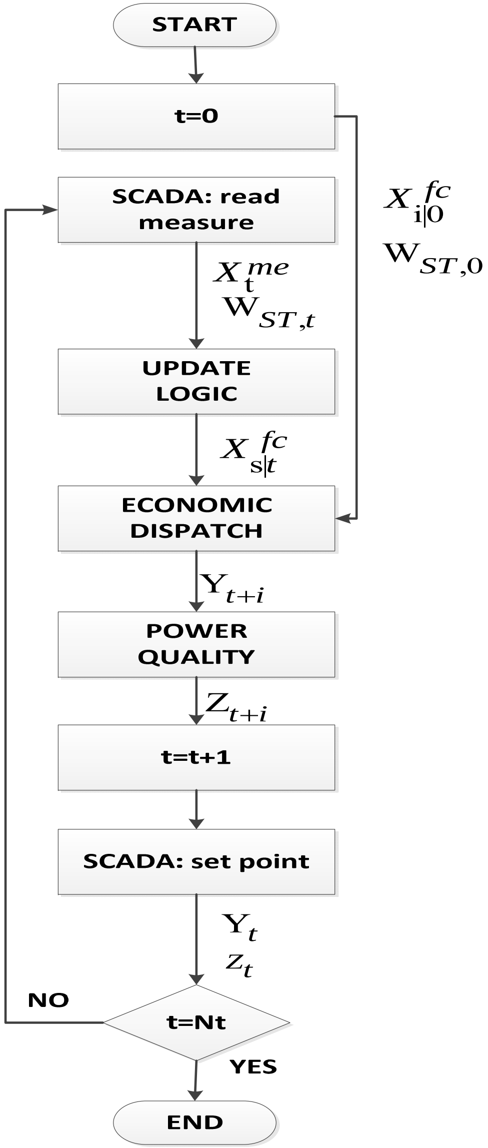
Quality issues

$$\left(P_{i,t}^{el}\right)^2 + \left(Q_{i,t}^{el}\right)^2 \le A^2$$

Capability constraints

Finds out the reactive power production of the units at the specified time sample

Non linear problem



Flow chart

X collects the set of quantities $\{P_{RES}, P_{EL}, P_{TL}\}$

Y the set of quantities $\{P_{BO}, P_{CHP,1}, P_{CHP,2}, P_{ST}\}$

Z the set of quantities $\{Q_{CHP,1}, Q_{CHP,2}, Q_{ST}, Q_{PV}\}$.

i=1,…,N_t and $s>t$.

• Primary controllers for islanded no-inertia microgrids

Primary regulation of islanded Microgrids is one of the most relevant topics in an academic and industrial world. **IEEE Std 1547-2018** defines the functionalities of **Grid-Supporting, Grid-Feeding and Grid Forming** inverters

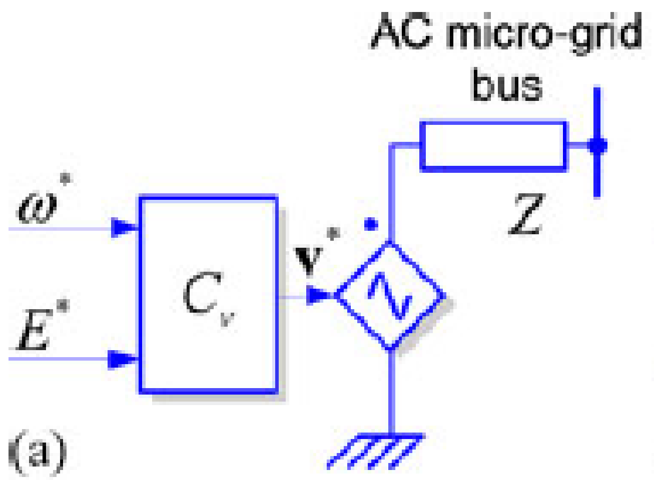
IEEE STANDARDS ASSOCIATION IEEE

IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems

Primary controllers for islanded no-inertia microgrids

Depending on their operation in an AC microgrid, power converters can be classified into grid-feeding, grid-supporting and grid-forming power converters

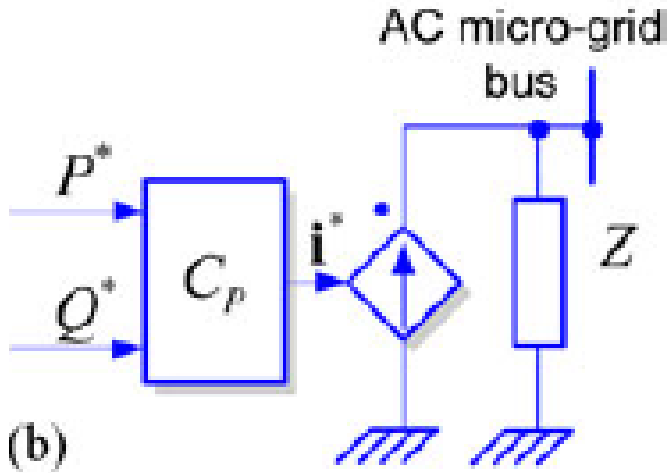
The grid-forming converters can be represented as an ideal AC voltage source with a low-output impedance, setting the voltage amplitude $E*$ and frequency $\omega*$ of the local grid by using a proper control loop



Primary controllers for islanded no-inertia microgrids

Depending on their operation in an AC microgrid, power converters can be classified into grid-feeding, grid-supporting and grid-forming power converters

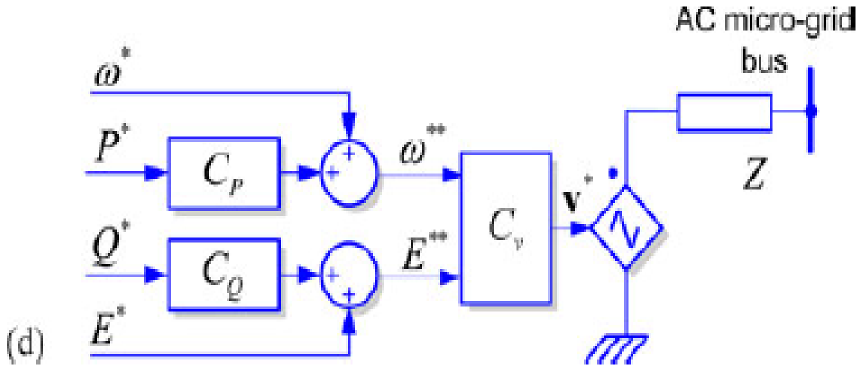
The grid-feeding power converters are mainly designed to deliver power to an energized grid. They can be represented as an ideal current source connected to the grid in parallel with high impedance



Primary controllers for islanded no-inertia microgrids

Depending on their operation in an AC microgrid, power converters can be classified into grid-feeding, grid-supporting and grid-forming power converters

