Power Conversion Systems on μGrids

3DMicroGrid Workshop: Design of Smart Microgrids

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November 8th, 2017

0. Schedule

- 1. Basic concepts and definitions:
  - Microgrids, definition and concepts
- 2. Roles for μGrid power converters:
  - Grid-feeding converters
  - Grid-forming converters
  - Grid-supporting converters
- 3. Synchronous power in microgrids
- 4. μGrid control structures
- 5. Synchronous services in microgrids
- 6. Final Conclusions

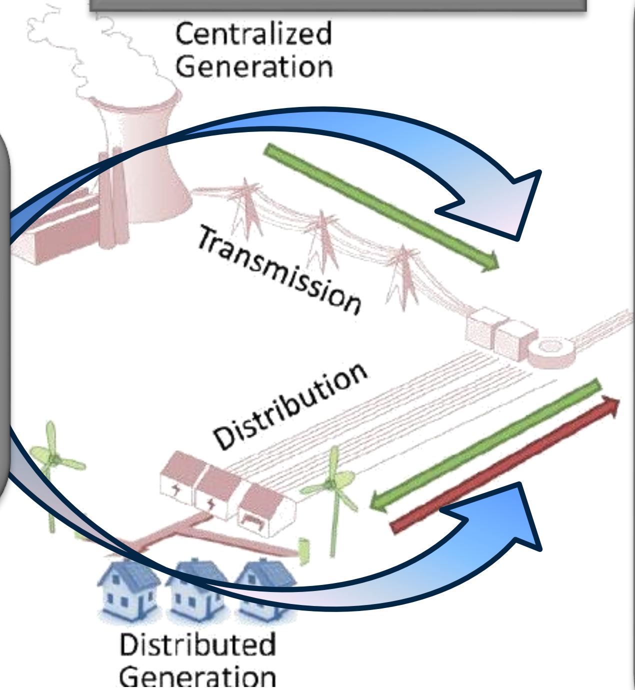
1. Basic concepts and definitions

1. Basic concepts and definitions

Increase of the Energy Demand

Centralized Generation

The main demand was supported by some big plants in unidirectional power flow.



The power flow is unidirectional: from the central power stations towards the consumer

Improvement of the Renewable Energies

Distributed Generation

New concept in which the energy demand is supported by local DG sources: The Microgrid.

- Reduction generation-consumer distance. On-site production.
- Ancillary Services as new advantages with storage Energy.
- High introduction of RE.

1. Basic concepts and definitions

Coordinated and Controlled electrical subsystem with:

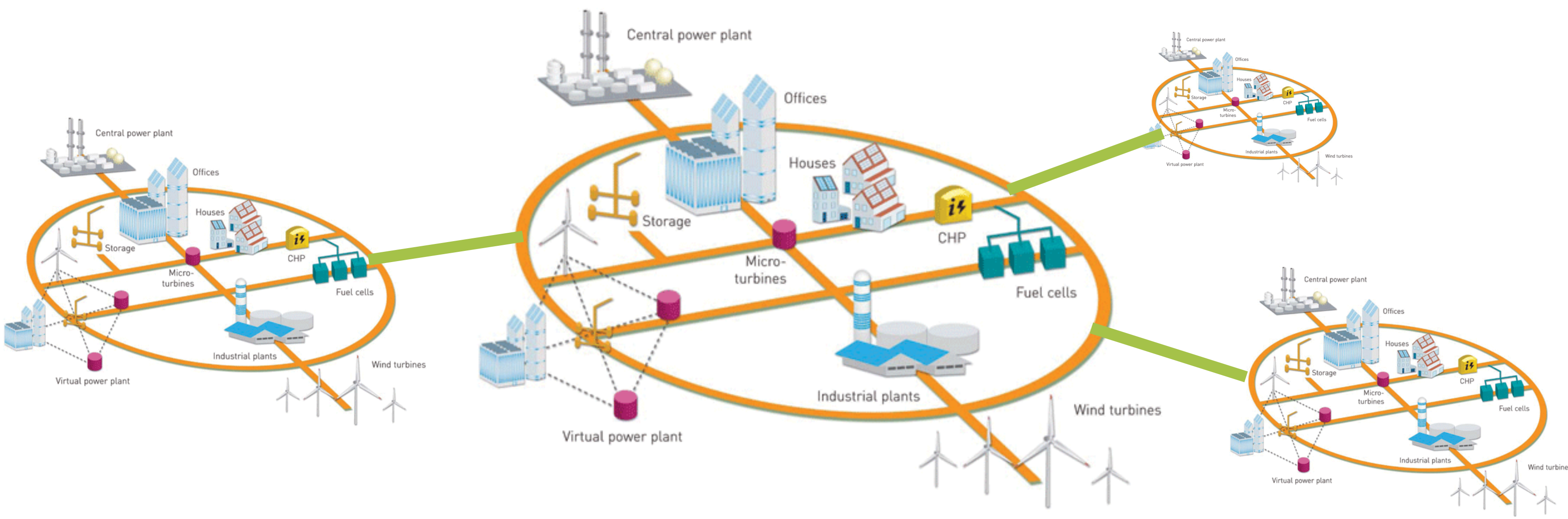
- Multiple distributed energy resource units
- Multiple consumers
- Interconnections at distribution voltage level
- Capable of grid independent and grid dispatchable interactive operations.

A **Microgrid** is a set of loads, some reviews and other expendable, generators and power distribution of various technologies, and energy storage systems, all with a high degree of local and remote controllability, which can operate as a functional unit autonomously, or in isolation from the mains or being connected to it.

1. Basic concepts and definitions

A micro-grid is conceptually considered as a small scale grid, formed by DG systems, EES devices and loads that are electrically interconnected and hierarchically controlled, with the capability to operate either as a grid connected or as an intentionally islanded system without harming the transmission grid's integrity.

Interconnected microgrids should operate in a collaborative way by implementing a scalable control structures with implementation of advanced functionalities for grid supporting



1. Basic concepts and definitions

Protection and control practice

- Bi-directional power flows
- Reactive Power Control for Voltage Regulation
- Redundancy

Non-conventional generation integration.

- Variabiity of renewable energy sources, specially suitable for Wind and Photovoltaics.
- Optimization of non-renewable power generation systems whose generation profiles can be controlled.
- Integration of short, medium and long term energy storage to mitigate the stochastic behavior of renewable sources.
- Modularity
- Low overload, short circuit ratings
- Power rate limits
- Potential for active load control

Supervisory and regulatory markets

- Fault tolerance.
- High penetration of DG without requiring re-design or re-engineering of the distribution system
- Hierarchical control to perform a coordinated interaction with management and control operations of the main grid

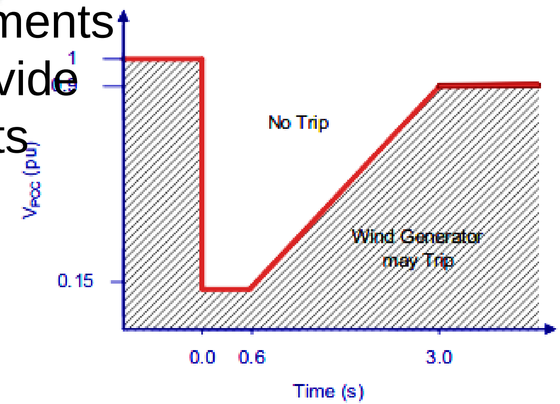
1. Basic concepts and definitions

Grid state

Modern DG systems with a high controllability and operability degree will permit to the microgrid play a major and decisive role in maintaining the stability of the electrical networks in the future, also under grid fault conditions.

Recent standards IEEE 1547 UL1741 give a guideline, for micro-grids with stand-alone capability, to be disconnected from the main grid.

In wind power and PV systems, the low voltage ride through (LVRT) requirements demand to remain connected to provide specific grid support during grid faults.



In the first DG units, the standards required their disconnection in any case of grid faults occurrence.

1. Basic concepts and definitions

Power Conversion requirements in μGrids

Power Requirements:

- Power level: 20-300 kW
- Voltage levels 200V – 13 kV
  - Actually, most of the conversion stage works at low voltage levels with a voltage step-up transformer. However new switches specifications and multilevel converters will move the standards at medium voltage ranges.
- Switching frequency: 10 kHz until 50 kHz

Control Requirements:

- Active strategies for MPPT, delta strategies, power limitation, etc…
- Grid-tie or island operation mode, as well as transition between them
- P/f and Q/v droop control
- Capability of droop curves modification through external high-order control loops
- Capability of receive external references of P, Q or V dispatched from the Microgrid Central Controller

2. Roles for μGrid power converters

2. Roles for µGrid power converters

2.1 Introduction

1. Grid-feeding units are controlled to extract maximum active power from their primary energy source and the required reactive power to support grid voltage sags and local demands of reactive current. Grid-feeding units are operated by the current controlled mode as normal grid-connected DER units.

2. Grid-Supporting units adjust the output active and reactive power (P and Q) based on the power dispatch strategies or the frequency and voltage variation of the load or the feeder busbar.

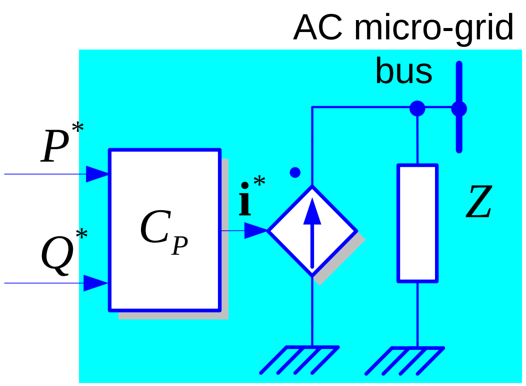
3. Grid-forming units regulate the system voltage and frequency through balancing the generation power and load demands when the microgrid operates in the islanded mode. In presence of the main grid the grid-forming units are changed to operate as grid-feeding units.

2. Roles for μGrid power converters

2.2 Grid-feeding power converters

Grid-feeding power converters are designed to deliver power to an energized grid. Are represented as an ideal current source connected to the grid in parallel with a high impedance.

Constant power injection, without supporting the grid

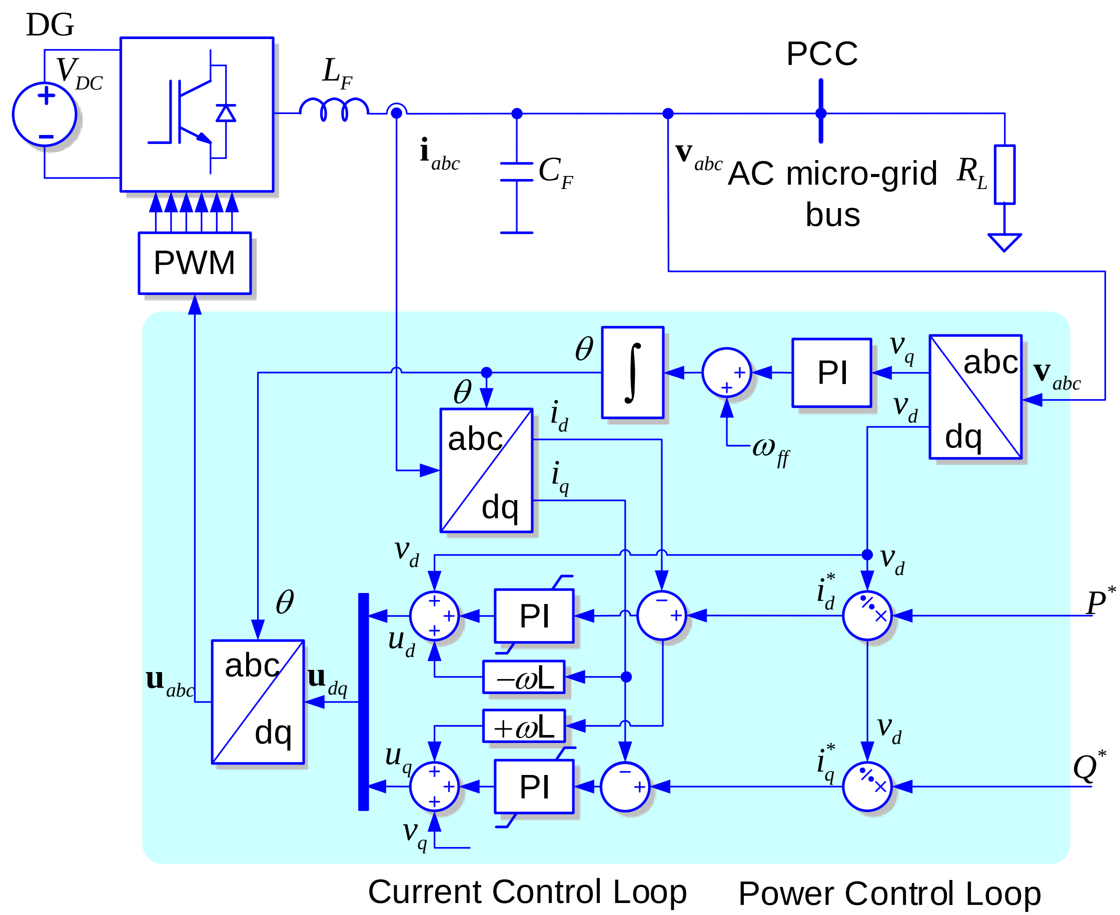


- This is the main role applied in grid-tie converters, usually controlled with a MPPT algorithm or by a power plant controller (secondary and tertiary control level).
- Can not operate alone feeding a load in a microgrid in island mode.
- Operate in parallel with any grid-feeding or with other role inverter in any grid-connection state.

2. Roles for μGrid power converters

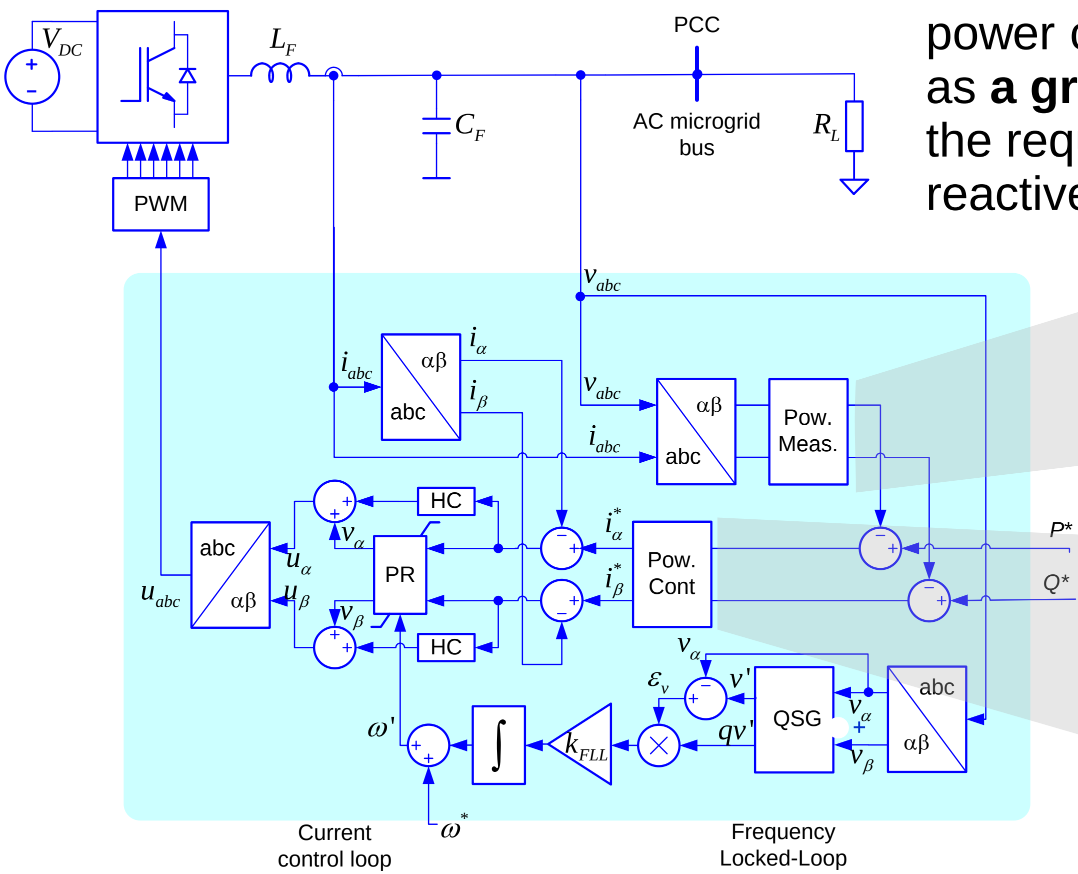
2.2 Grid-feeding power converters

- The inner current controller of grid-feeding converters lays on fast control loops that regulate the current injected, external controller sets the reference current to regulate the P and Q delivered to the grid.
- Most of this controllers are based on regular PI controllers working on dq synchronous reference frame.
- A good synchronization technique is necessary in order to provide the proper P and Q



2. Roles for µGrid power converters

2.2 Grid-feeding power converters



<u>Grid-connected Mode</u>:
the current reference $\mathbf{i}_{\alpha\beta}$*, is given by a power controller, and the VSI operates as **a grid-feeding** converter, injecting the required value of active and reactive power, P* and Q*.

$$p = v_\alpha i_\alpha + v_\beta i_\beta$$
$$q = v_\beta i_\alpha - v_\alpha i_\beta$$

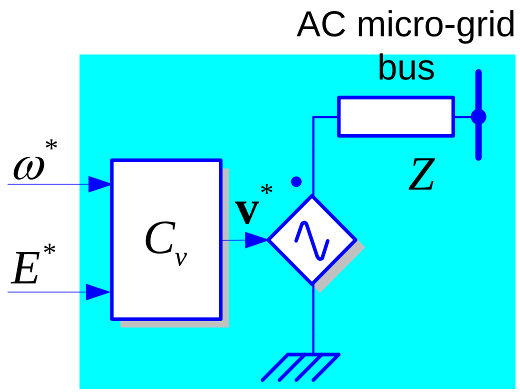
For open loop:

$$\begin{bmatrix} i^*_\alpha \\ i^*_\beta \end{bmatrix} = \frac{P^*}{\left|\mathbf{v}^+_{\alpha\beta}\right|^2} \cdot \begin{bmatrix} v^+_\alpha \\ v^+_\beta \end{bmatrix} + \frac{Q^*}{\left|\mathbf{v}^+_{\alpha\beta}\right|^2} \cdot \begin{bmatrix} v^+_\alpha \\ v^+_\beta \end{bmatrix}$$

2. Roles for μGrid power converters

2.3 Grid-forming power converters

Grid-forming power converters can be represented by an ideal AC voltage source with a low output impedance (Z), setting the voltage amplitude, E^*, and frequency, ω^*, of the local grid.