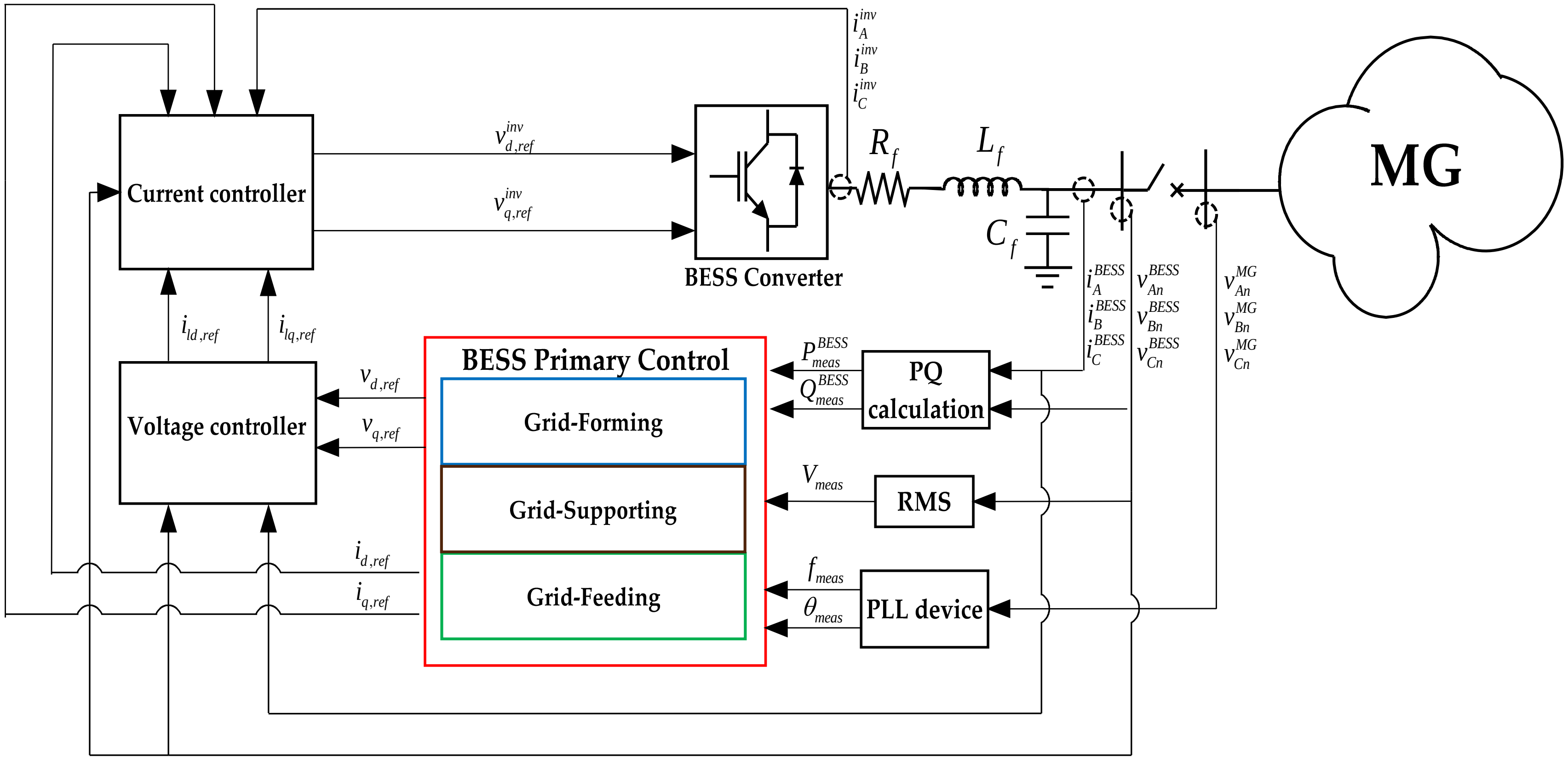
The grid-supporting converters can be represented as an ideal ac voltage source in series with a link impedance. These converters regulate their output current/voltage to keep the value of the grid frequency and voltage amplitude close to their rated values



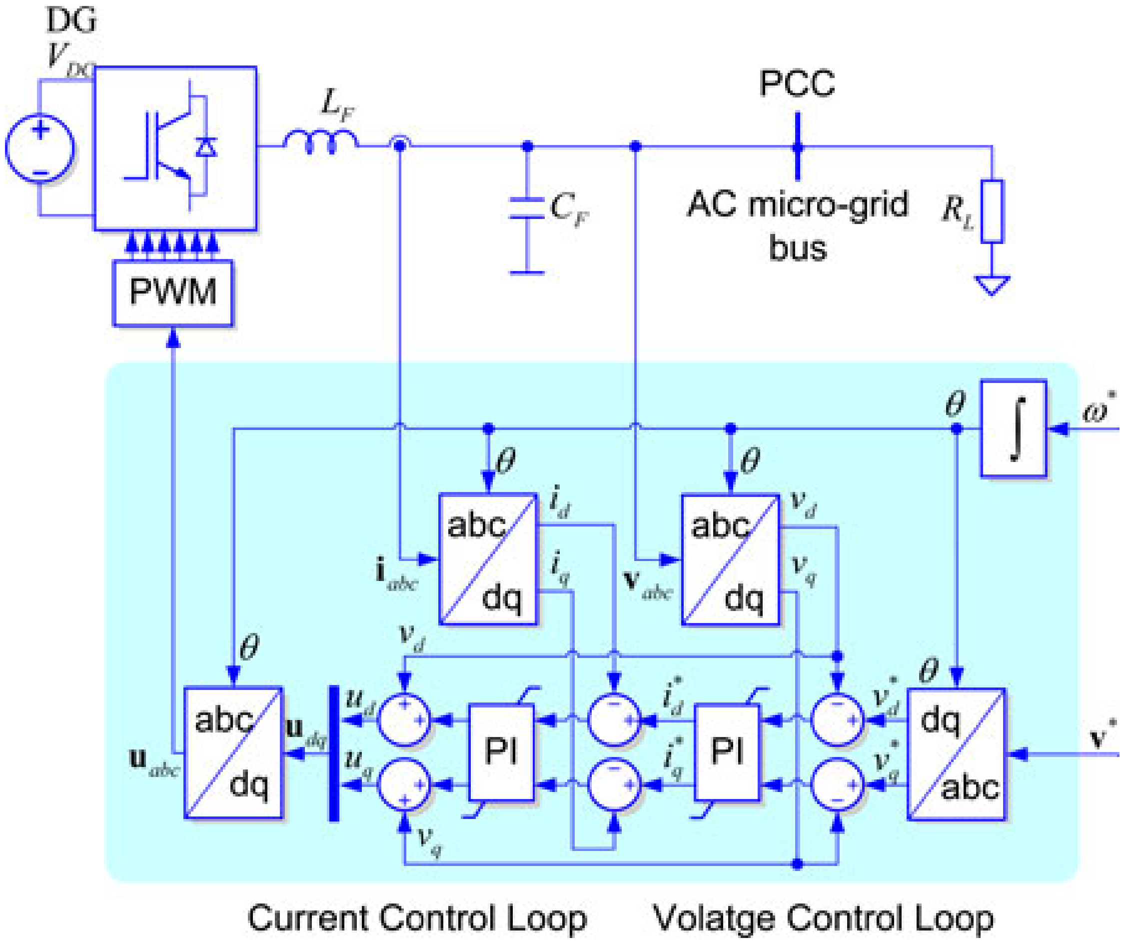
Primary controllers for islanded no-inertia microgrids

- External level: communication based (e.g. Master/slave) or Communicationless (e.g. droop)
- Voltage loop
- Current loop