- Operates only in islanded microgrid condition, disconnected from the mains.
- Voltage and frequency controlled in closed loop.
- Parallelized only with near high band-width communications.
- Usually feed by stable DC-sources: batteries, fuel cells, etc

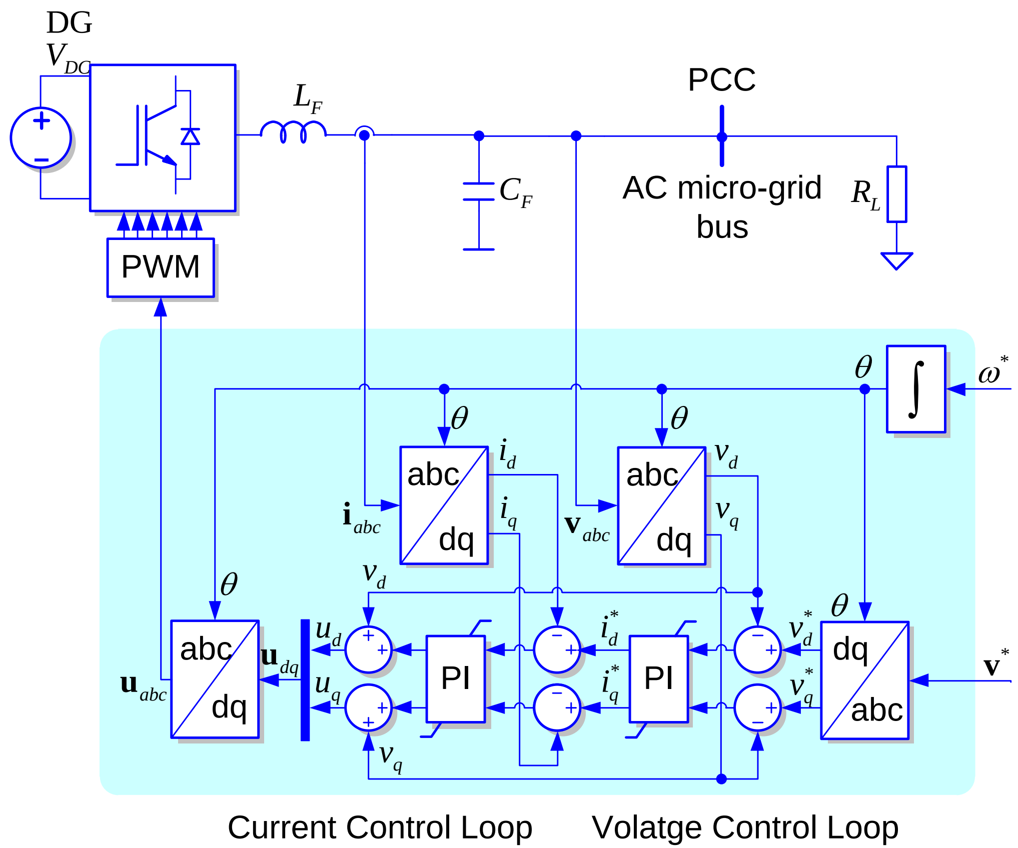
Island operation: The micro-grid voltage and frequency reference values, ***E**** and ***ω****, will experience small and slow variations, ***δE*** and ***δω***, to resynchronize in phase-angle, frequency and amplitude with the main network voltage before reconnecting, from island to grid-connected mode transition.

2. Roles for µGrid power converters

2.3 Grid-forming power converters

The DG does not actively regulate the voltage at the PCC in grid-connected mode, so the direct voltage regulation (or grid-forming operation) is only available in grid island mode.

The main control structure of a grid-forming power converter consists of two cascaded loops. The error between the reference and the measured voltage is the input to a controller whose output establishes the current reference, i^*.

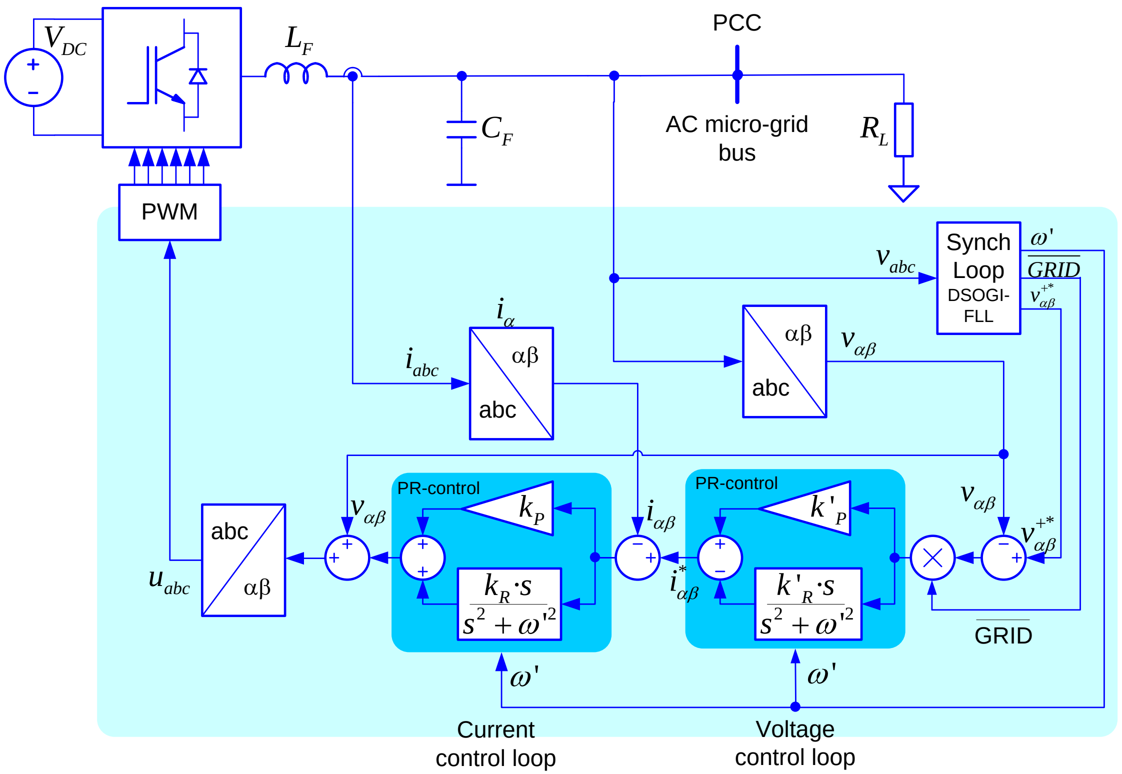


2. Roles for µGrid power converters

2.3 Grid-forming power converters

Island Mode:

ICA operates as a **grid-forming** converter and gives the required current, $\mathbf{i_{\alpha\beta}^*}$, to obtain the sinusoidal reference voltage, $\mathbf{v_{\alpha\beta}^*}$, imposing thus the micro-grid voltage and frequency.



In this case the converter is controlled as a grid-forming.

$$\mathbf{v}_{\alpha\beta}^{*+} = \mathbf{v}_{NOM}$$

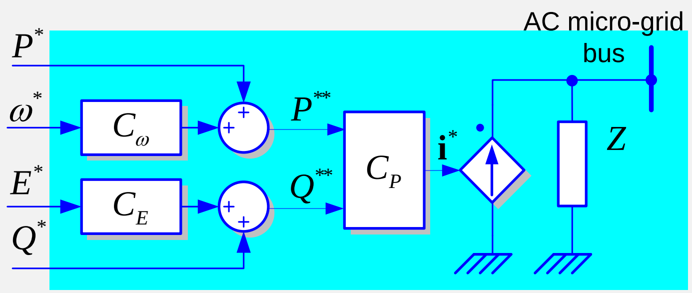
$$\omega' = 2\pi f_{NOM}$$

2. Roles for µGrid power converters

2.4 Grid-supporting power converters

Grid-Feeding Based

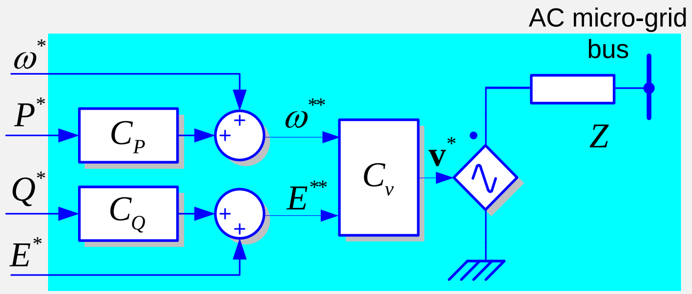
Controlled as a current source with a parallel impedance.



- It's the general case of the WT or PV with a MPPT algorithm, but they should provide a given amount of power for regulatory purposes in case of grid failures.

Grid-Forming Based

Controlled as a voltage source with a link impedance.



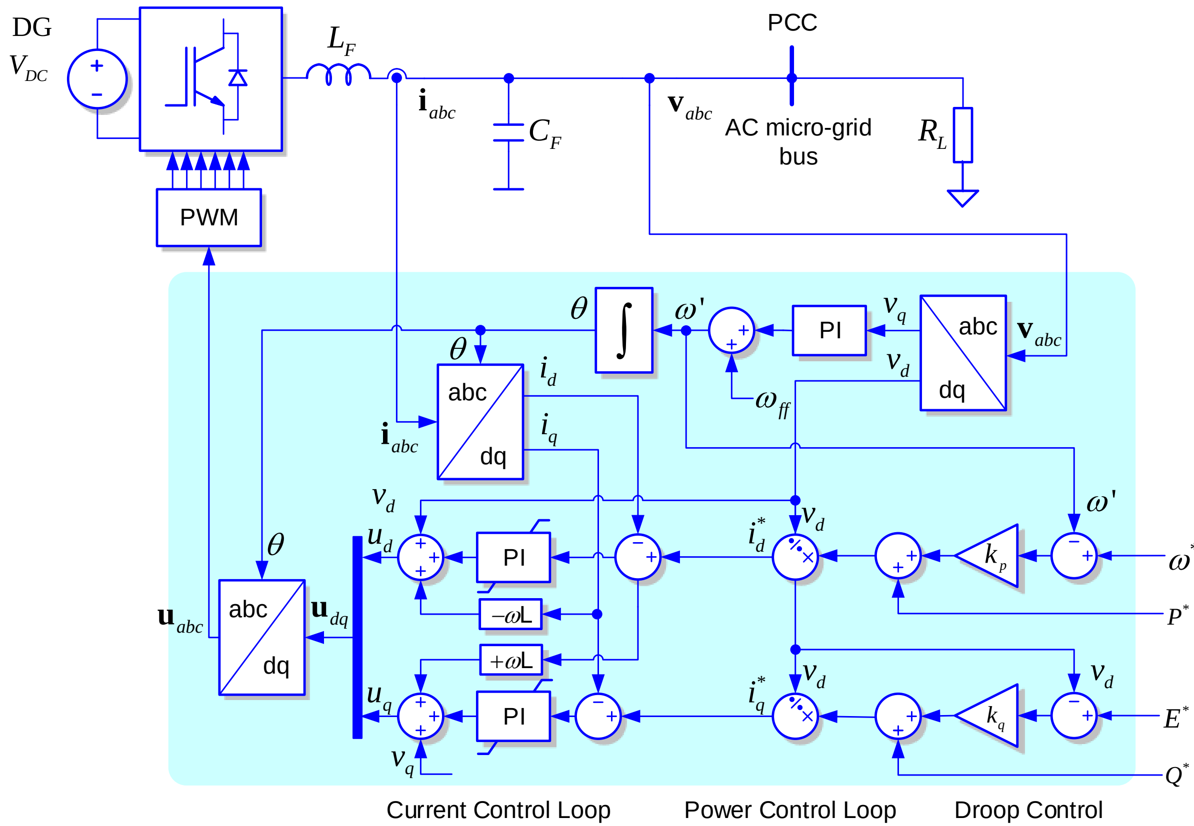
- Equivalent with simplified synchronous machine scheme.
- The power flow is controlled through the voltage imposed by the VSI, the PCC voltage and the line impedance, Z, (real or virtual).

2. Roles for µGrid power converters

2.4 Grid-supporting power converters – grid-feeding based structure

Controlled with an active and reactive power reference to be injected into the grid, corrected according with the deviation of the nominal grid voltage or frequency values:

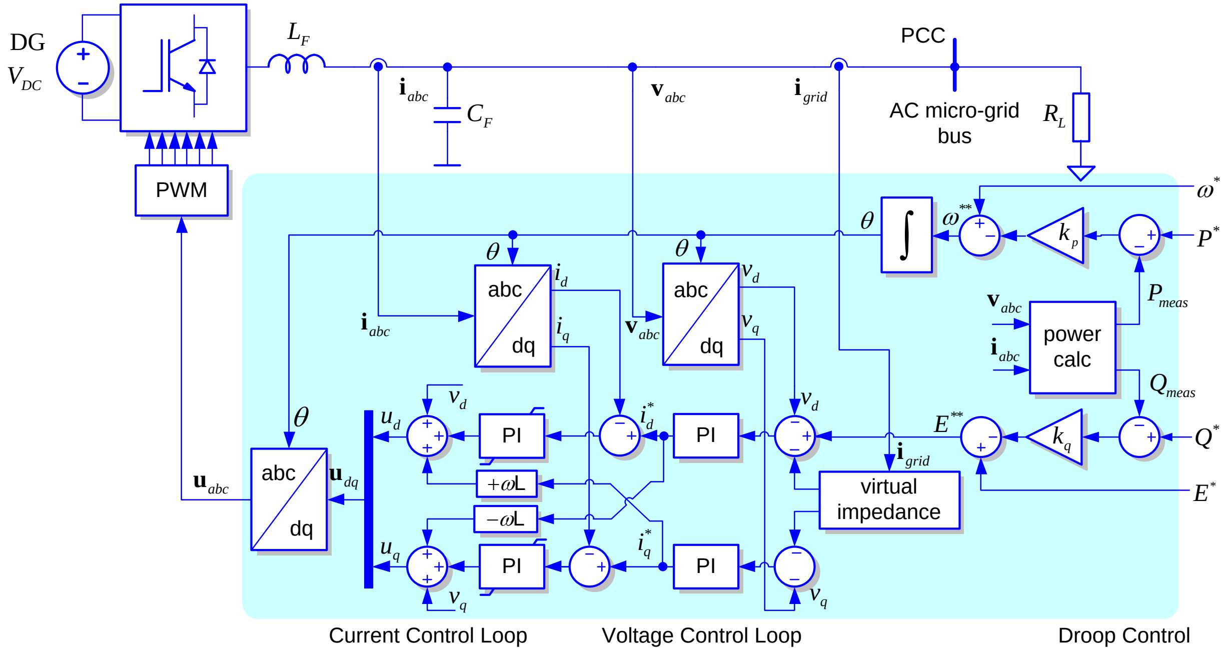
- Voltage and frequency support regulation.
- Requires to operate in parallel with a grid-forming or with a grid-supporting based on a grid-forming.
- Easily parallelized with high bandwidth communication or by Droop control algorithm



2. Roles for μGrid power converters

2.4 Grid-supporting power converters – grid-forming based structure

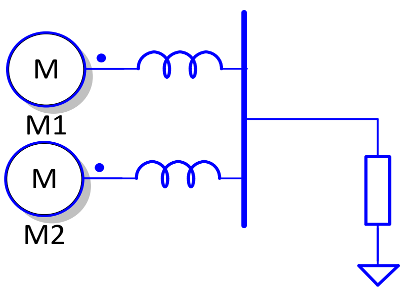
- Voltage and frequency support.
- Can operate, with voltage and frequency supporting capabilities, in any grid operation mode.
- Don't require the connection of any grid-forming converter in the micro-grid, neither in island mode.

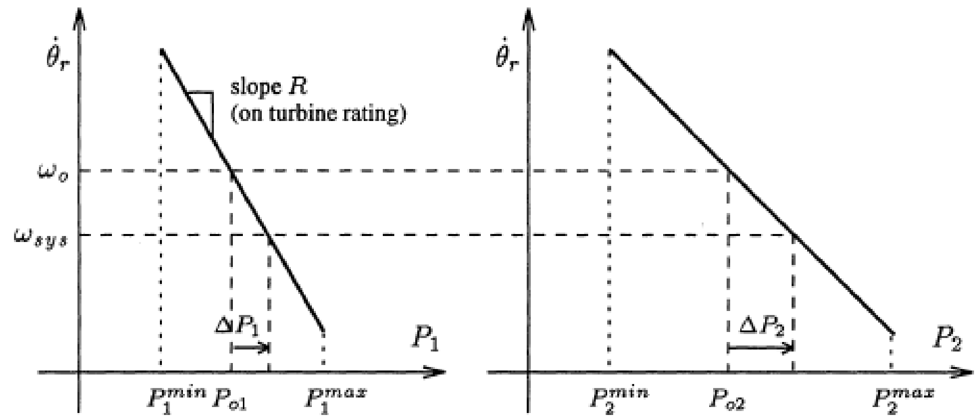


2. Roles for µGrid power converters

2.4 Grid-supporting power converters – droop curves

Inverter grid support through the droop control mimic the governor regulation capability of the synchronous generator in grid-connection mode. This droop is implemented in the governor machine's control for load sharing proposes, between others.





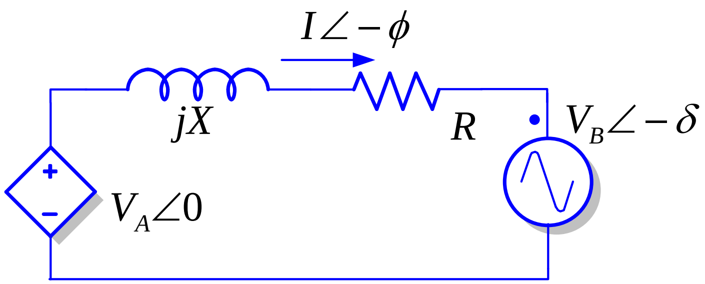
Also decrease the injected reactive power when the grid voltage amplitude increases

Droop control algorithms are used to control the power sharing in micro-grids without using communication channels. These techniques are implemented in grid-supporting converters to regulate the exchange of P and Q with the grid in order to maintain the f_{grid} and E_{grid} under control.

2. Roles for µGrid power converters

2.5 Grid-supporting power converters – line impedance influence

The power exchange between two voltage source, V_A and V_B, connected through a impedance line *Z*, *Z*=*R*+jX_L is defined by the following expressions:



$$P_A = \frac{V_A}{R^2+X^2}\left[R\left(V_A - V_B\cos\delta\right) + XV_B\sin\delta\right]$$

$$Q_A = \frac{V_A}{R^2+X^2}\left[-RV_B\sin\delta + X\left(V_A - V_B\cos\delta\right)\right]$$

Type of Line	R (Ω/km)	X (Ω/km)	R/X (p.u.)
Low Voltage Line	0.642	0.083	7.7
Medium Voltage Line	0.161	0.190	0.85
High Voltage Line	0.06	0.191	0.31

Low Voltage Line ≈ Resistive Line

$$P_A \approx \frac{(V_A - V_B)\cdot V_A}{R_L} \qquad Q_A \approx \frac{\delta\cdot V_A\cdot V_B}{R_L}$$

High Voltage Line ≈ Inductive Line

$$P_A \approx \frac{\delta\cdot V_A\cdot V_B}{X_L} \qquad Q_A \approx \frac{(V_A - V_B)\cdot V_A}{X_L}$$

2. Roles for μGrid power converters

2.5 Grid-supporting power converters – line impedance influence

Direct droop control – Inductive line

In line impedance of strong electrical grids, reactance is much more important than the resistive X>> R and R/Z is close to zero and θ is aprox. 90º. Moreover, as the power angle δ is small, the following simplifications can be used:

$$P_A = -\frac{U_A U_B}{X}\cos(\theta+\delta) \qquad \sin\delta \approx \delta$$

$$Q_A = \frac{U_A^2}{X} - \frac{U_A U_B}{X}\sin(\theta+\delta) \qquad \cos\delta \approx 1$$

With these assumptions, previous equations are simplified in:

$$U_A - U_B \approx \frac{XQ_A}{U_A} \qquad \delta \approx \frac{XP_A}{U_A U_B}$$

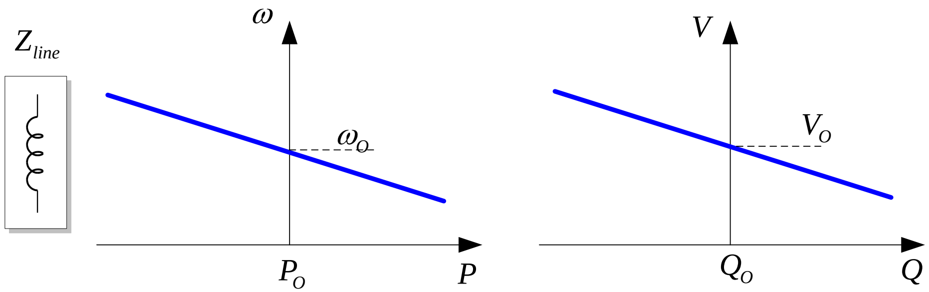
With these equations a relationship between power angle and active power is deduced, while the voltage difference depends mainly of the reactive power, Q.

2. Roles for µGrid power converters

2.5 Grid-supporting power converters – droop with line impedance

The line impedance is mainly inductive. $R_{line} = 0$

$$V - V_O = -k_q (Q - Q_O)$$
$$f - f_O = -k_p (P - P_O)$$

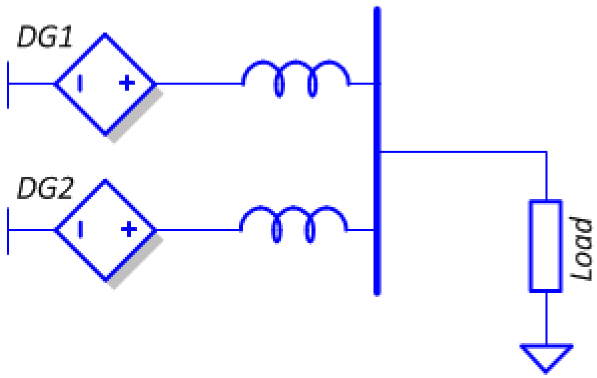


f_O and U_O are the rated frequency and grid voltage.
P_O and Q_O are the active and reactive setting points for the inverter
K_P and K_Q determines the power sharing between inverters composing the microgrid

Each of the grid-supporting power converters operating in a micro-grid will adjust its P* and Q* reference according to its *P/f* and *Q/V* droop characteristic to participate in the regulation of the micro-grid *f* and *V*, respectively

2. Roles for μGrid power converters

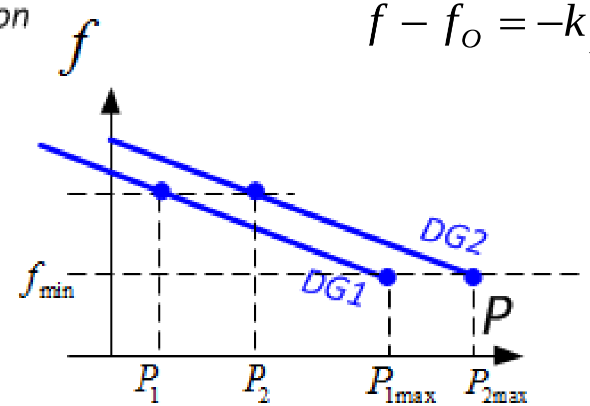
2.5 Grid-supporting power converters – droop with line impedance



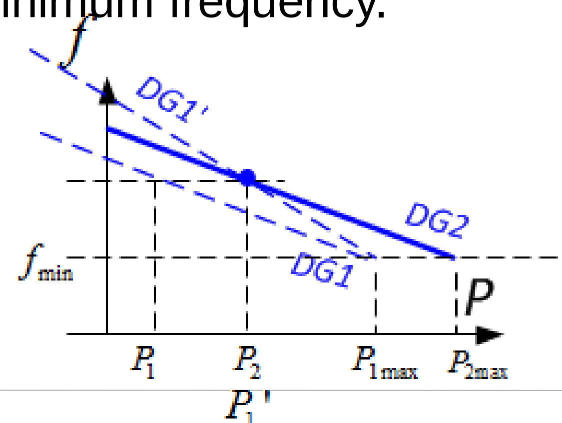
The active power is shared among all the inverters, at a new frequency value according to the droop settings of each VSI

Initial condition

$$f - f_O = -k_p\left(P - P_O\right)$$



The droop is defined to insure that both systems are at rated power at the same minimum frequency.



2. Roles for μGrid power converters

2.5 Grid-supporting power converters – droop with line impedance

Direct droop control – Resistive line

In line impedance of weak electrical grids, resistance is much more important than the reactance R>> X and X/Z is aprox. zero and θ is aprox. zero as well. This is the usual case in low voltage grids as small stand-alone grids.:

$$P_A = \frac{U_A^2}{R} - \frac{U_A U_B}{R}\cos(\delta) \qquad \cos\delta \approx 1$$

$$Q_A = \frac{U_A U_B}{R}\sin(\delta) \qquad \sin\delta \approx \delta$$

With these assumptions, previous equations are simplified in:

$$\delta \approx \frac{R Q_A}{U_A U_B} \qquad U_A - U_B \approx \frac{R P_A}{U_A}$$

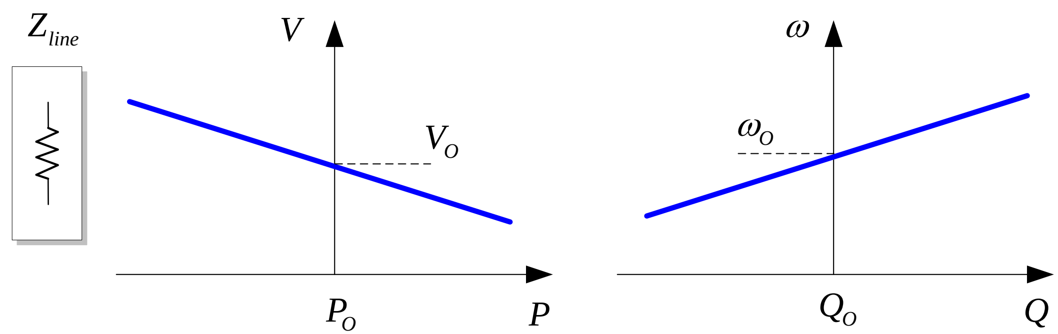
In low voltage grids the active power influences on the voltage amplitude, while the reactive power influence on the frequency of network

2. Roles for μGrid power converters

2.5 Grid-supporting power converters – droop with line impedance

Direct droop control – Resistive line

$$V - V_O = -k_p\left(P - P_O\right)$$
$$f - f_O = k_q\left(Q - Q_O\right)$$



f_O and U_O are the rated frequency and grid voltage.
P_O and Q_O are the active and reactive setting points for the inverter
K_P and K_Q determines the power sharing between inverters composing the microgrid

The voltage amplitude in LV networks depends mainly on *P* flow, while their *f* is mainly affected by *Q* injection

2. Roles for µGrid power converters

2.5 Grid-supporting power converters – droop pros and cons

Effective solution for regulating the voltage magnitude and frequency in MV networks

Highly dependent on the R/X ratio of the line, cannot be directly applied any grid.

It's no necessary any communication channel.

sophisticated grid impedance estimation algorithms are necessary.

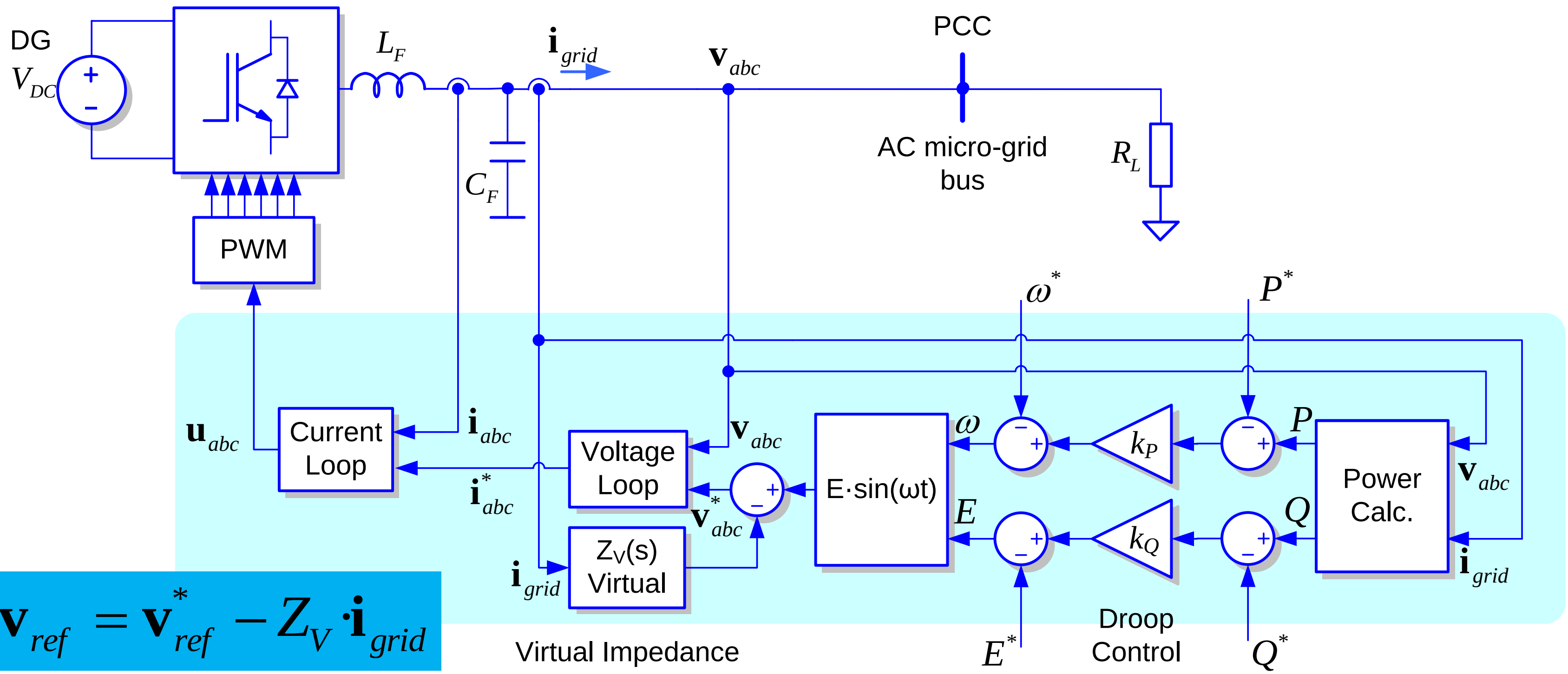
Largely deployed in power systems

A small mismatching in the grid impedance estimation results in an inefficient power sharing among the droop controlled distributed generators. Don't allow sharing harmonics

2. Roles for µGrid power converters

2.6 Grid-supporting power converters – virtual output impedance

An effective solution to minimize the effect of the line impedance characteristic consists on emulating a dominant impedance which is virtually connected at the output of the power converter.



$$\mathbf{v}_{ref} = \mathbf{v}^*_{ref} - Z_V \cdot \mathbf{i}_{grid}$$

The value of *Zv* sets the dynamic of the controller

2. Roles for μGrid power converters

2.6 Grid-supporting power converters – grid-forming based structure

Droop Control Drawbacks:

1. Slow transient response
2. Trade-off between the power sharing accuracy and the frequency and voltage deviations
3. Unbalanced harmonic current sharing
4. High dependency on the inverter output impedance
5. Power sharing is degraded if the output impedance plus the line impedance are unbalanced
6. To solve these problems bulky inductors are included between the inverter and the ac bus

Virtual Impedance Benefits:

1. The overall system is more damped
2. Provides automatic harmonic current sharing
3. Phase errors have a very low effect in power sharing

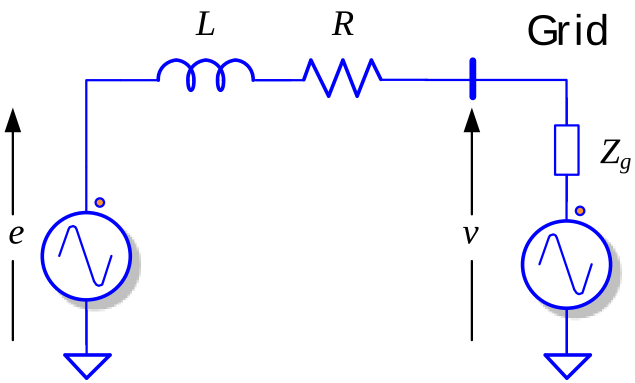
3. Synchronous Power in μGrid

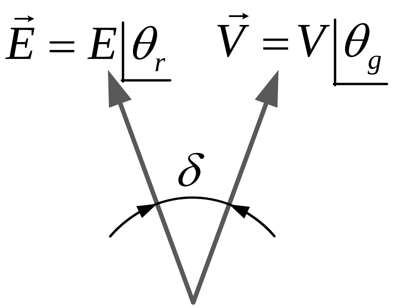
3. Synchronous Power in μGrid

3.1 Synchronous Power Converter – The electrical characteristic

The equivalent model of a grid connected synchronous generator is easy to represent.

The relationship of magnitudes and angles determine the P and Q transfer





The electrical performance is represented by a first order differential equation

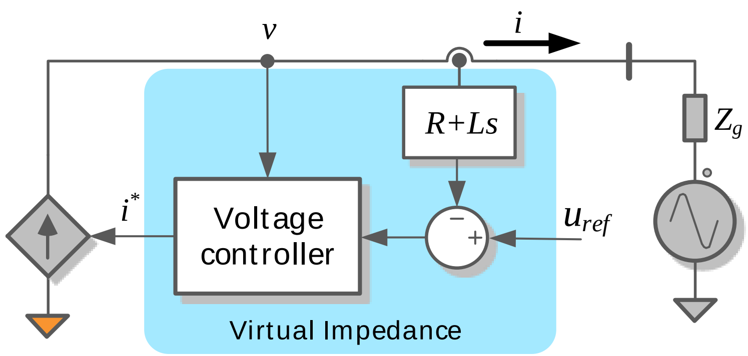
The performance of this equation can be programmed to be emulated in a converter

$$e(t) = v(t) + Ri(t) + L\frac{di(t)}{dt} \qquad v(s) = e(s) - i(s)(R + Ls)$$

3. Synchronous Power in µGrid

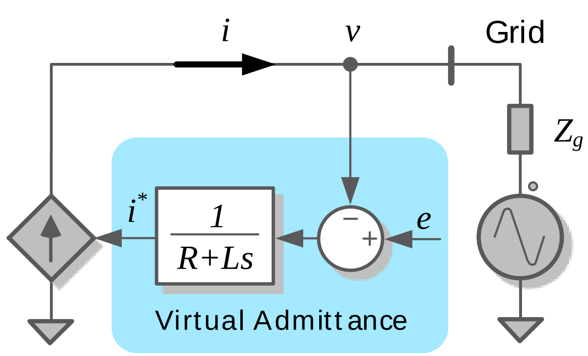
3.1 Synchronous Power Converter – The electrical characteristic

Grid connection based on a virtual admittance



$$v(s) = e(s) - i(s)(R + Ls)$$

The measured current is affected by a derivative term for calculating the voltage reference, with high noise sensitivity or limited bandwith.



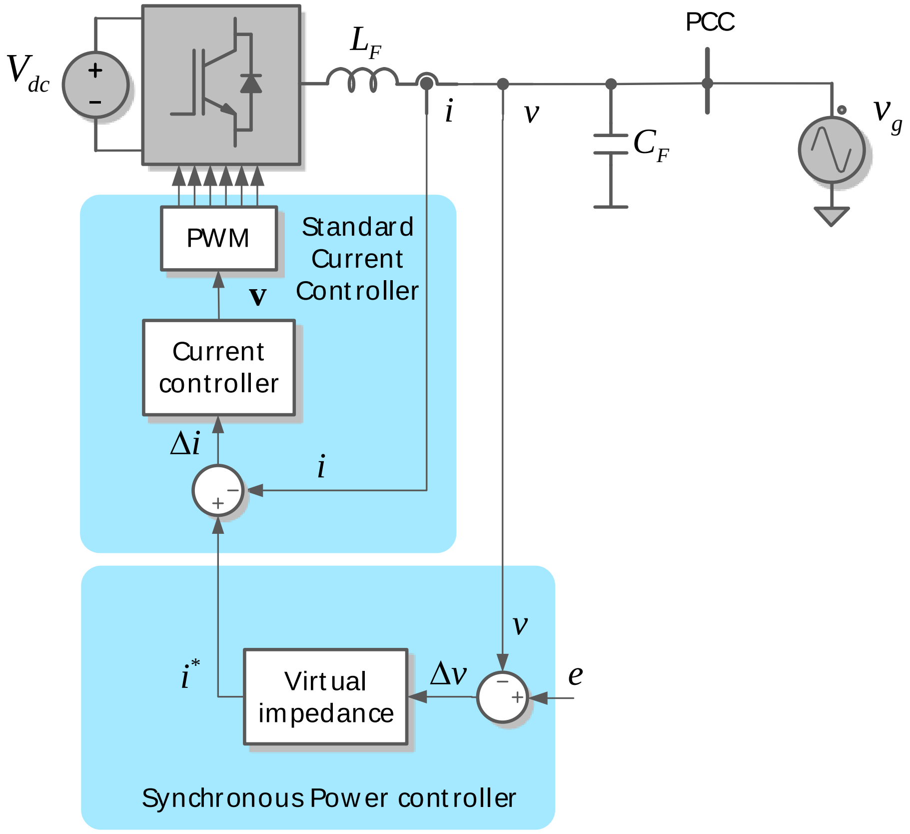
The implementation of virtual impedance need an additional voltage controller, as a difference with the virtual admittance concept.

$$i(s) = \frac{1}{R + sL}\left(e(s) - v(s)\right)$$

3. Synchronous Power in μGrid

3.1 Synchronous Power Converter – The electrical characteristic

- The SPC does not change the hardware configuration
- The SPC set a dynamic constraint on the time constant of the current controller
- The SPC does not require a grid synchronization system
- The value of *RL* can be adjusted to have a friendly interaction with the grid



3. Synchronous Power in μGrid

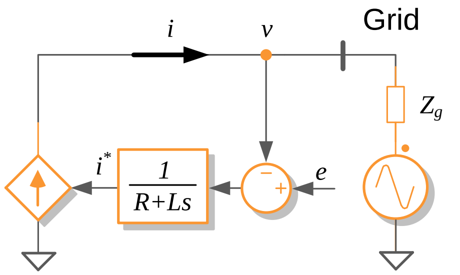
3.1 Synchronous Power Converter – The electrical characteristic

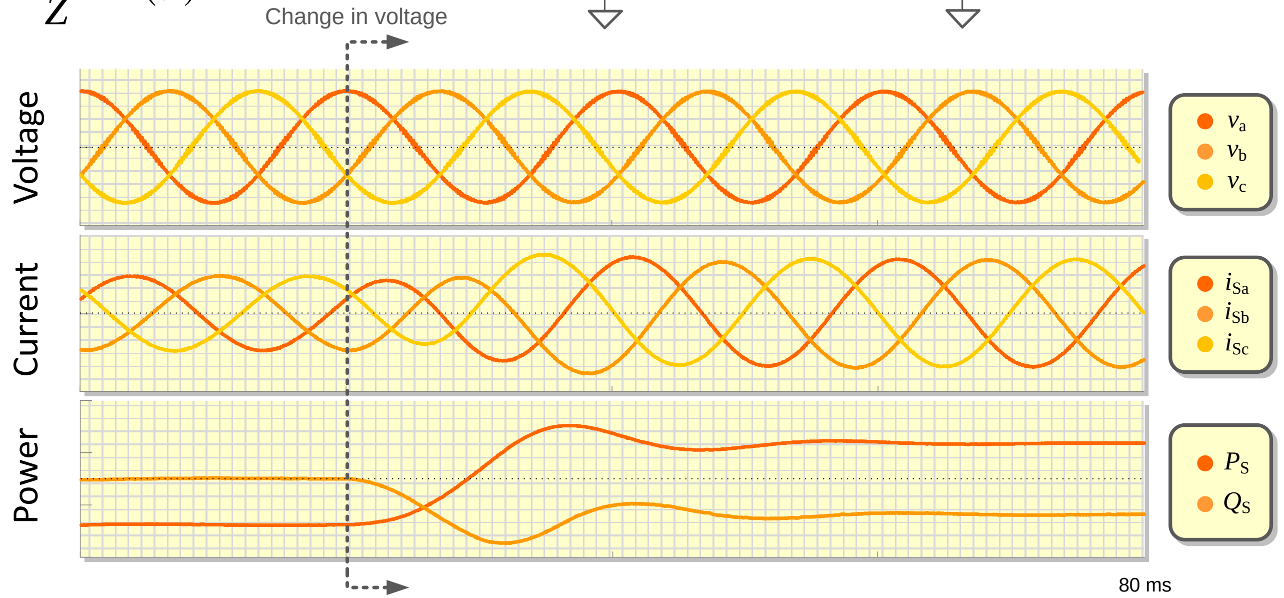
Power transfer between the grid and the SPC