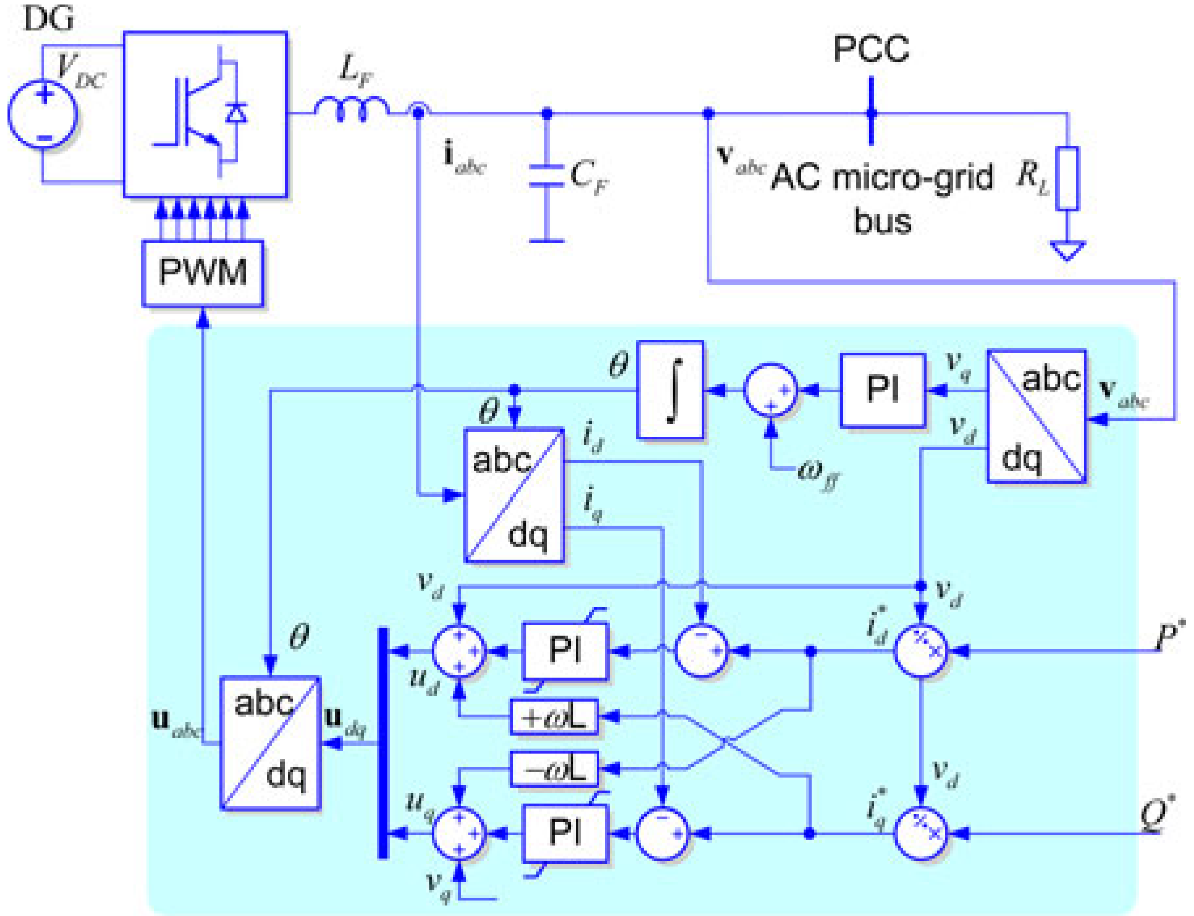
MG primary Controllers: general scheme



MG primary Controllers: Grid Forming

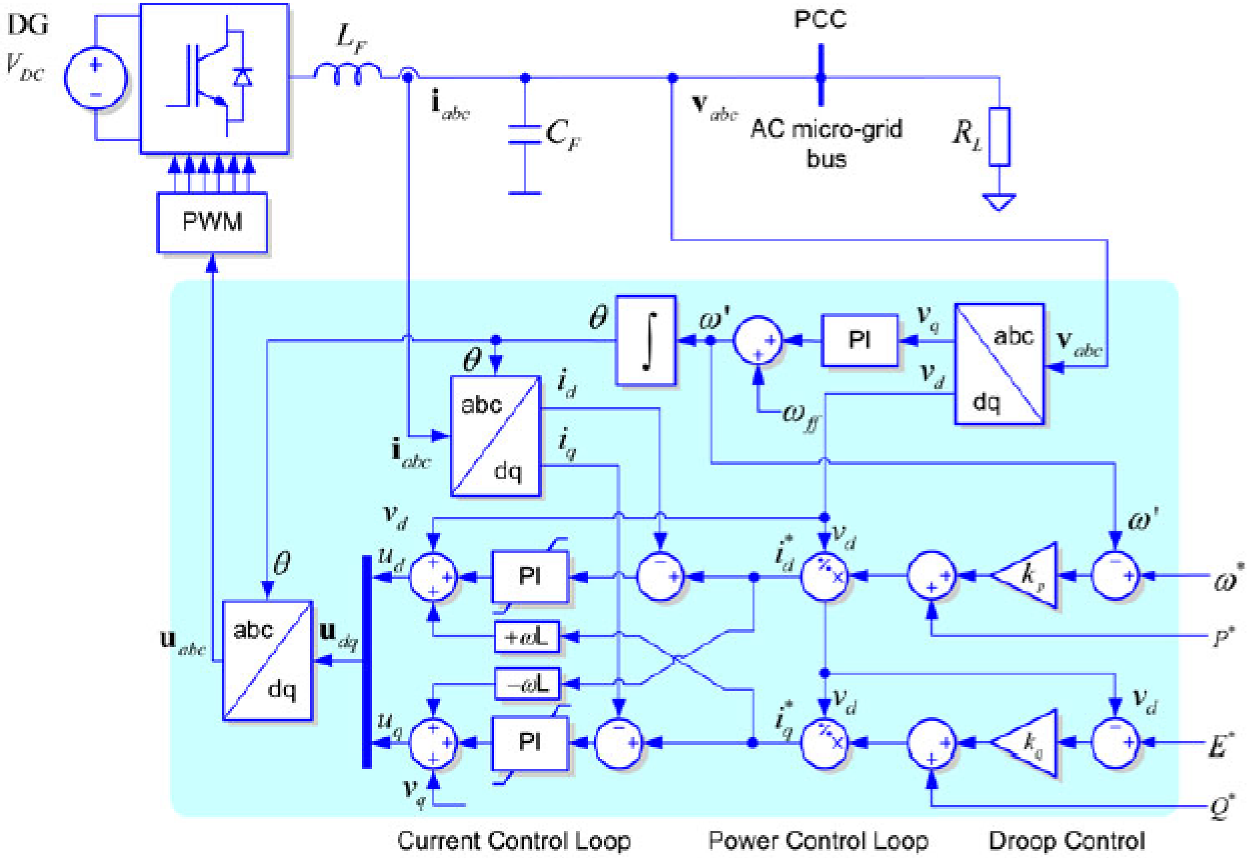


MG primary Controllers: Grid feeding



Current Control Loop
Power Control Loop

MG primary Controllers: Grid supporting

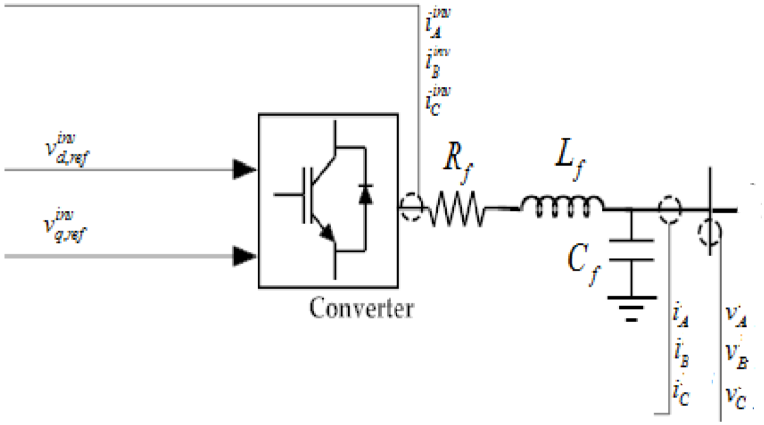


Current controller

KVL neglecting converter dynamics

$$\frac{di_d^{inv}}{dt} = -\frac{R_f}{L_f} i_d^{inv} + \omega i_q^{inv} + \frac{1}{L_f} v_{d,ref}^{inv} - \frac{1}{L_f} v_d$$

$$\frac{di_q^{inv}}{dt} = -\frac{R_f}{L_f} i_q^{inv} - \omega i_d^{inv} + \frac{1}{L_f} v_{q,ref}^{inv} - \frac{1}{L_f} v_q$$