– The power transfer is regulated changing the relationship between the internal and the external voltage

$$P = \frac{EV}{Z}\cos(\phi-\delta) - \frac{V^2}{Z}\cos(\phi),$$

$$Q = \frac{EV}{Z}\sin(\phi-\delta) - \frac{V^2}{Z}\sin(\phi),$$



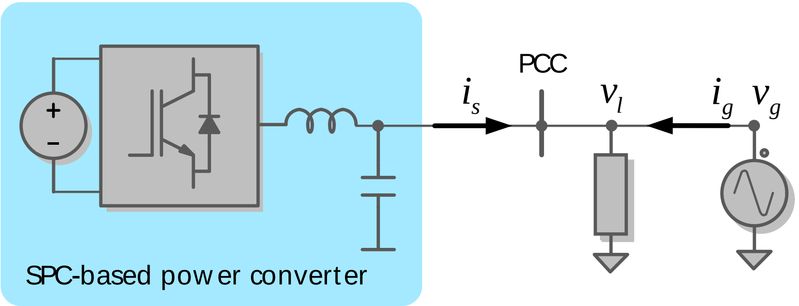


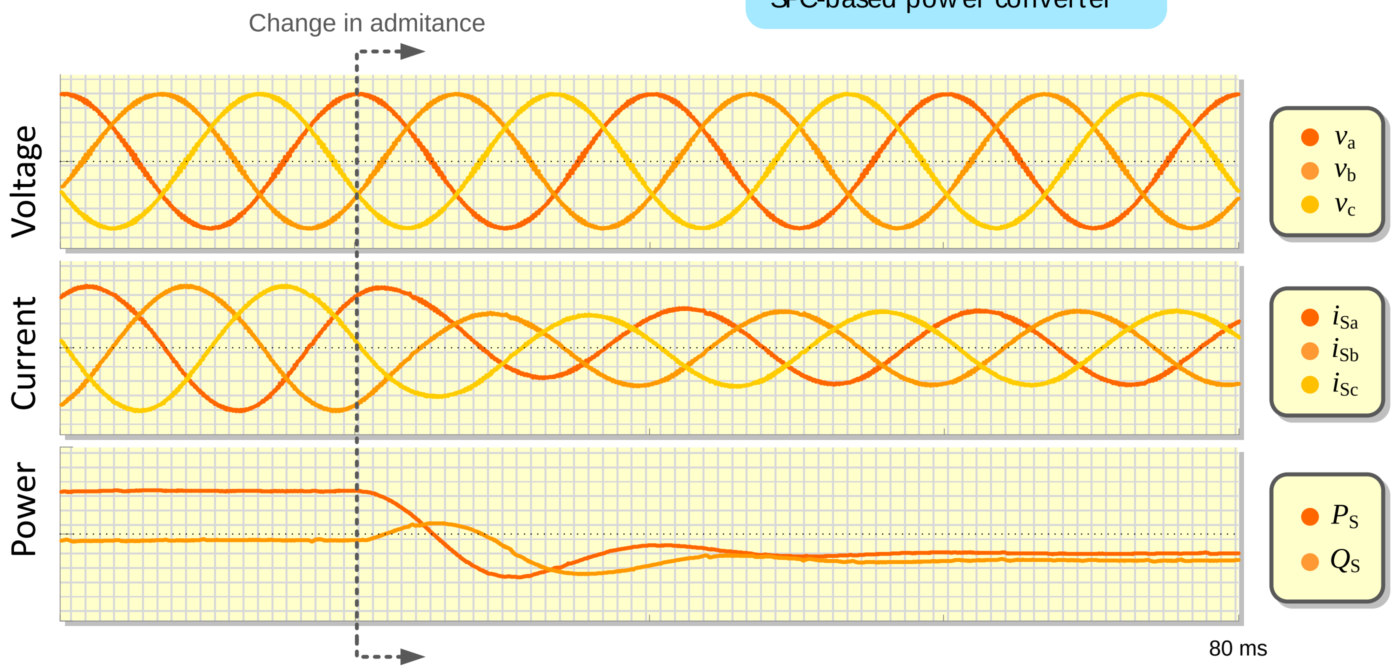
3. Synchronous Power in μGrid

3.1 Synchronous Power Converter – The electrical characteristic

Change in the virtual admittance

- Permits to set a dominant inductive behavior
- Permits regulating the power sharing
- Makes the parallel connection easier
- Contributes to reject distortions

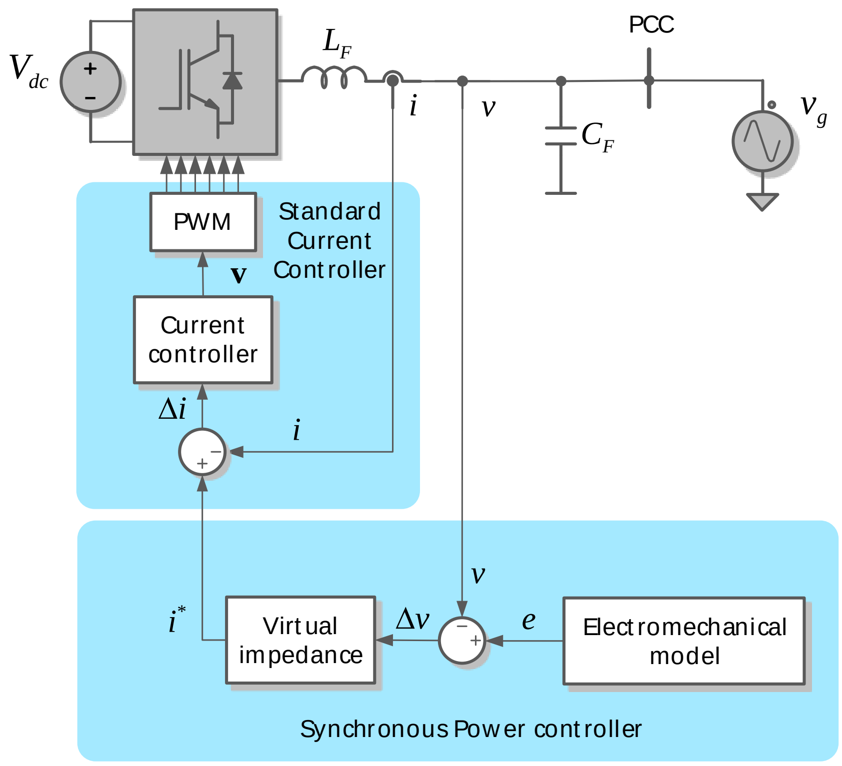




3. Synchronous Power in μGrid

3.2 Synchronous Power Converter – The mechanical characteristic

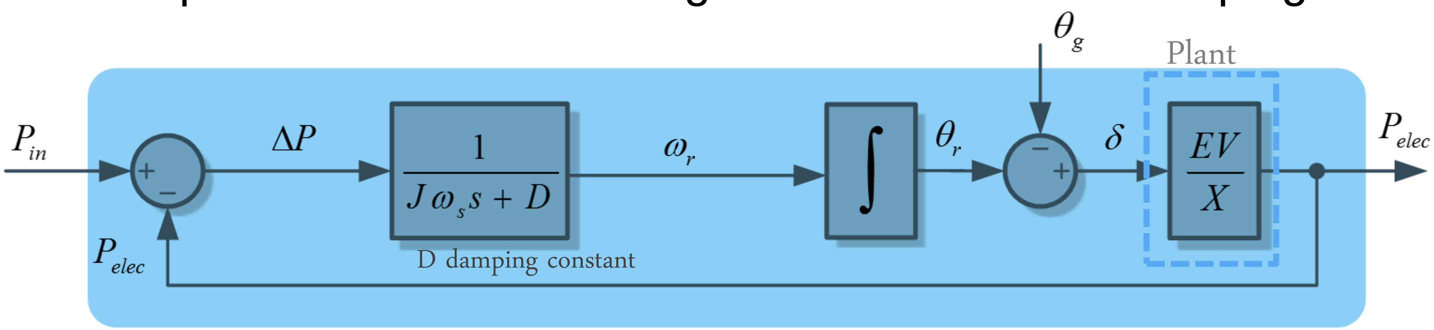
- The electromichanical characteristics affects an outer loop of the SPC.
- This structure is similar to the one found in a SG, but it is digitally implemented by software



3. Synchronous Power in μGrid

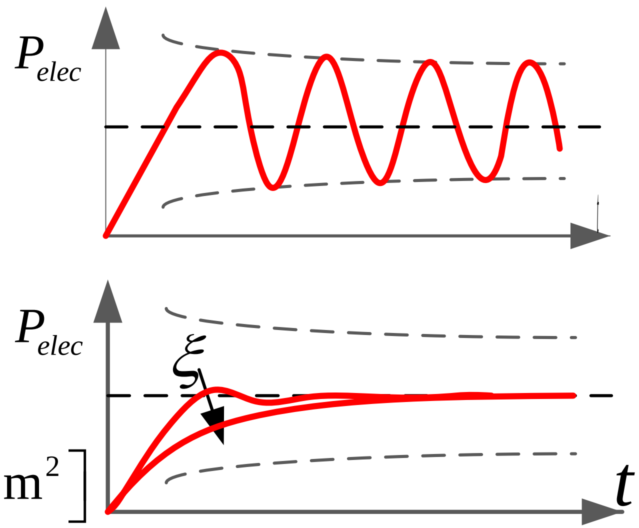
3.2 Synchronous Power Converter – The mechanical characteristic

Closed-loop electromechanical diagram with additional damping windings



The PLC can be programmed in order to have a damped response

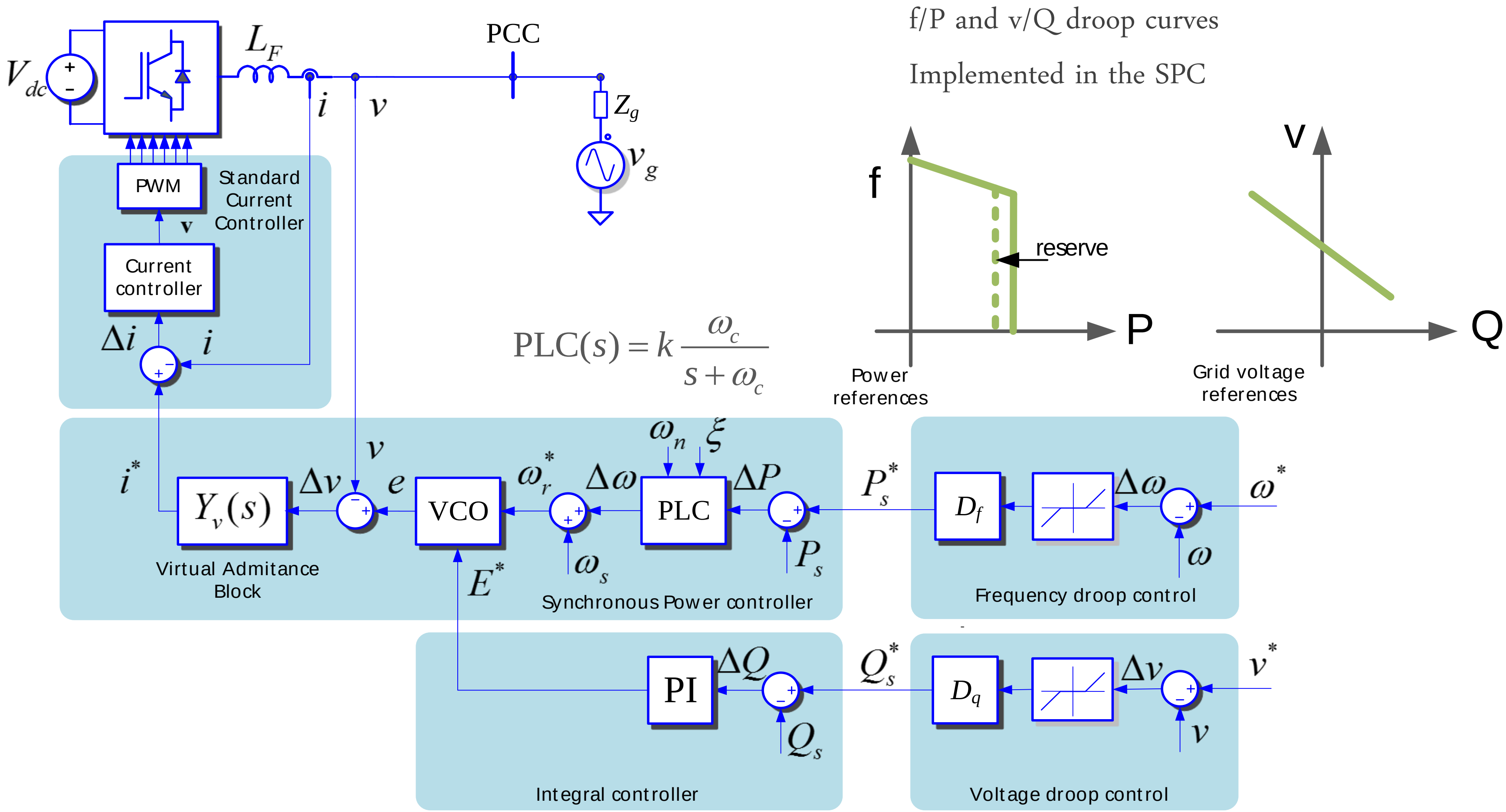
$$\frac{P_{out}}{P_{in}} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$



$$\omega_n = \sqrt{\frac{P_{max}}{J\omega_S}} \qquad P_{\max} = \frac{EV}{X} \qquad J = \frac{P_{max}}{\omega_n^2\,\omega_S}\ \left[\mathrm{kg\,m^2}\right]$$

3. Synchronous Power in μGrid

3.3 Synchronous Power Converter – The electromechanical bloc

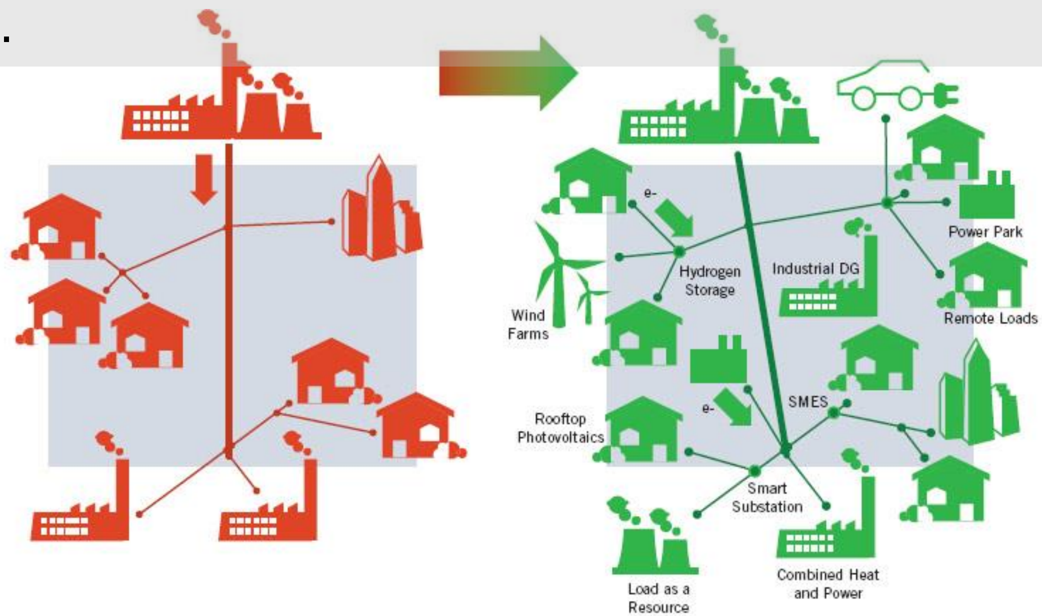


5. Synchronous Services in μGrid

5. Synchronous Services in μGrid

5.1 Introduction

- The current electrical power generation scenario is unsustainable in the long run.
- Distributed generation proposes a new electric power systems approach.
- The uncontrolled penetration of distributed generation may hinder the safe operation of the electrical system.
- Distributed generators should be provided with advanced grid support functionalities.



5. Synchronous Services in µGrid

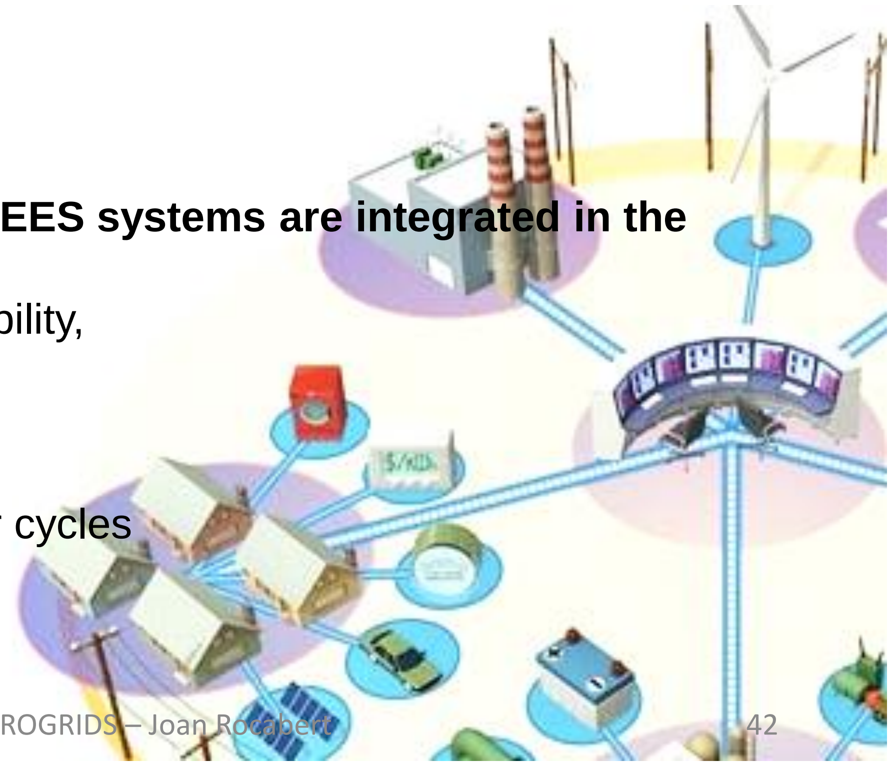
5.2 Regulation

The IEEE Standard 1547.2-2008 specifies the ancillary services that distributed power generation systems may offer to the EPS:

- generation scheduling optimization,
- enhanced system control and dispatch services,
- reactive power supply and voltage and frequency control regulation,
- black-start restoration,
- energy imbalance compensation,
- spinning reserve operation,
- and others.

These services can be further extended if EES systems are integrated in the microgrid.