So, defining

$$u_d = \omega L_f i_q^{inv} + v_{d,ref}^{inv} - v_d$$

$$u_q = -\omega L_f i_d^{inv} + v_{q,ref}^{inv} - v_q$$

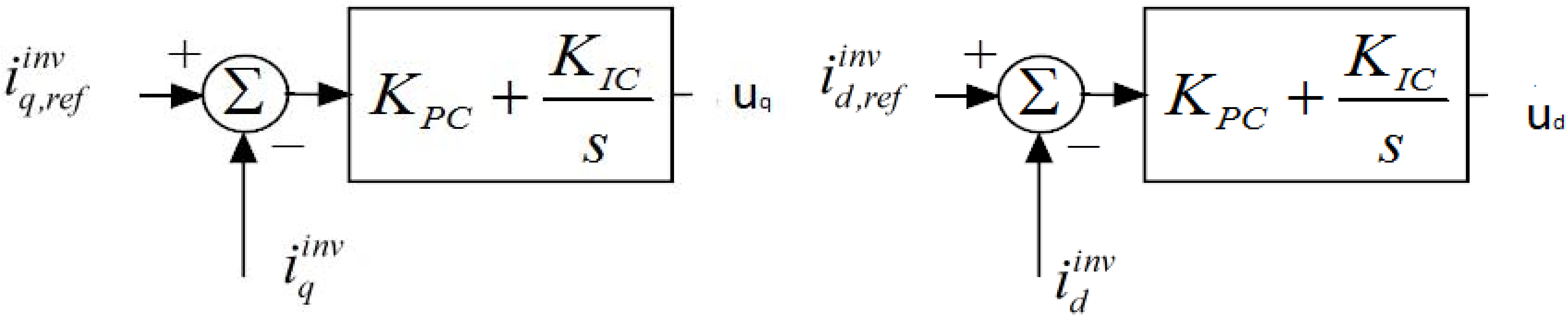
The process is

$$\frac{di_d^{inv}}{dt} = -\frac{R_f}{L_f} i_d^{inv} + \frac{1}{L_f} u_d$$

$$\frac{di_q^{inv}}{dt} = -\frac{R_f}{L_f} i_q^{inv} + \frac{1}{L_f} u_q$$

Current controller

That can be controlled with two PI controllers



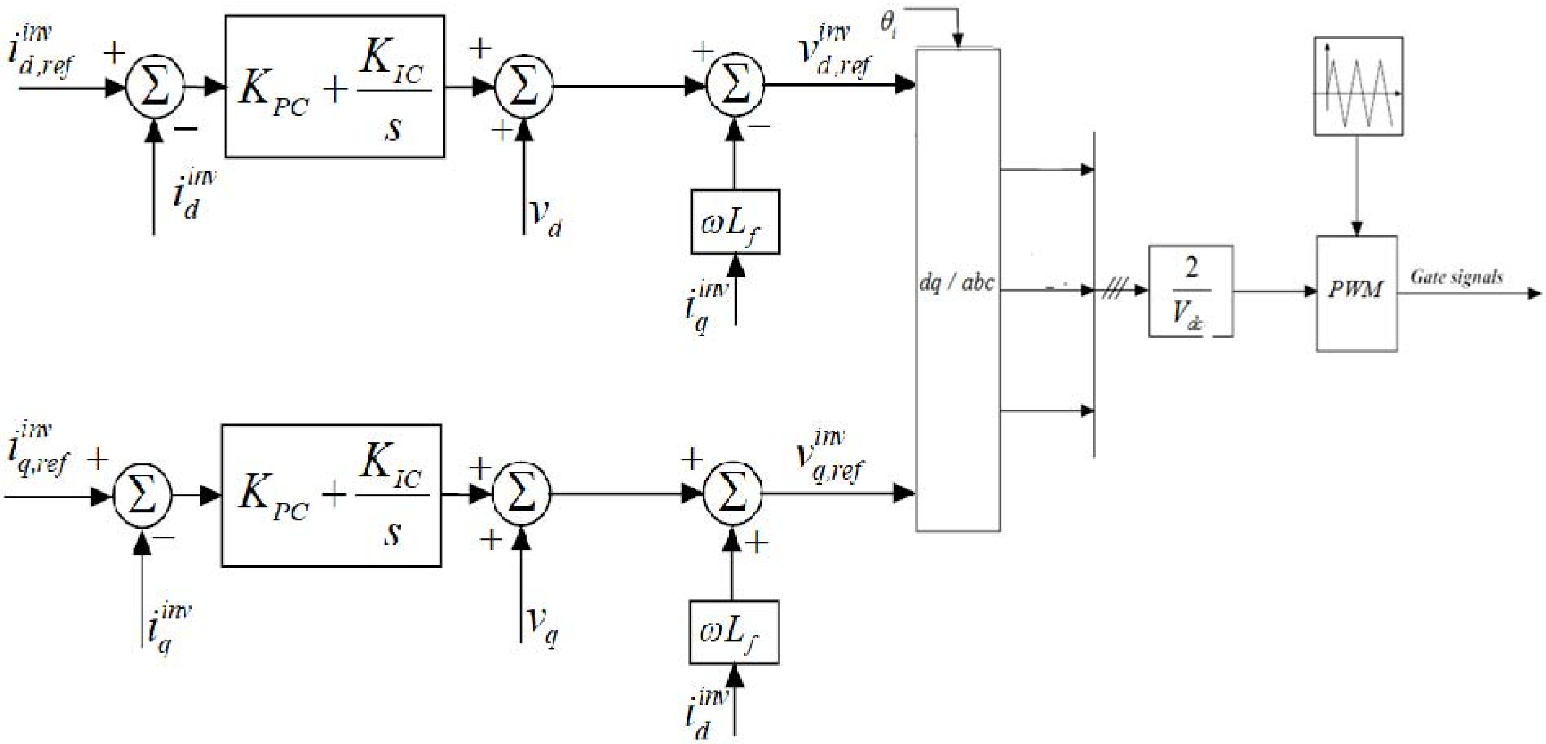
The inverter voltages can be calculated as follows:

$$v_{d,ref}^{inv} = u_d - \omega L_f i_q^{inv} + v_d$$

$$v_{q,ref}^{inv} = u_q + \omega L_f i_d^{inv} + v_q$$

Current controller

The final control scheme is:

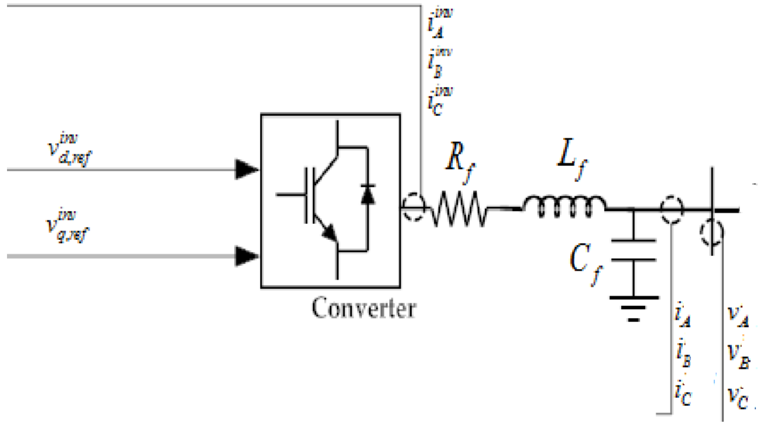


Voltage controller

KCL neglecting current controller dynamics

$$\frac{dv_d}{dt} = \omega v_q + \frac{1}{C_f} i_d^{inv} - \frac{1}{C_f} i_d$$

$$\frac{dv_q}{dt} = -\omega v_d + \frac{1}{C_f} i_q^{inv} - \frac{1}{C_f} i_q$$



So, defining

$$x_d = \omega C_f v_q + i_d^{inv} - i_d$$

$$x_q = -\omega C_f v_d + i_q^{inv} - i_q$$

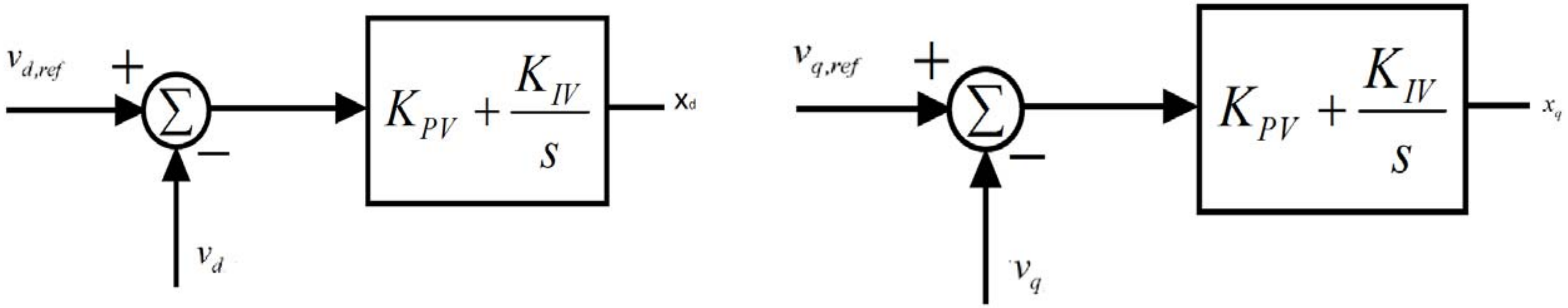
The process is

$$\frac{dv_d}{dt} = x_d$$

$$\frac{dv_q}{dt} = x_q$$

Voltage controller

That can be controlled with two PI controllers



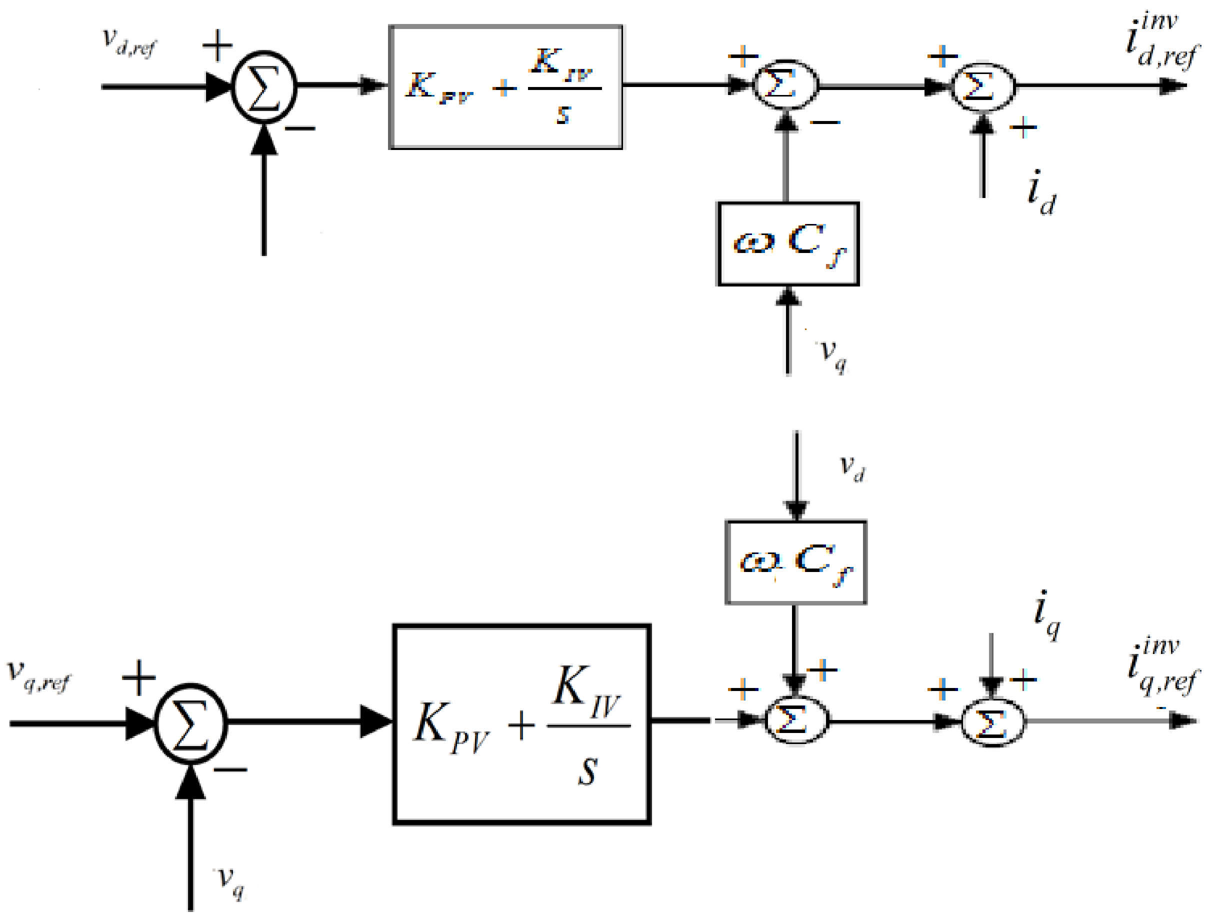
The reference signals for the current controller can be calculated as follows:

$$i_{d,ref}^{inv} = -\omega C_f v_q + x_d + i_d$$

$$i_{q,ref}^{inv} = \omega C_f v_d + x_q + i_q$$

Voltage controller

The final control scheme is



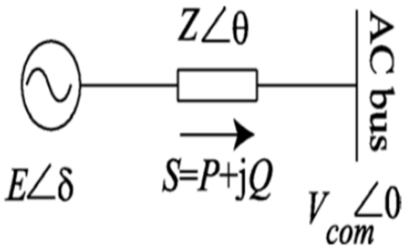
External level: communication based (e.g. Master/slave) or Communicationless (e.g. droop)

Master/slave: one inverter is the slack bus while the other are PQ sources (e.g. storage is master and PVs are slave)

Needs an ICT structure (e.g. if the storage reaches its limit in absorption, the PV must curtail)

Droop is more challenging because it does not need any communication link

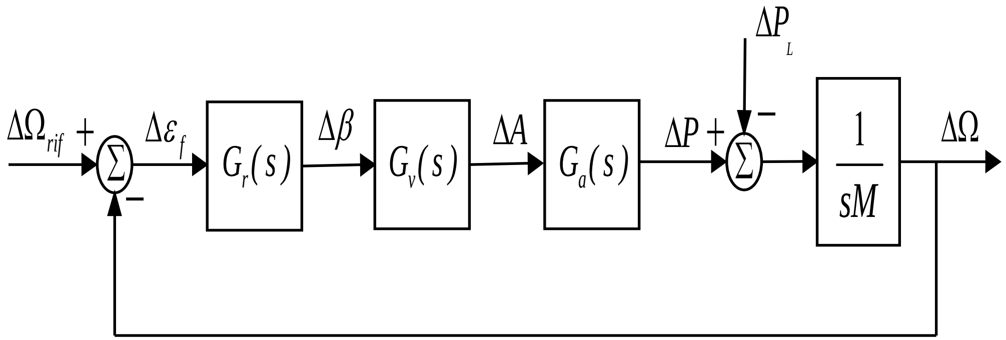
External level: droop control



$$\begin{cases} P = \dfrac{V_{com}E}{Z}\cos(\theta-\delta) - \dfrac{V_{com}^2}{Z}\cos(\theta) \\ Q = \dfrac{V_{com}E}{Z}\sin(\theta-\delta) - \dfrac{V_{com}^2}{Z}\sin(\theta) \end{cases}$$

$$\begin{cases} P = \dfrac{V_{com}E}{Z}\delta \\ Q = \dfrac{V_{com}(E-V_{com})}{Z} \end{cases}$$

Traditional Power System *(f-P)*



Machines share the load power without any communication network
A frequency error exists that needs a secondary control

External level: droop control

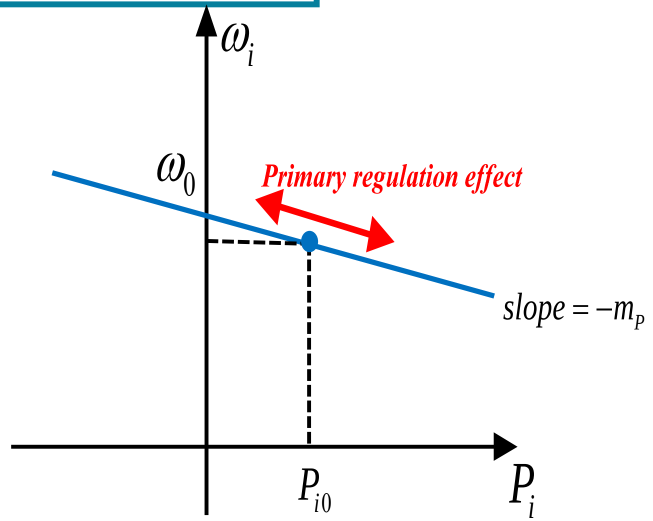
Main goals of droop control strategy in Grid-Supporting inverters are:

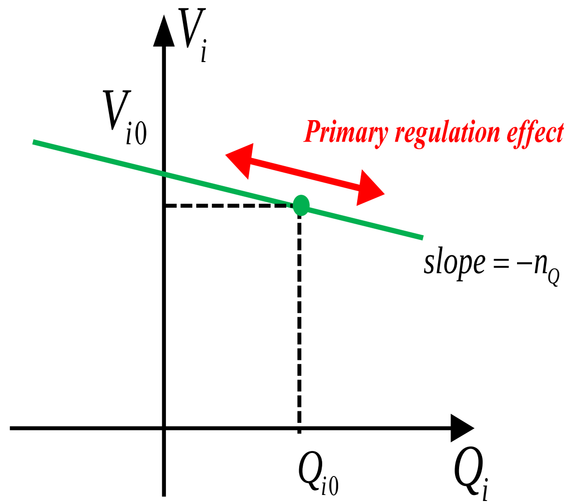
- to maintain MG voltage and frequency stability (acting together with voltage and current control loops);
- to guarantee an equal active and reactive powers sharing among the inverters connected to the MG.