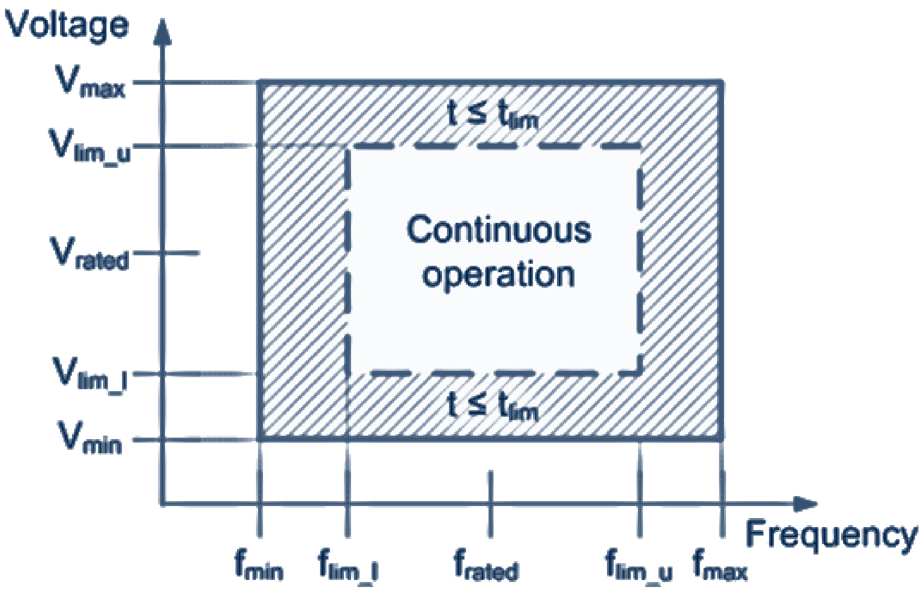
- extension of the operational reserve capability,
- frequency regulation,
- peak shaving,
- back-up of intentional electrical islands,
- optimized management of daily wind/solar cycles



5. Synchronous Services in μGrid

5.3 Grid Codes – Operational Window

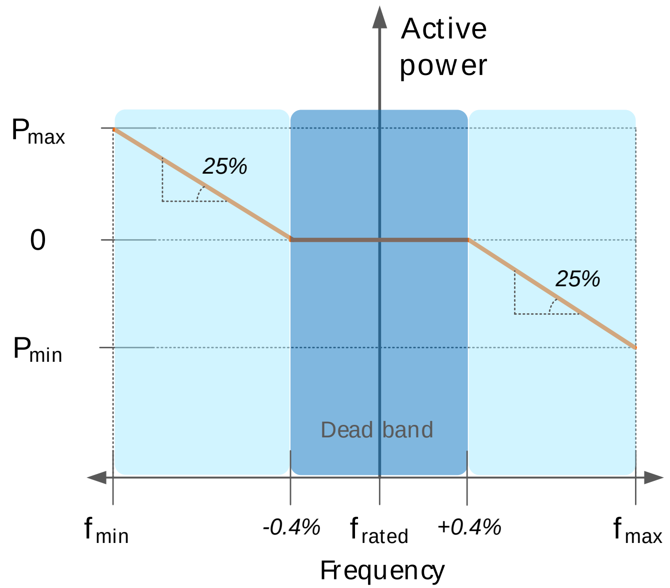
- The generation units should be able to work normally within given operational margins.
- The frequency window is usually in the range of 2-3Hz, while the amplitude changes between 5-10% around the nominal value.

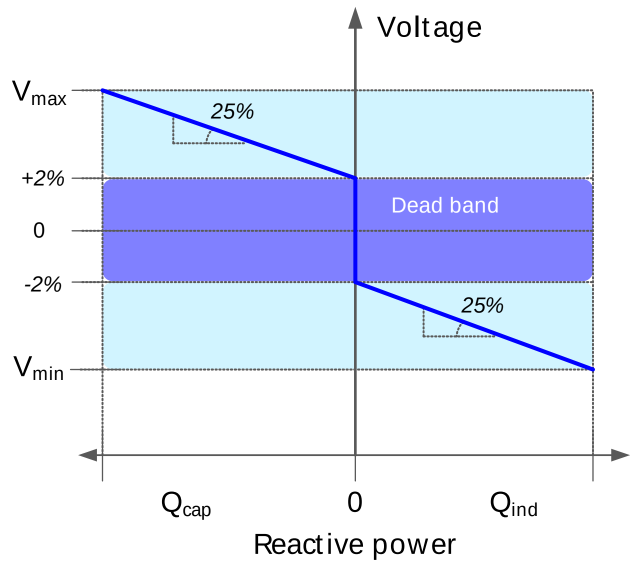


5. Synchronous Services in μGrid

5.4 Grid Codes – Grid voltage regulation

- The generation systems should contribute to regulate the voltage and the frequency.
- The grid codes define a regulation pattern for the delivery of active/reactive power as a function of the frequency/voltage level.
- The generators may be asked also to follow an active/reactive power reference given by the grid operator.

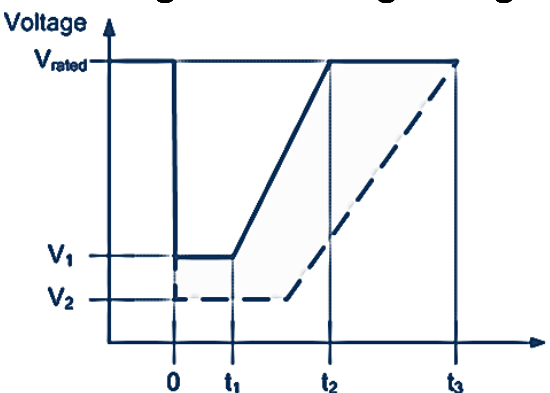


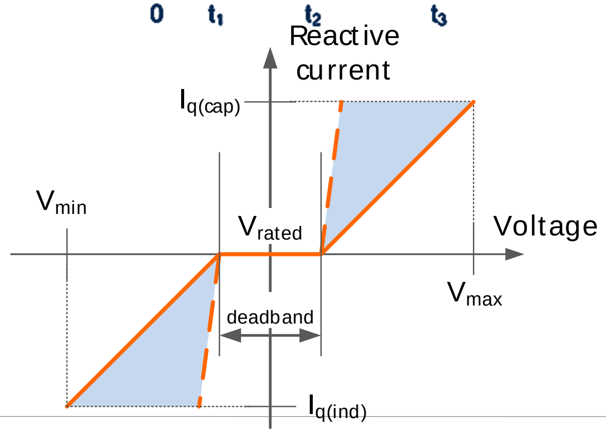


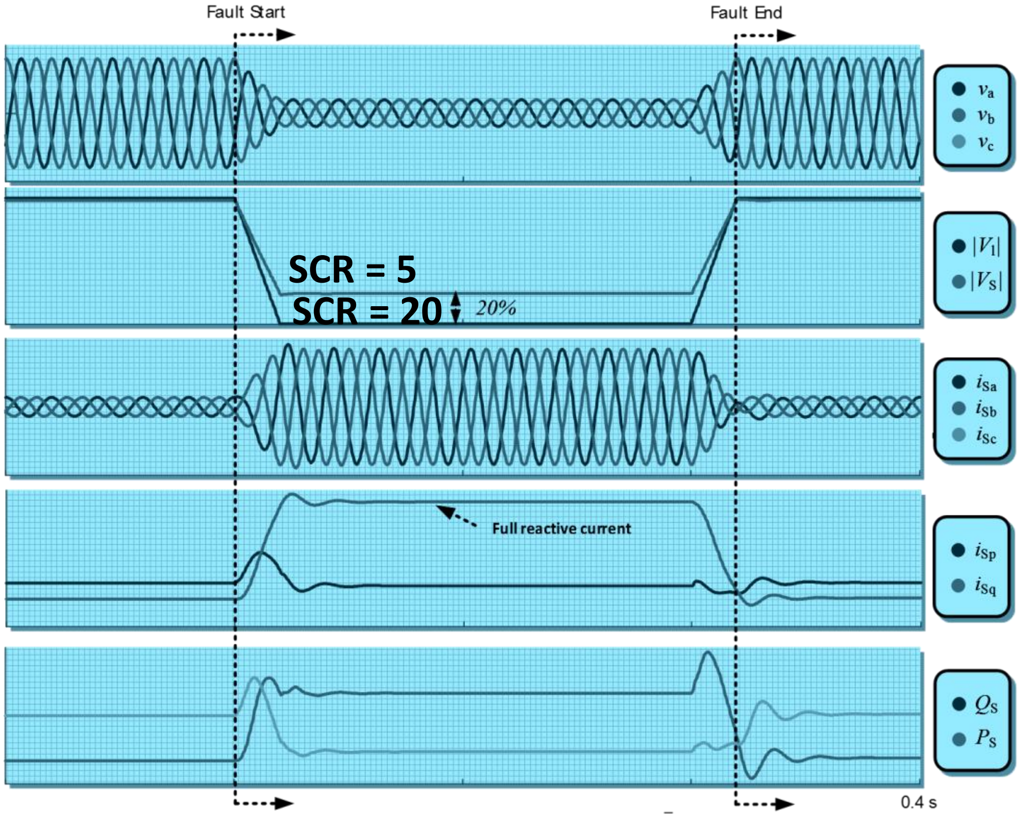
5. Synchronous Services in μGrid

5.5 Grid Codes – High and Low Voltage Ride Through

- The grid codes require distributed generators to remain connected to the grid, provided the depth and duration of the fault doesn't exceed certain limits.
- The grid-connected power converters are required to deliver reactive current, during the voltage sag.

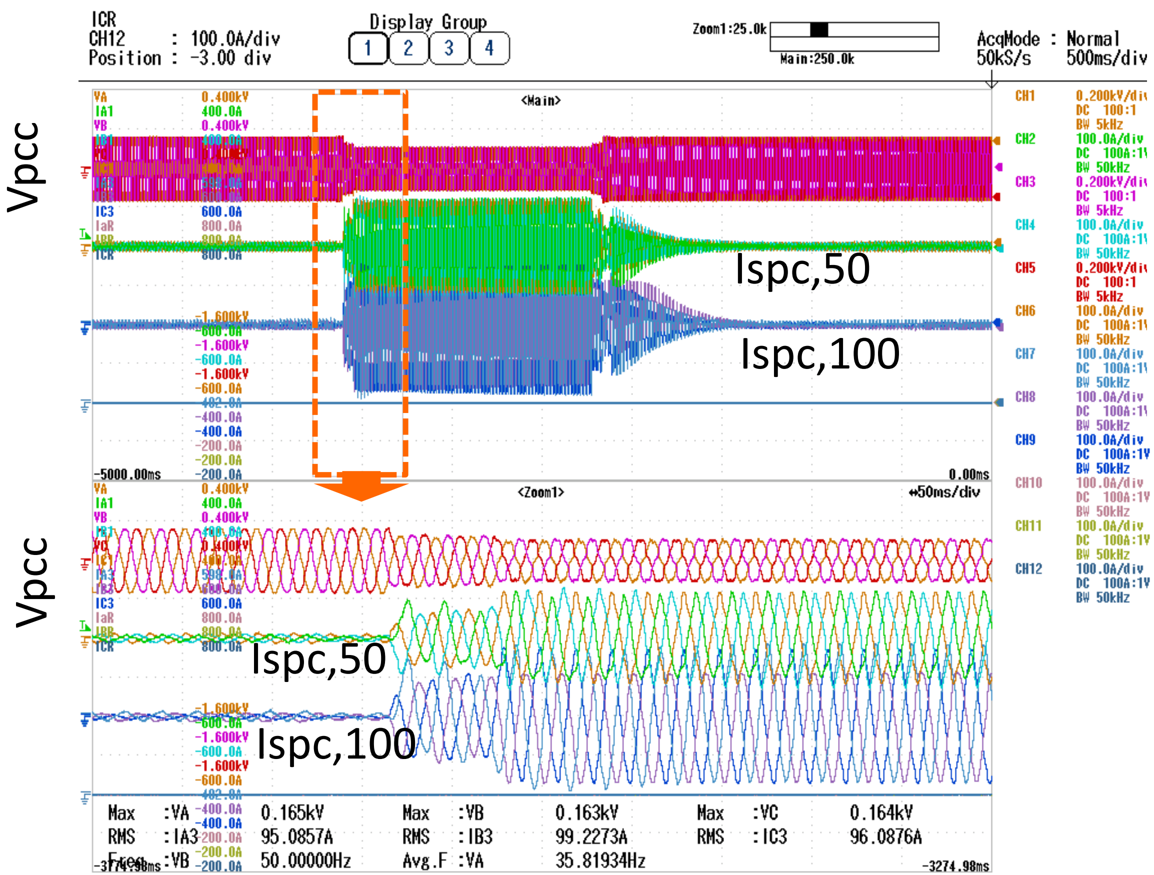


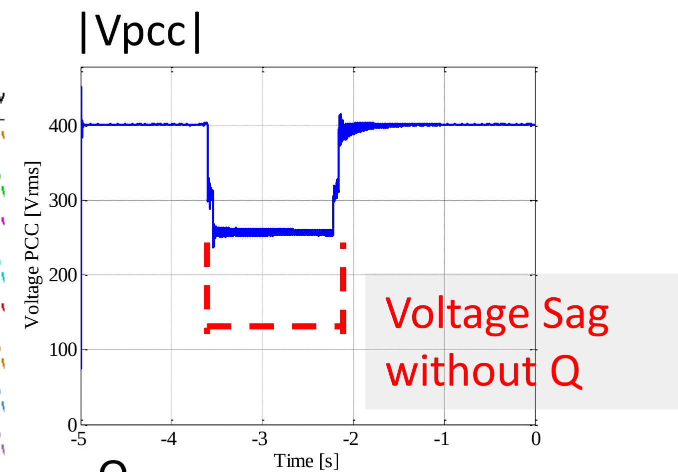


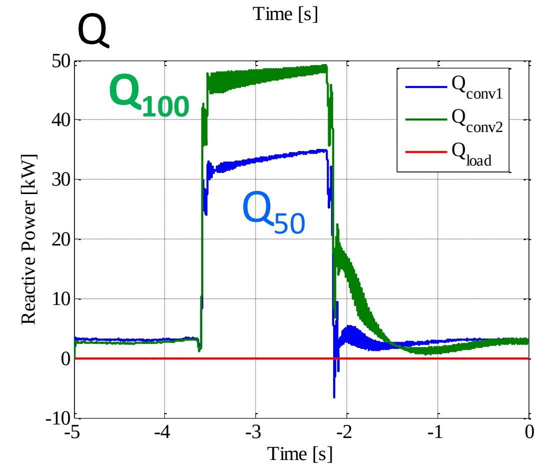


5. Synchronous Services in µGrid

5.5 Grid Codes – Low Voltage Ride Through – Experimental Results



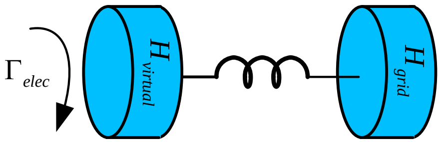


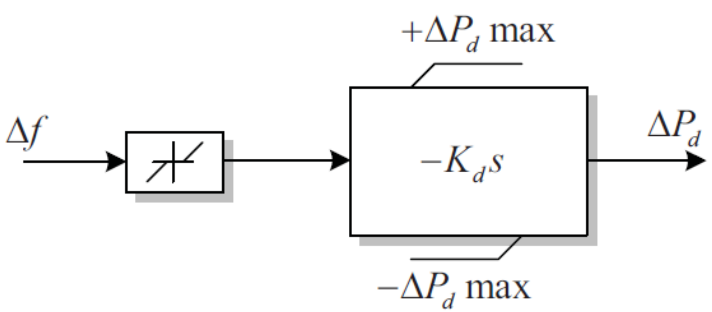


5. Synchronous Services in μGrid

5.6 The SPC beyond the grid-codes requirements – Inertia Emulation

Conventional synchronous generators support instantaneously the frequency of the system with the inertia of the generator, SPC-based generators emulate the inertia in case of power variations without needing any frequency measurement





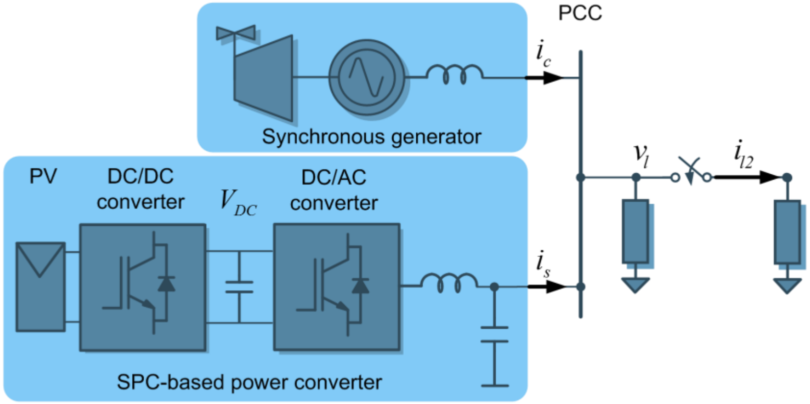
- Implemented as P_D controller with Δf as input
- The gain *Kd* should be adjustable between 0 and 15 sec.
- In order to be able to generate the required saturation levels, energy storage of any technology is required able to inject or absorb at least 5-10% active power for at least 2 sec.
- The deadband of frequency variation will be limited to 10 mHz.

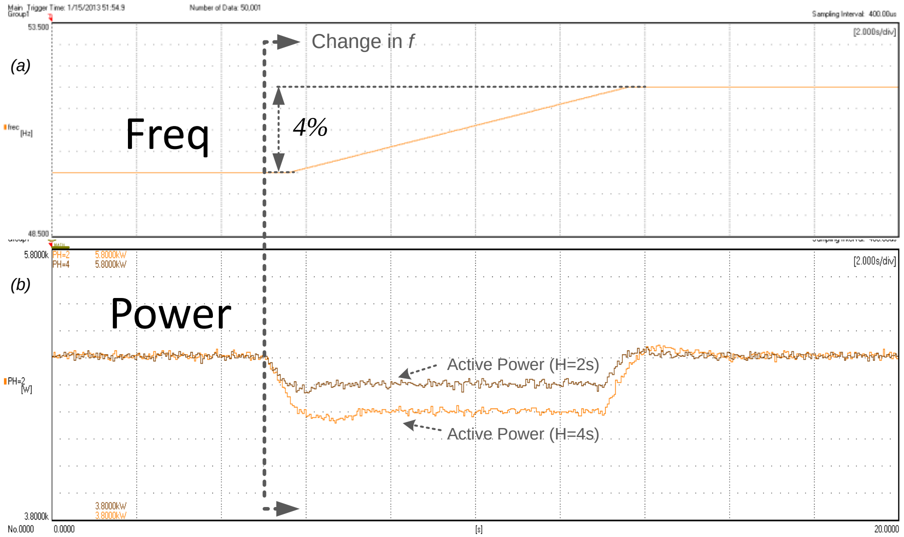
5. Synchronous Services in μGrid

5.6 The SPC beyond the grid-codes requirements – Inertia Emulation

The inertia can be varied to improve the frequency support during any frequency transient.

The higher the inertia the higher is the active power variation during the transient





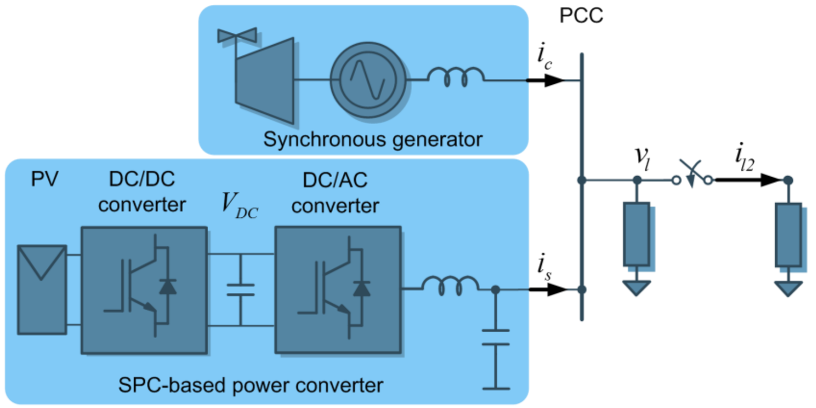
5. Synchronous Services in µGrid

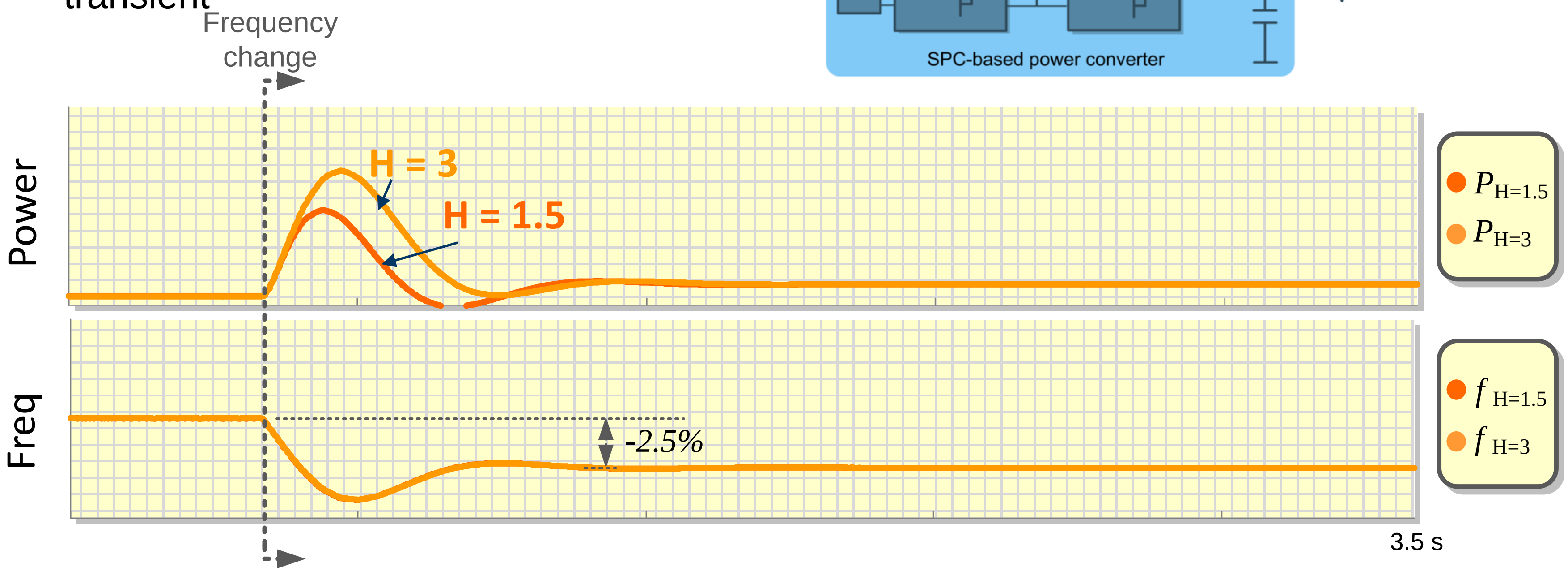
5.6 The SPC beyond the grid-codes requirements – Inertia Emulation

Strong grid, frequency perturbation.

The inertia can be varied to improve the frequency support during a transient

The higher the inertia the higher is the active power variation during the transient

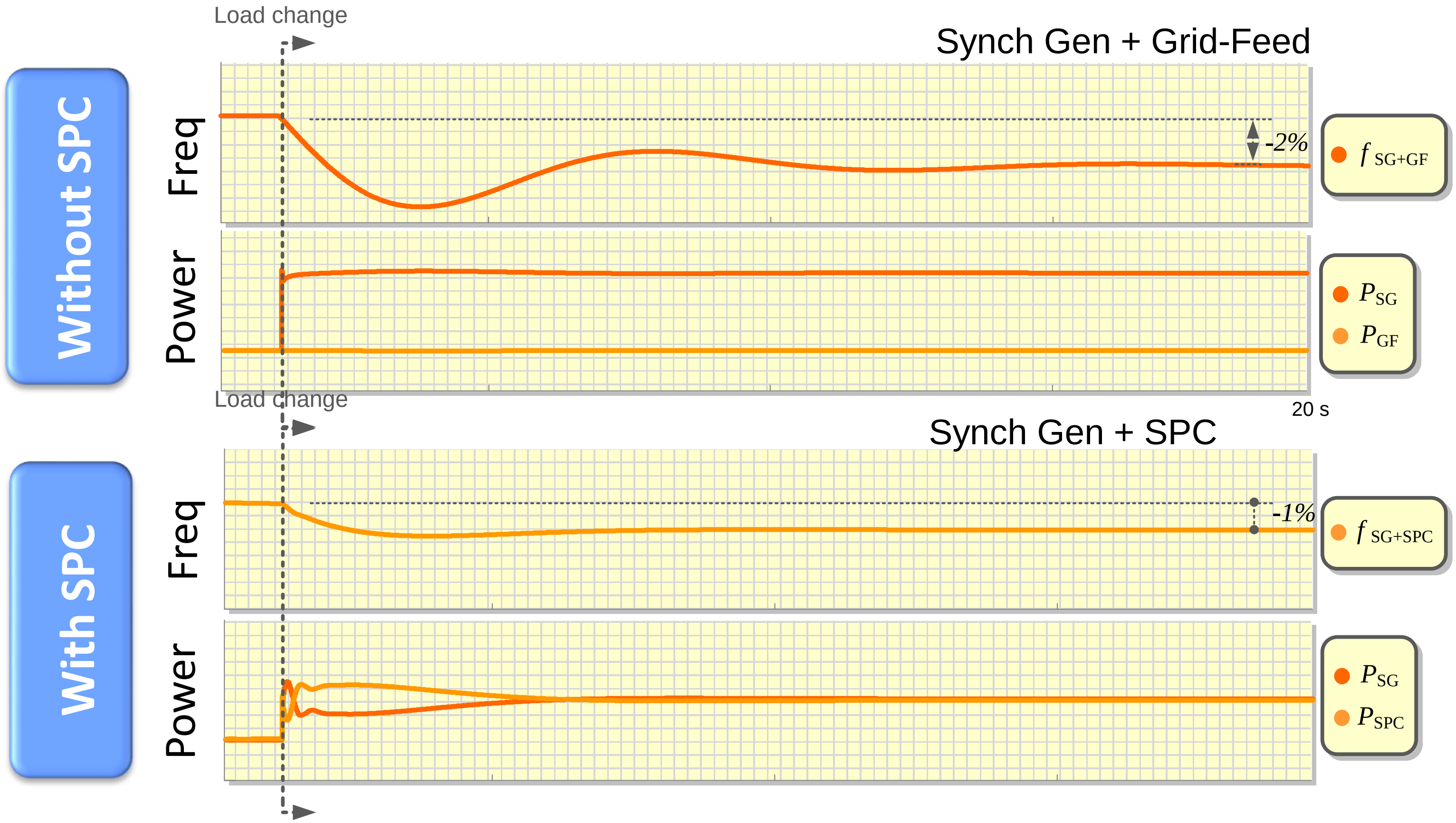




5. Synchronous Services in μGrid

5.6 The SPC beyond the grid-codes requirements – Inertia Emulation

Weak grid, load connection.



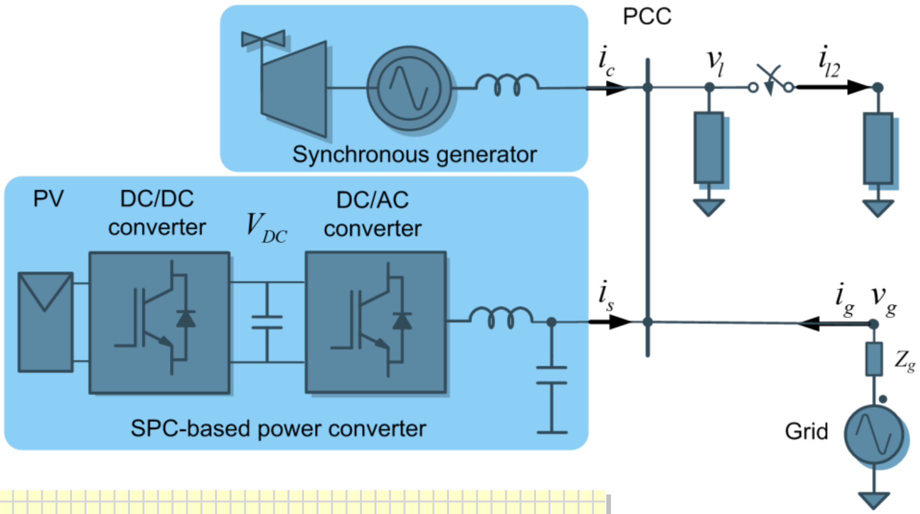
5. Synchronous Services in μGrid

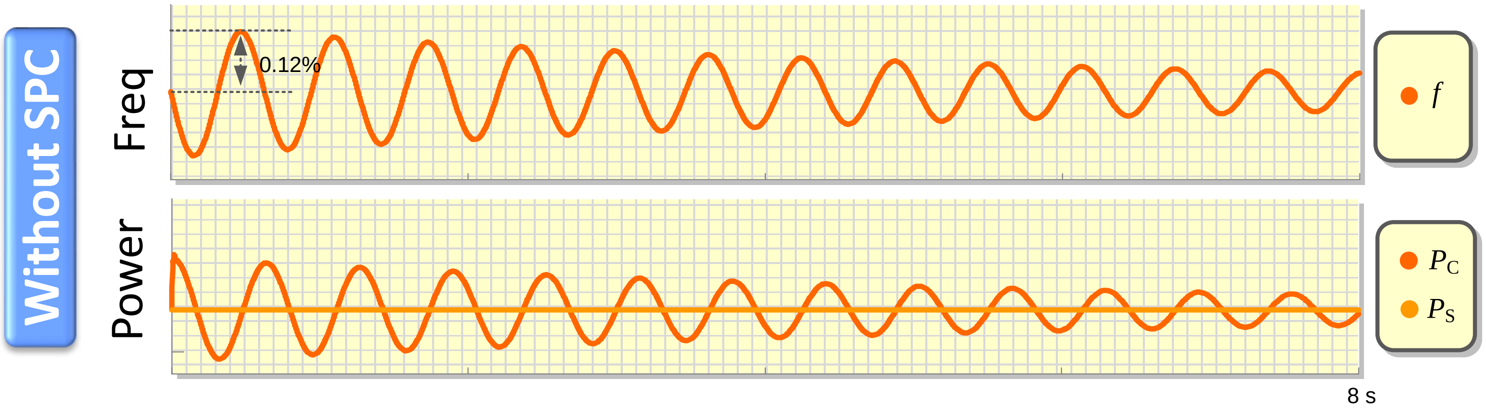
5.7 The SPC beyond the grid-codes requirements – Power Oscillation Damping

A 25% change in the load will act as the perturbation

The system is connected to a grid with a SCR = 5

Power Oscillation with low Damping





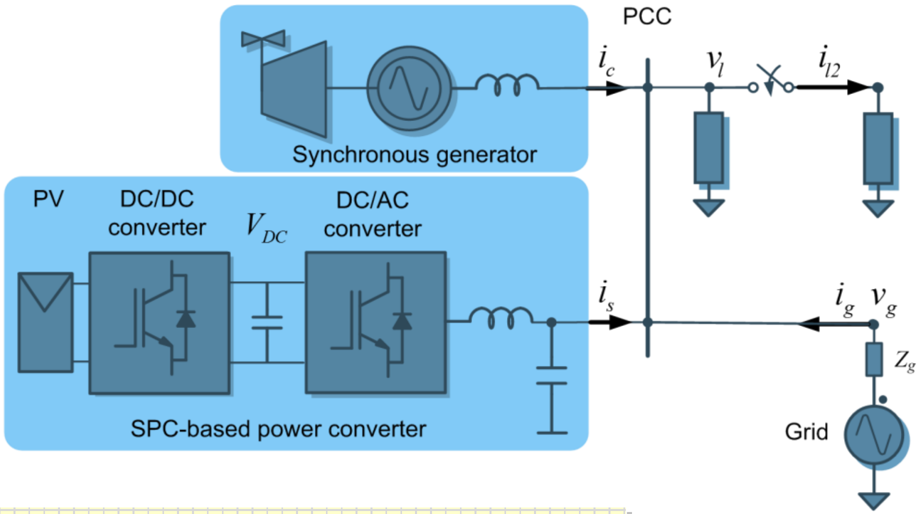
5. Synchronous Services in µGrid

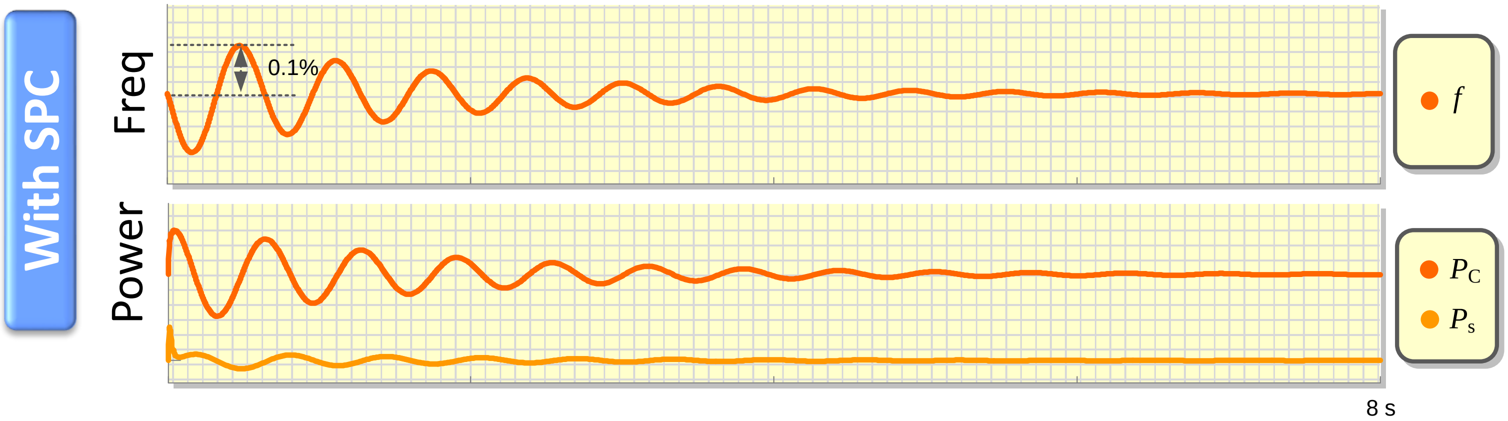
5.7 The SPC beyond the grid-codes requirements – Power Oscillation Damping

A 25% change in the load will act as the perturbation

The system is connected to a grid with a SCR = 5

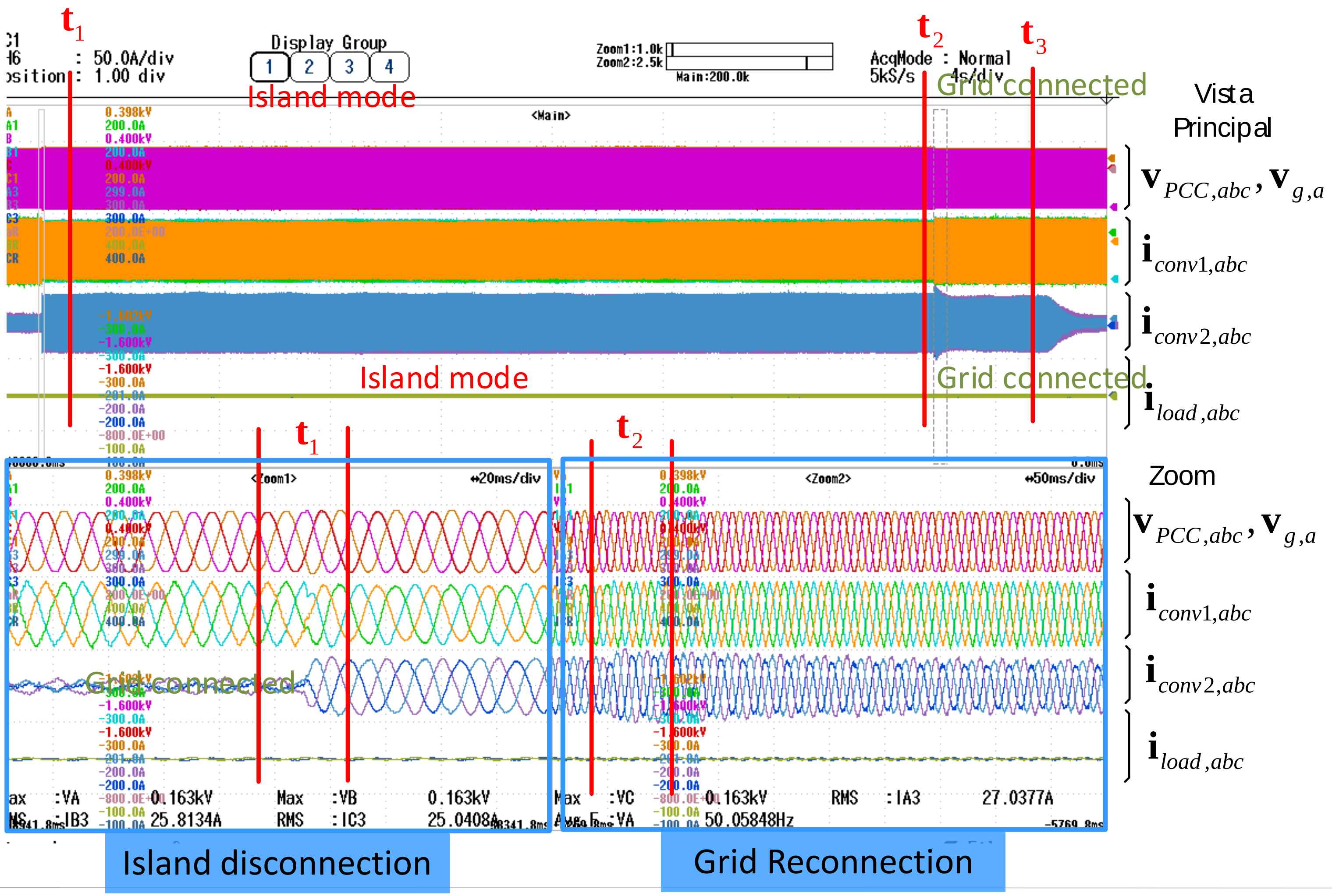
The active and reactive power controllers are active