The droop control laws for the *i*-th inverter are reported below:

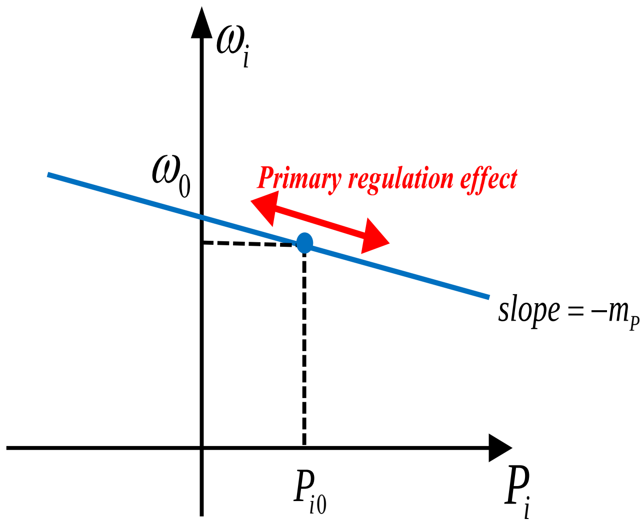
$$\boxed{\omega_i - \omega_0 = m_i (P_{i0} - P_i)}$$

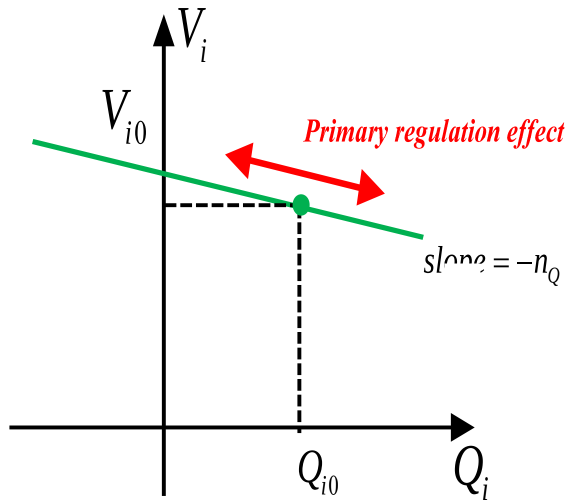
$$\boxed{V_i - V_{i0} = n_i (Q_{i0} - Q_i)}$$





Droop control and inner loops





$$\omega_i - \omega_0 = m_i (P_{i0} - P_i)$$

$$\theta_i = \int_0^t \omega_i(s)\,ds + \theta_{i0}$$

?

$$V_i - V_{i0} = n_i (Q_{i0} - Q_i)$$

$$v_{d,i}^{ref} = V_i$$

$$v_{q,i}^{ref} = 0$$

To voltage controller

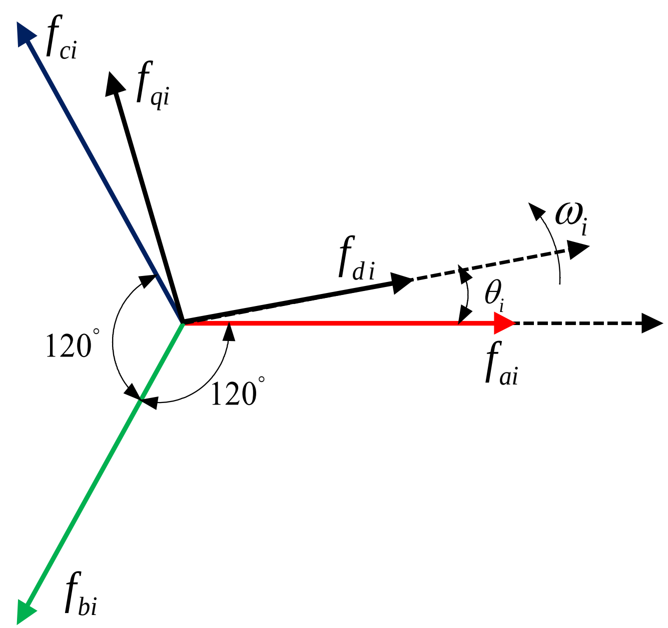
Droop control and inner loops

$$\omega_i - \omega_0 = m_i (P_{i0} - P_i)$$

$$\theta_i = \int_0^t \omega_i(s)\,ds + \theta_{i0}$$

Park angle for voltage and current controllers

$$K_P(\theta_i) = \sqrt{\frac{2}{3}} \begin{bmatrix} cos(\theta_i) & cos(\theta_i - \frac{2}{3}\pi) & cos(\theta_i + \frac{2}{3}\pi) \\ -sin(\theta_i) & -sin(\theta_i - \frac{2}{3}\pi) & -sin(\theta_i + \frac{2}{3}\pi) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$



Active power droop control

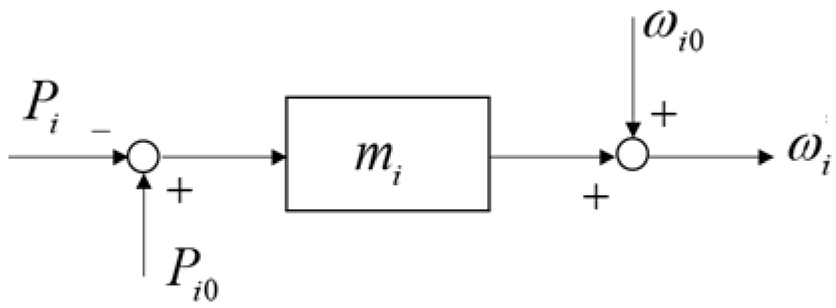
As one can show that $\lim_{t\to\infty}\omega_i(t)=\tilde{\omega} \quad \forall i=1,\dots,N_{inv}$

Choosing $m_{P_1}P_{10}=m_{P_2}P_{20}=\dots=m_{P_i}P_{i0}=\dots=m_{P_{N_{inv}}}P_{N_{inv}0}=k$

One has $m_{P_1}P_1=m_{P_2}P_2=\dots=m_{P_i}P_i=\dots=m_{P_{N_{inv}}}P_{N_{inv}}=k$

But $\sum_{i=1}^{N_{inv}}P_i=P_{load}$

So $$P_i=\frac{P_{load}}{m_{P_i}\sum_{i=1}^{N_{inv}}\frac{1}{m_{P_i}}}$$



Active power sharing

Reactive power droop control

$$Q_i = \frac{\left(V_i - V_{PCC}\cos\delta\right)}{X_{C,i}} V_i \approx \frac{\left(V_i - V_{PCC}\right)}{X_{C,i}} V_i \qquad V_i - V_{i0} = n_i (Q_{i0} - Q_i)$$

$$Q_i = \frac{V_{i0} + n_i Q_{i0} - V_{PCC}}{X_{C,i} + n_i V_i} V_i \cong \frac{V_{i0} + n_i Q_{i0} - V_{PCC}}{X_{C,i} + n_i V_{PCC}} V_{PCC}$$

IF
- *i)* $n_i Q_{i0}$=const,
- *ii)* V_{i0} does not depend on i (i.e. it is the same for all inverters)
- *iii)* $X_{C,i} \ll n_i V_i$,

$$Q_i n_i \cong \left(V_{i0} + n_i Q_{i0} - V_{PCC}\right) = const$$

Reactive power sharing

Reactive power droop control

Reactance influences reactive power sharing;

Reactive power «loop flow» if $n_i Q_{i0} + V_{i0} \neq const$

Voltage profile uncontrolled.

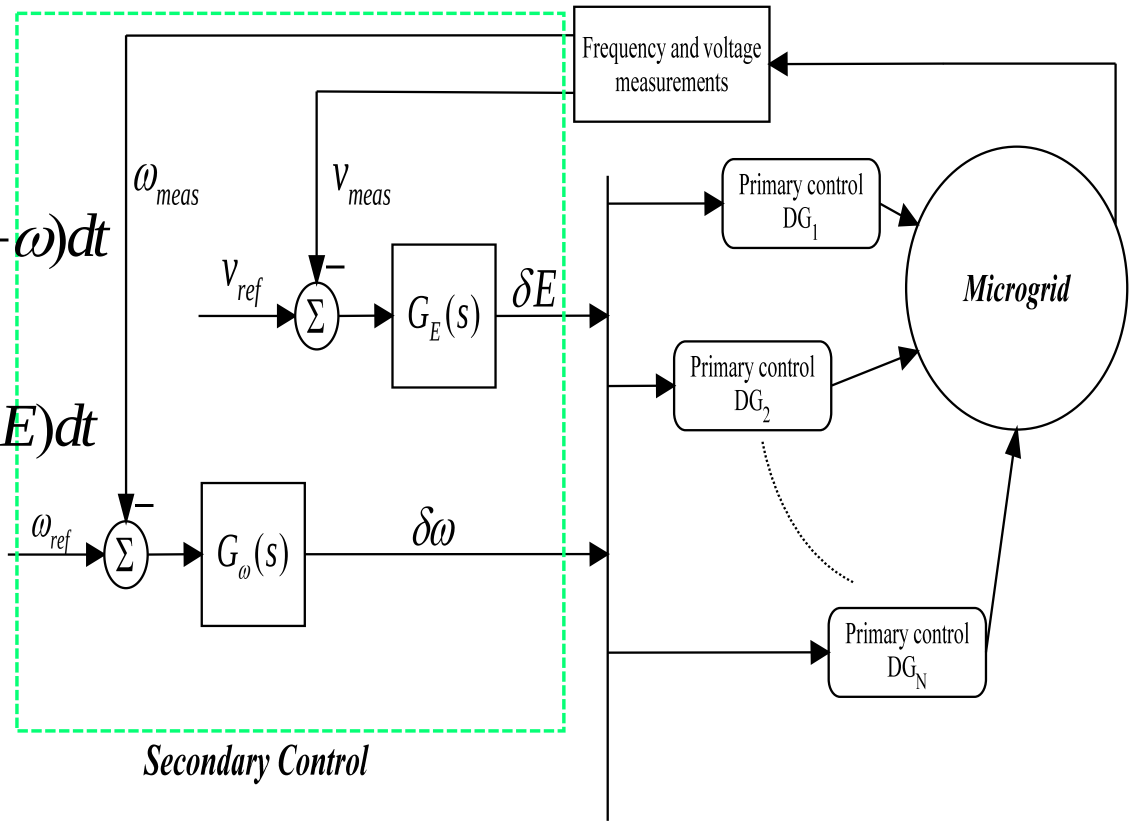
Traditional secondary control for Islanded Microgrids