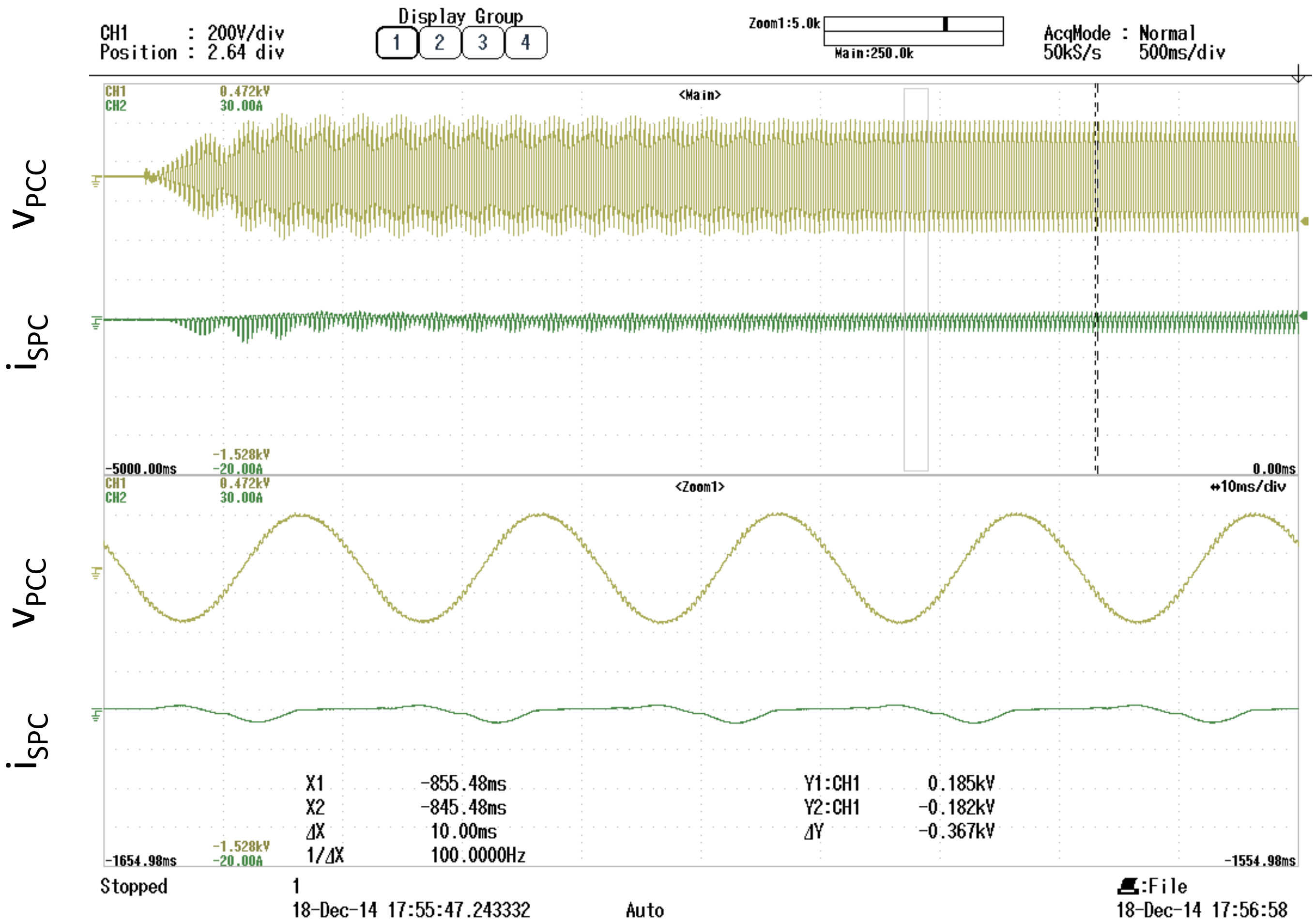
5. Synchronous Services in µGrid

5.8 The SPC beyond the grid-codes requirements – Island Mode



5. Synchronous Services in µGrid

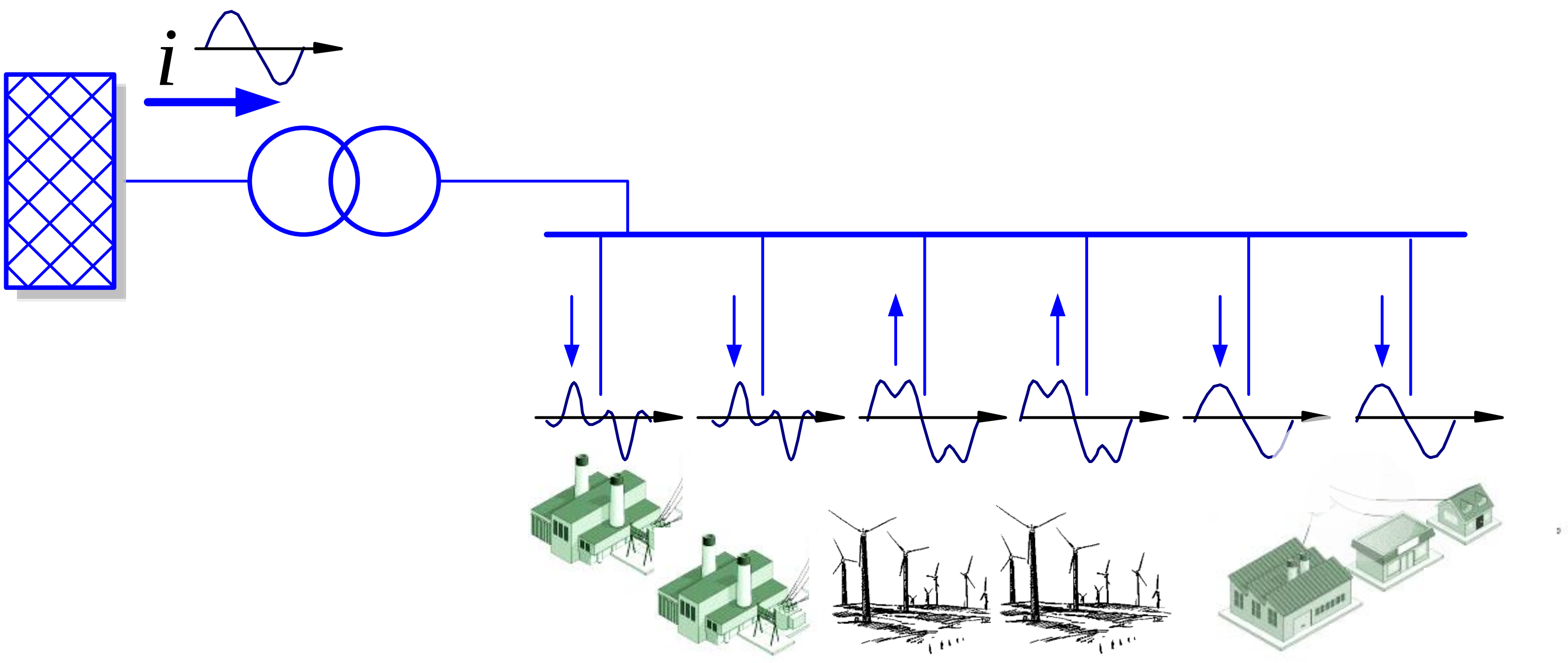
5.9 The SPC beyond the grid-codes requirements – Blackstart Mode



5. Synchronous Services in μGrid

5.10 The SPC beyond the grid-codes requirements – Harmonics

Harmonics and unbalance compensation, flicker reduction, transient voltage support during grid-faults or reactive power compensation are actually common functionalities in modern DG systems.



5. Synchronous Services in μGrid

5.10The SPC beyond the grid-codes requirements – Harmonics

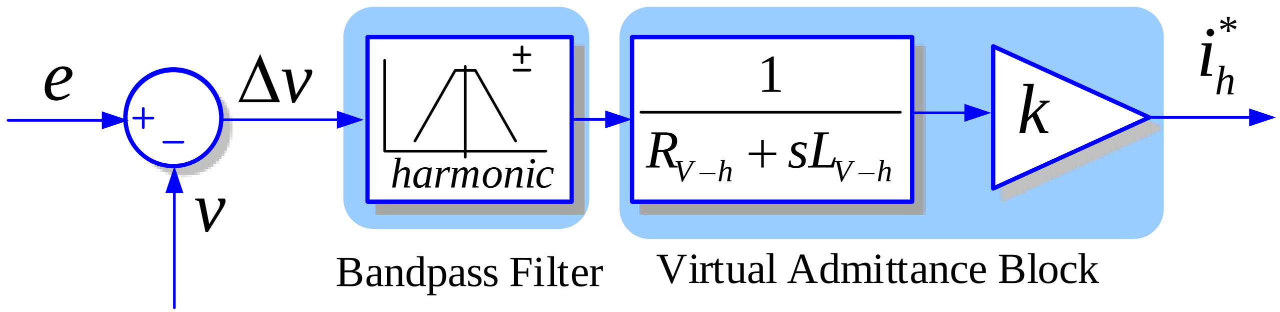
- A bandpass filter is needed to separate sequences of different harmonics. The equivalent transfer function for each harmonic is represented as:

$$G_{BP}(s) = \frac{k \cdot (h \cdot \omega_0) \cdot s}{s^2 + k \cdot (h \cdot \omega_0) \cdot s + (h \cdot \omega_0)^2}$$

- Which leads to represent the virtual admittance for each harmonics as:

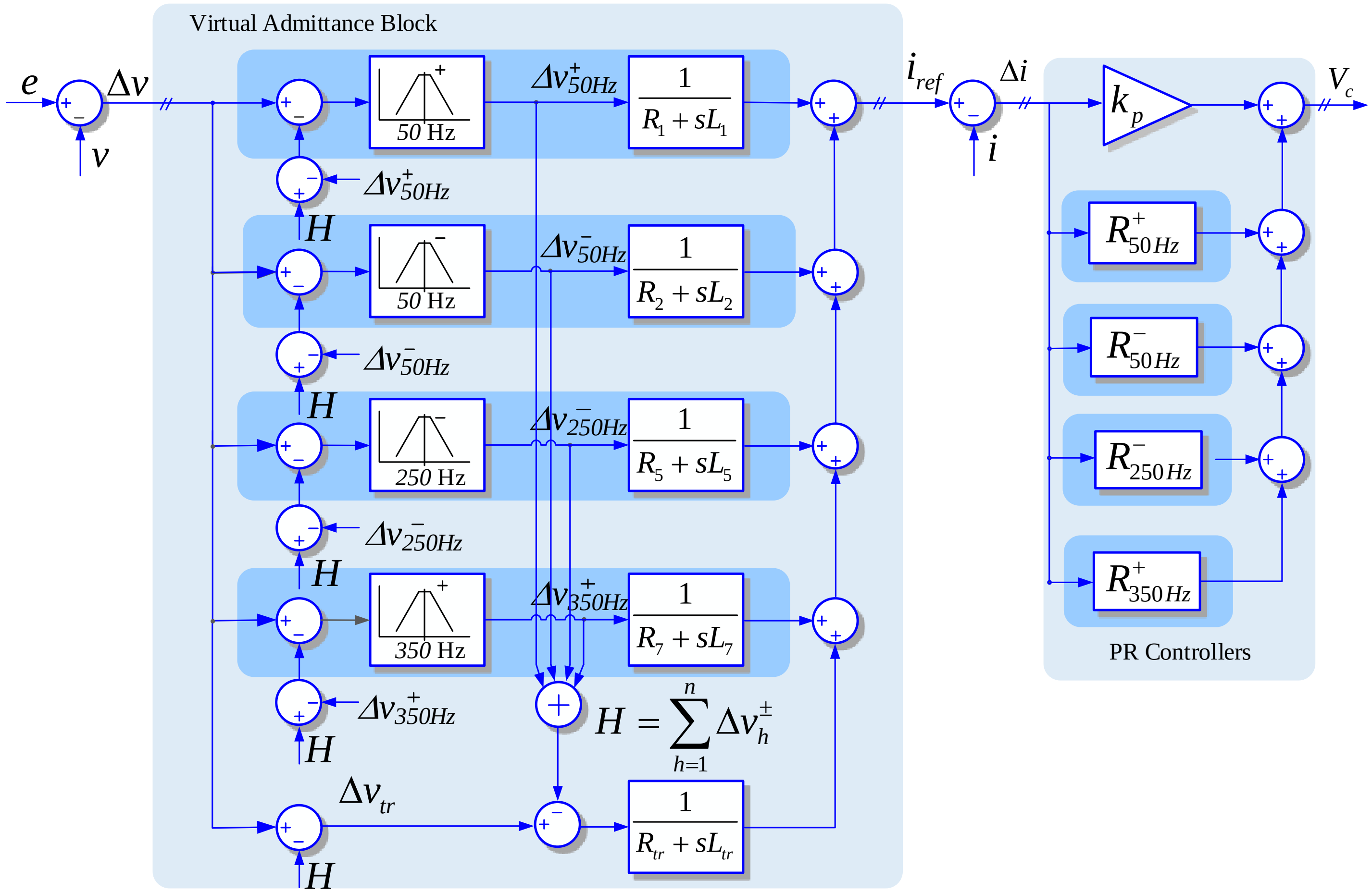
$$Y_{V-h}(s) = \frac{1}{R_{V-h} + s \cdot L_{V-h}}$$

- Each virtual admittance has a *k* gain, which affect the block on the dynamic and the steady state by modifying the current output from the block.



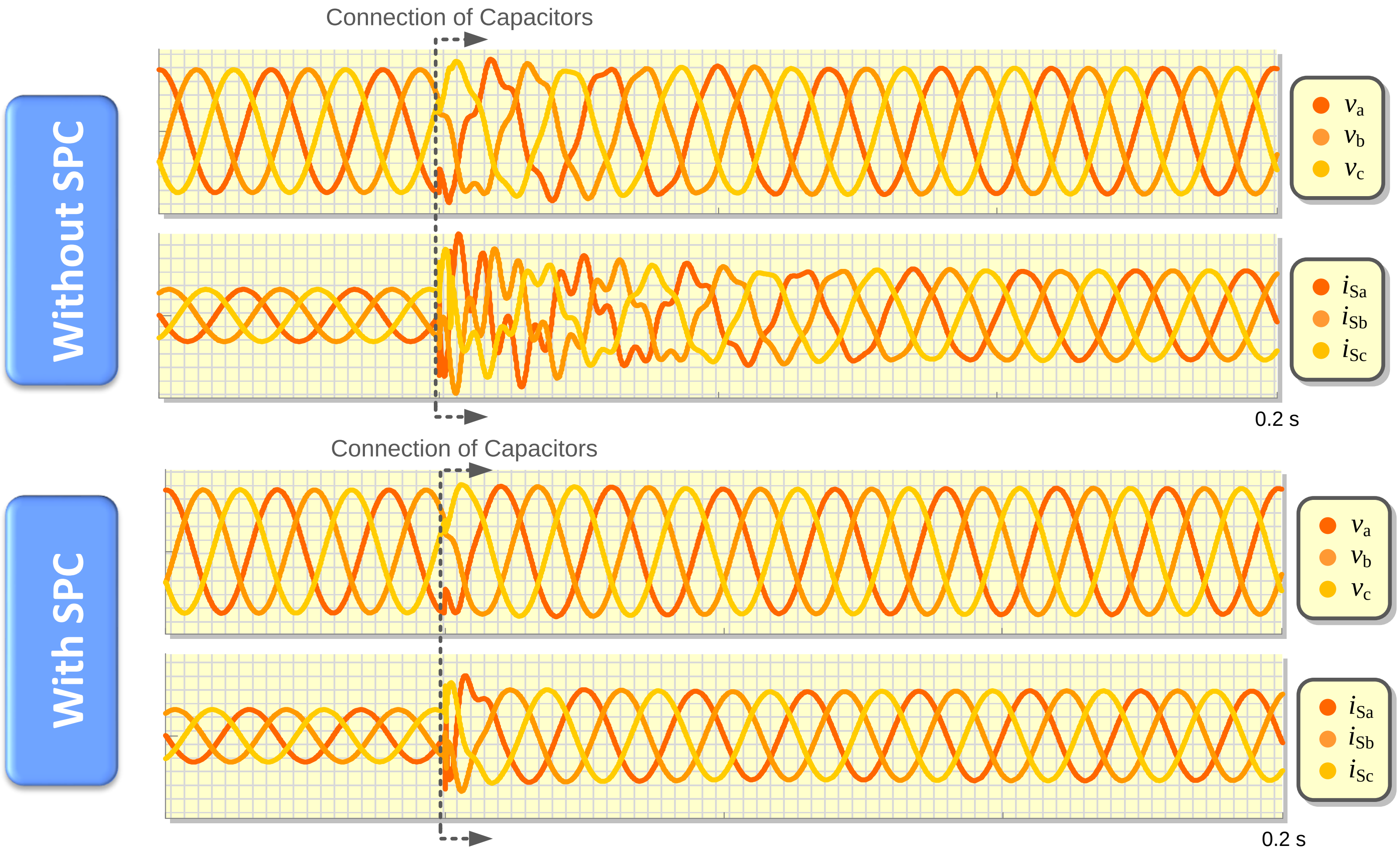
5. Synchronous Services in μGrid

5.10 The SPC beyond the grid-codes requirements – Harmonics



5. Synchronous Services in μGrid

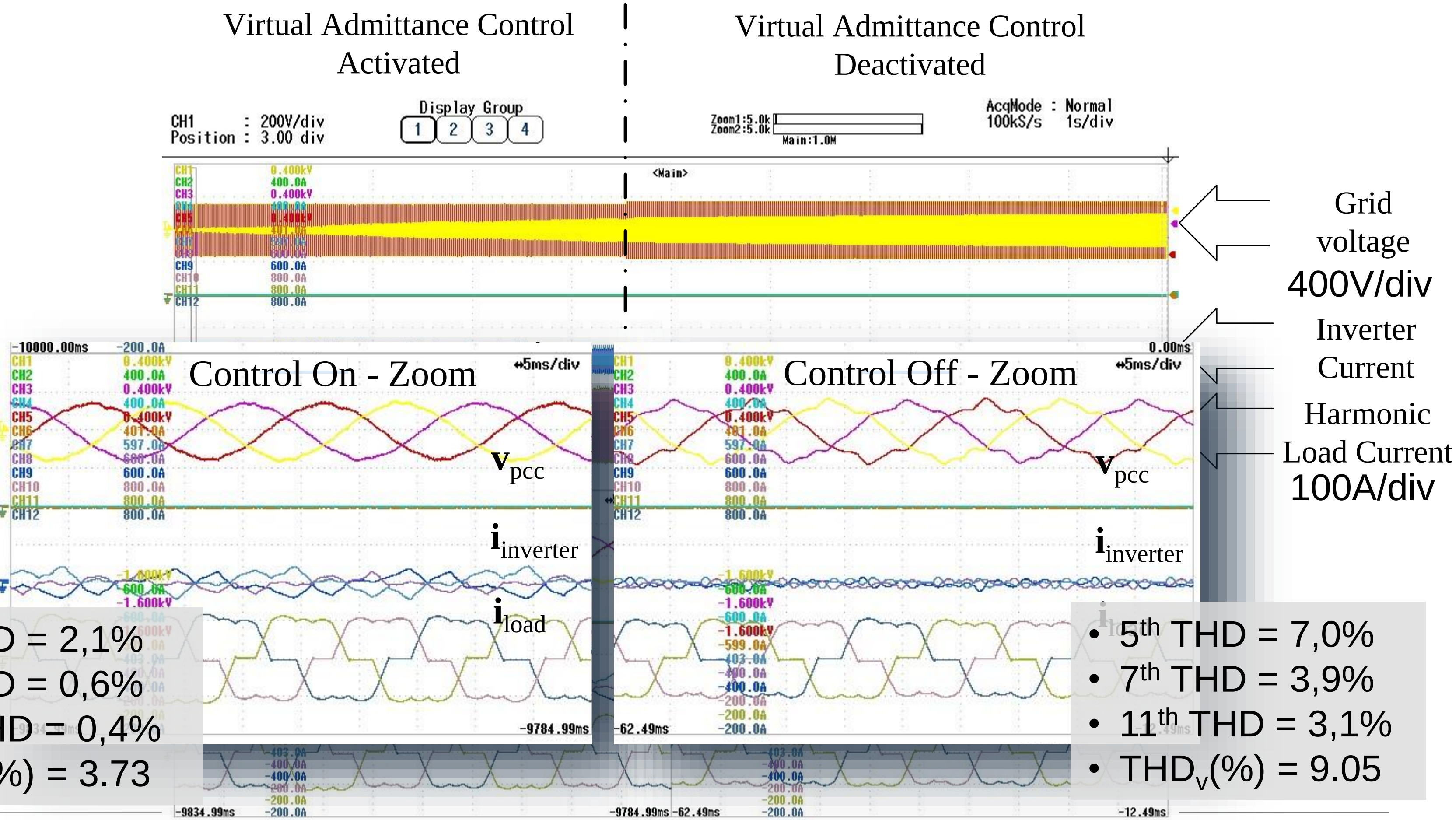
5.10 The SPC beyond the grid-codes requirements – Harmonics



5. Synchronous Services in μGrid

5.10 The SPC beyond the grid-codes requirements – Harmonics

Compensation of harmonics 5th, 7th and 11th.