- Centralized controller
- Designed to have slower dynamic response than the primary
- Decoupled dynamic analysis of primary and secondary control loops

PI regulators

$$\delta\omega = K_{P\omega}(\omega_{ref} - \omega) + K_{I\omega}\int(\omega_{ref} - \omega)dt$$

$$\delta E = K_{PE}(v_{ref} - E) + K_{IE}\int(v_{ref} - E)dt$$

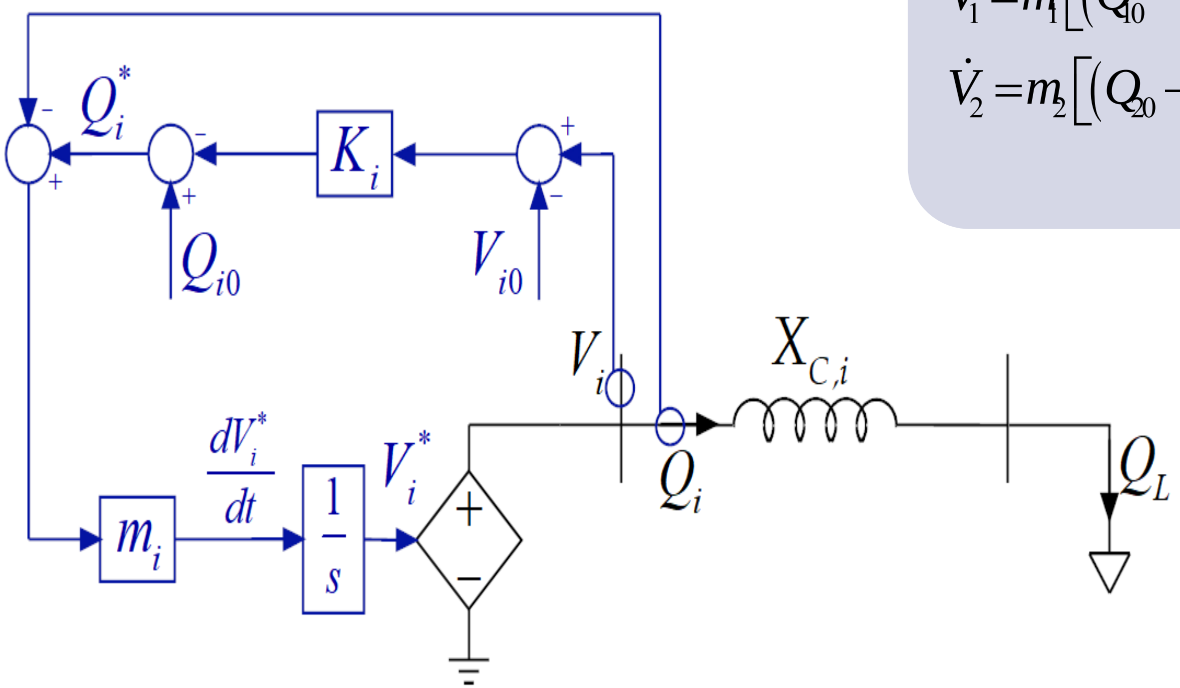


Research lines: 1) Advanced droop control

Control law

$$\dot{V}_1 = m_1\left[\left(Q_{10} - Q_1\right) - K_1\left(V_1 - V_{10}\right)\right]$$

$$\dot{V}_2 = m_2\left[\left(Q_{20} - Q_2\right) - K_2\left(V_2 - V_{20}\right)\right]$$



Research lines: 1) Advanced droop control

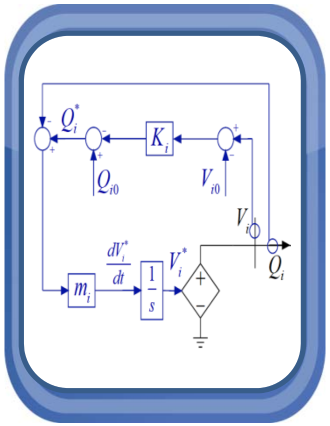
Pros	Cons
• n_i control dynamics without affecting steady state; • Possibility to control voltage with k; • Better reactive power sharing	• K_i depend on connection reactances; • n_i are empirically chosen; • Control suffers from coupling with P channel.

Research lines: 1) Advanced droop control

Enhancement of the sharing algorithm to account for cable reactances.

Test with meshed grids with many inverters.

Test in presence of synchronous machines



Research lines: 2) Model based controllers for MGs

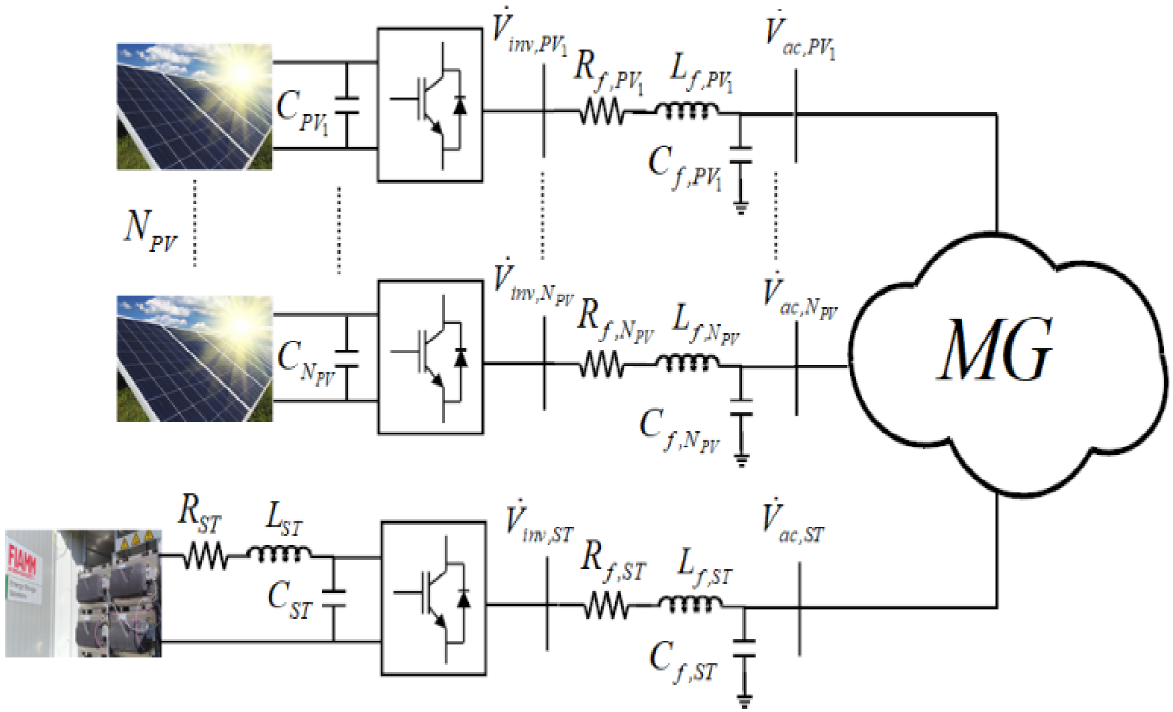
Control objectives:

1) restore the system frequency and voltage after a contingency without any communication systems among the local controllers (i.e. the proposed structure combines the action of the **classic primary and secondary frequency and voltage regulators with no need of communication links**)

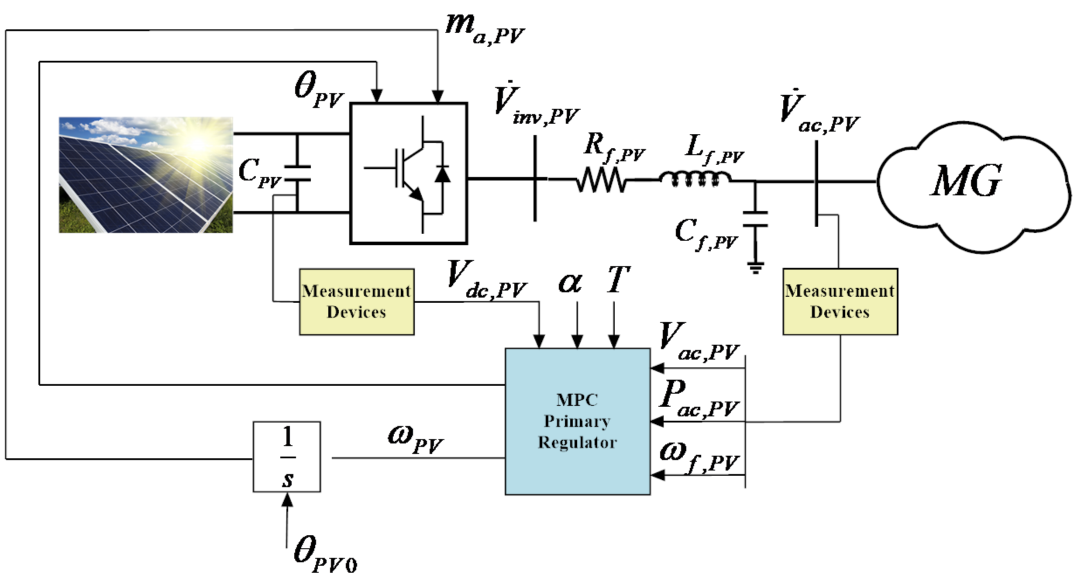
2) guarantee the possibility of new PV units plug-and-play

3) account for the storage technical limits in terms of SOC and maximum absorption/injection power. This implies that when the storage power and SOC are within the limits, the PV units must work at their MPP; while their power production must be curtailed when one of such limits is violated

Research lines: 2) Model based controllers for MGs

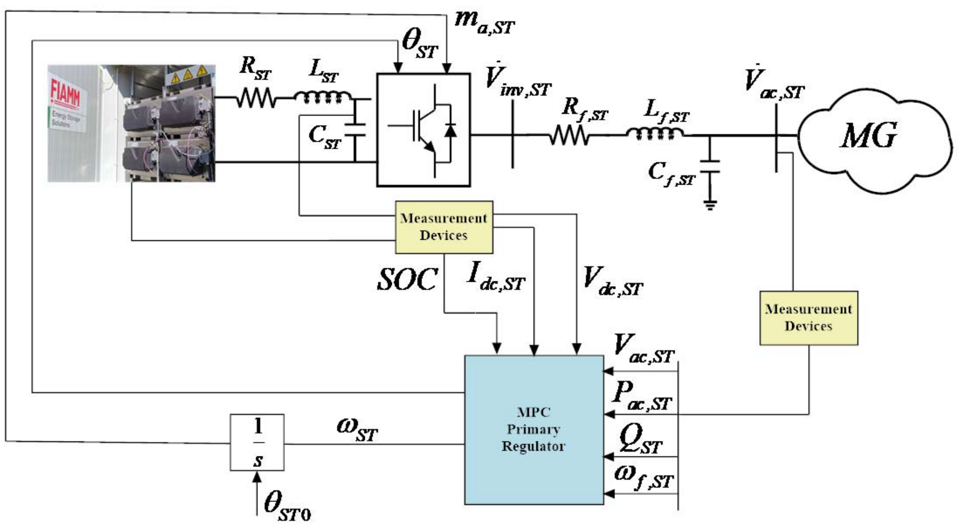


Research lines: 2) Model based controllers for MGs



PV controller

Research lines: 2) Model based controllers for MGs



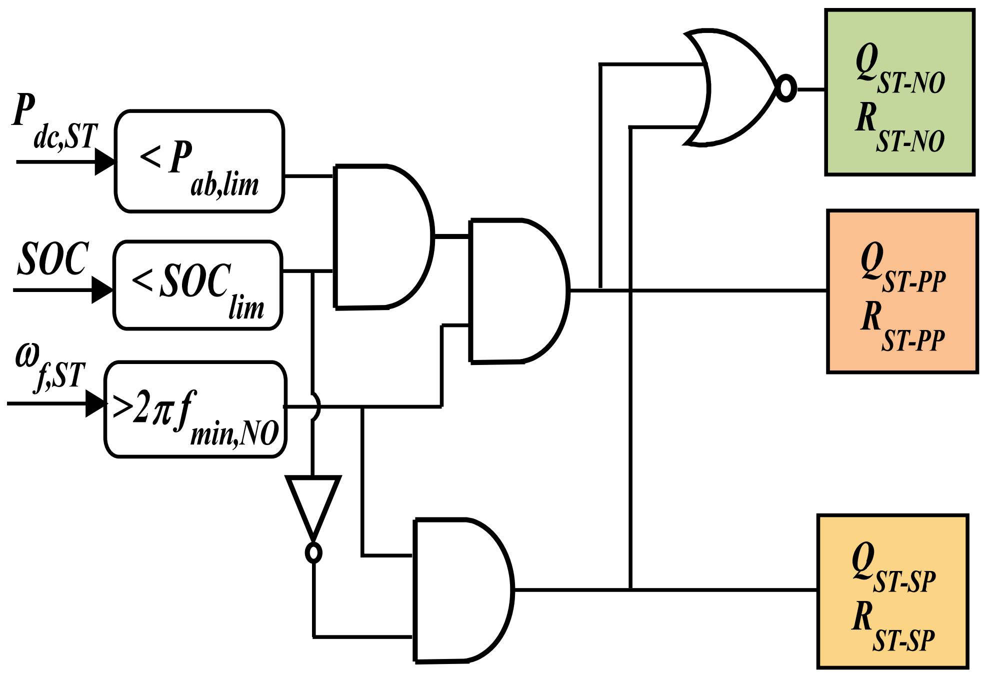
Storage controller

Research lines: 2) Model based controllers for MGs

	ST converter	PV converter
Normal Operation mode	NO	NO
Power Priority mode	PP	PP-SP
SOC Priority mode	SP	PP-SP

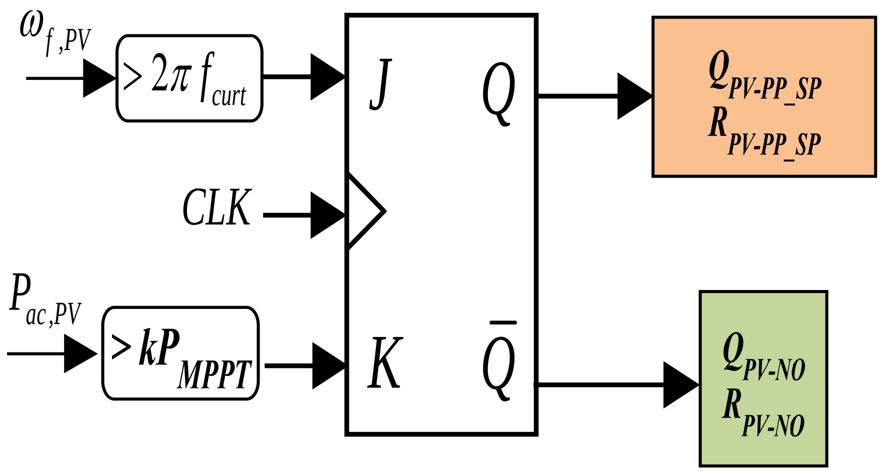
Operating modes

Research lines: 2) Model based controllers for MGs



Automatic transition: Storage controller

Research lines: 2) Model based controllers for MGs



Automatic transition: PV controller