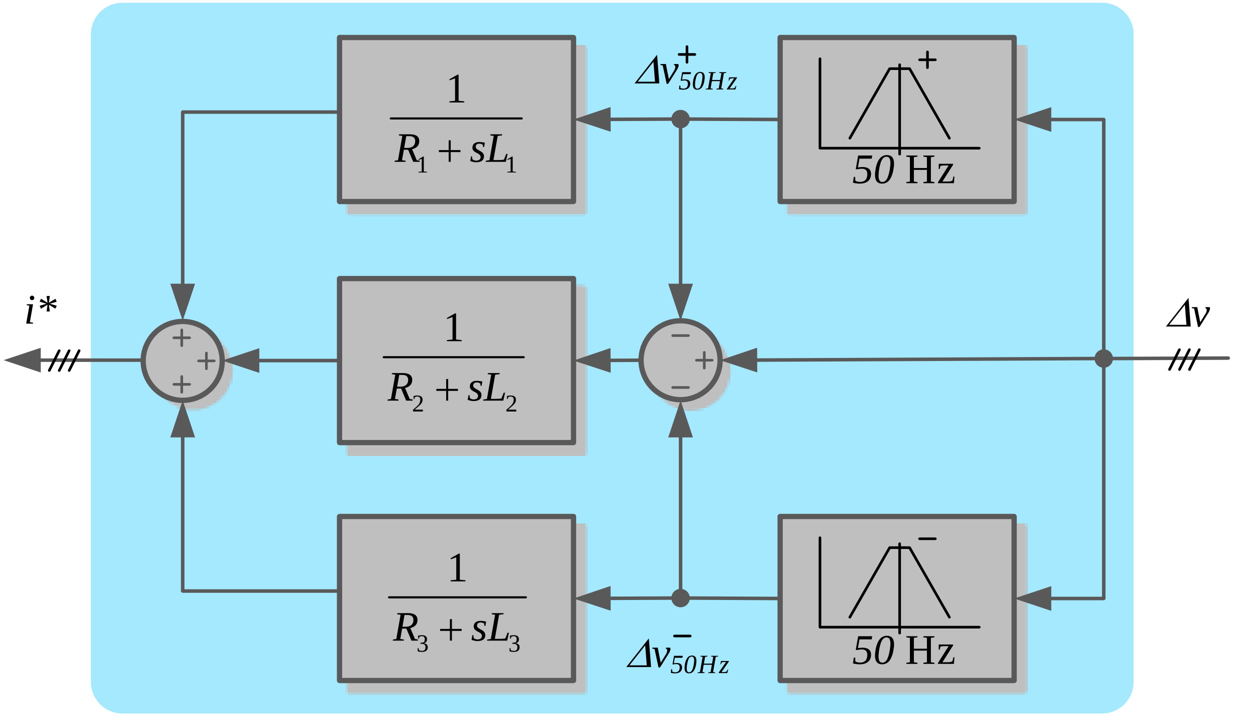
- 5^{th} THD = 2,1%
- 7^{th} THD = 0,6%
- 11^{th} THD = 0,4%
- $THD_v(\%)$ = 3.73

- 5^{th} THD = 7,0%
- 7^{th} THD = 3,9%
- 11^{th} THD = 3,1%
- $THD_v(\%)$ = 9.05

5. Synchronous Services in μGrid

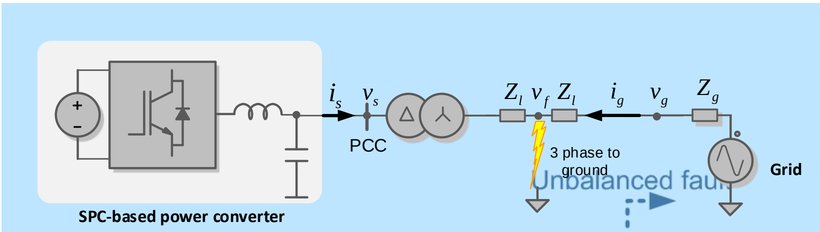
5.11 The SPC beyond the grid-codes requirements – Unbalance Sag/load

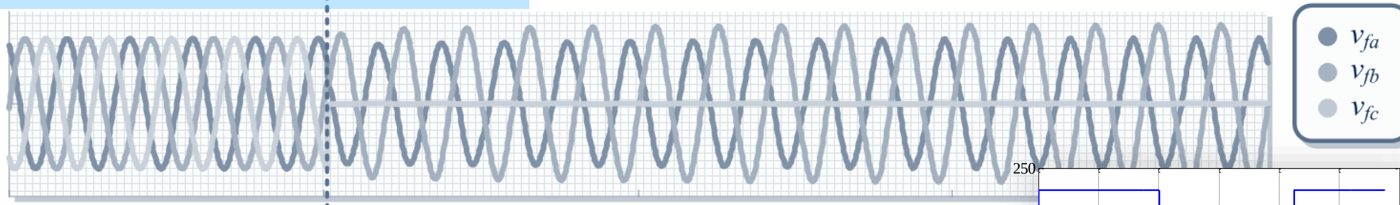
The value of virtual admittance of the SPC can take different values for positive- and negative-sequences, so the response of the system during unbalanced loads can be improved.



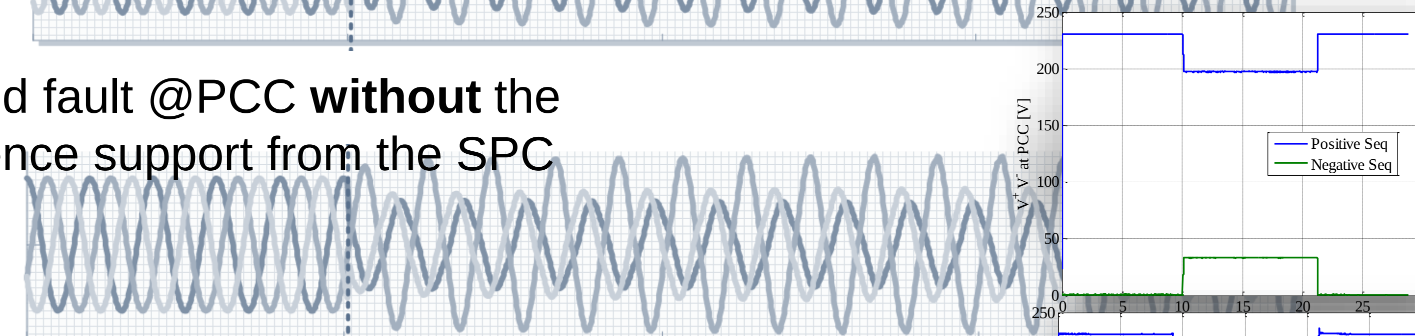
5. Synchronous Services in µGrid

5.11 The SPC beyond the grid-codes requirements – Unbalanced fault

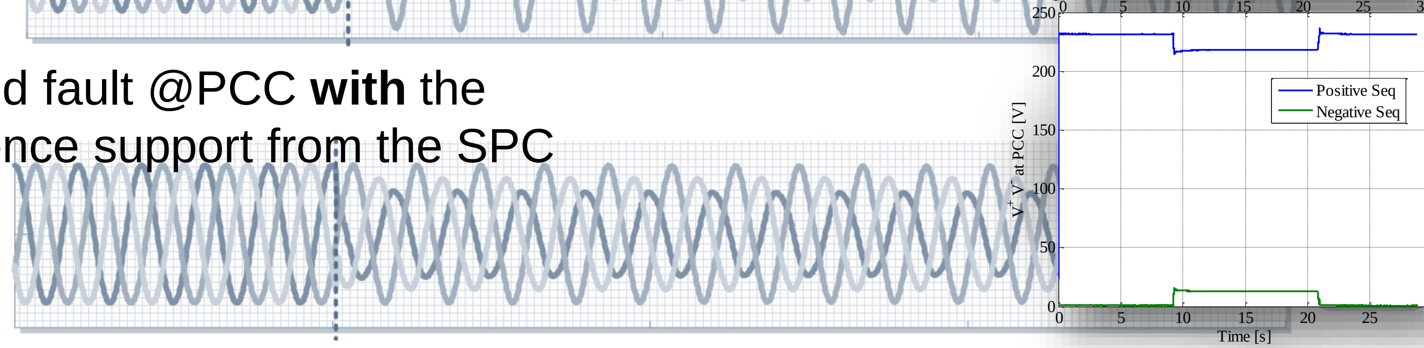




Phase to ground fault @PCC **without** the negative sequence support from the SPC

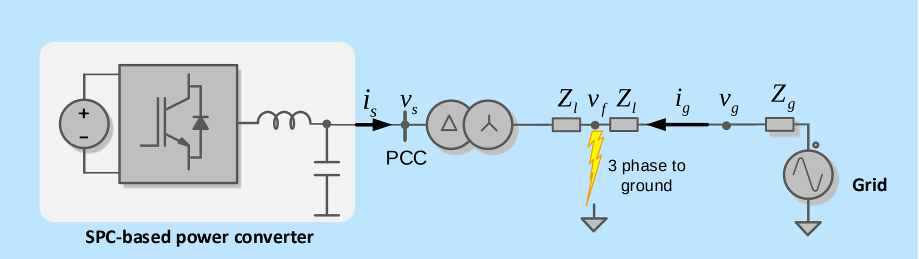


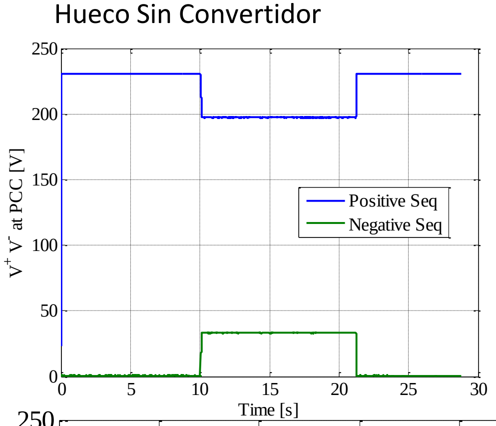
Phase to ground fault @PCC **with** the negative sequence support from the SPC

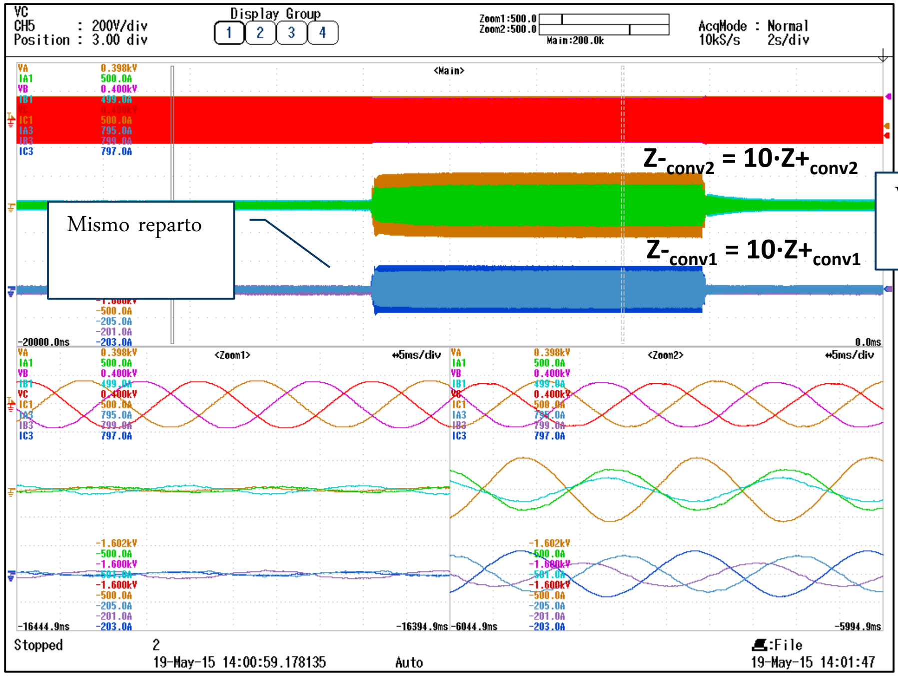


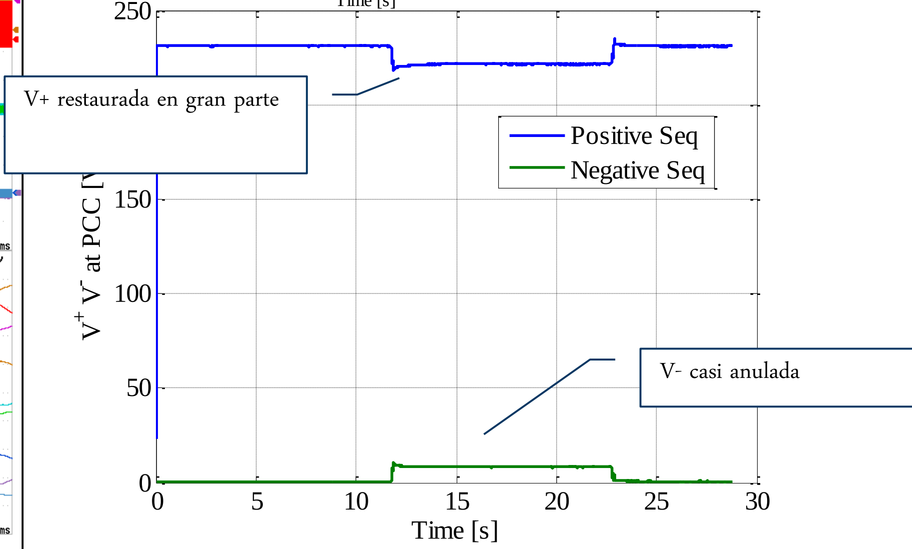
5. Synchronous Services in µGrid

5.11 The SPC beyond the grid-codes requirements – Unbalanced Sag









6. Conclusions

6. Conclusions

- Power control of power electronics converter is performed through voltage and/or current control in the microgrid.
- The control techniques of the power converters forming the micro-grid are according to the power converter role in the microgrid environment: Grid forming, grid feeding or grid supporting.
- The droop control schemes for inductive, resistive and generic lines have been presented as an effective solution to support the amplitude and frequency of the voltage in AC micro-grids.
- This technique is being also used for P and Q power sharing between paralleled inverters.
- the virtual impedance concept has been introduced and its suitability to control power sharing in paralleled power converters has been pointed out in a higher performance, compared with the droop control.

6. Conclusions

- However virtual impedance it is implemented with a derivative term so noise and non-linear problems affects sternly its performance
- the virtual admittance control strategy performs the converter as a current source to control the current in front of a large variety of transient conditions, like a synchronous generator does.
- In a similar way the swing equations of the synchronous generator are also emulated, but with dynamic design parameters like damping, inertia and impedance.
- The Synchronous Power Converter inject to the grid the reference power in a dynamic way in order to avoid large transients in the voltage or in the frequency.
- The SPC is easily parallelized without any type of communication requirement between them.
- The SPC is easily integrated from small to large power converters.

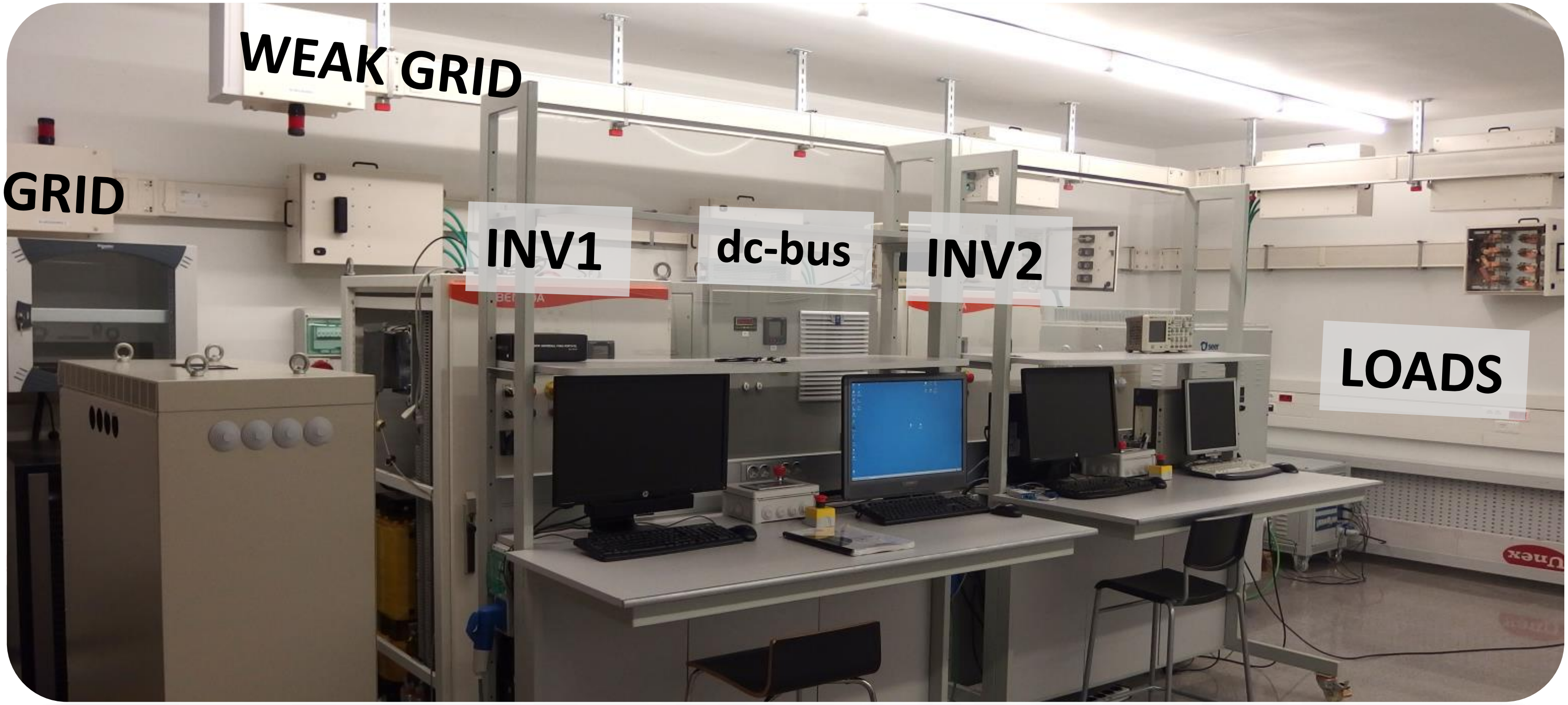
6. Conclusions

- The SPC add service functionalities to DG from renewable and from energy storage devices.
- The SPC accepts external reference of P, Q, V or f, from the TSO or DSO, in the same way of electrical plants.
- The SPC helps to stabilize the grid in front a voltage and frequency deviation, voltage sags, unbalance faults or loads, harmonics, between others quality issues.
- Additional value functionalities are also complelemented like:
  - Black-Start Capability
  - Island mode operation and resynchronization process
  - Damping of power oscillations
  - Inertia Emulation

- The SPC in ESS it is a very powerful tool to work in cooperation with DG sources in order to offer synchronous strategies in order to support and stabilize the grid

6. Conclusions

SEER's SPC Work bench



Thanks
for your attention

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seer Renewable Electrical Energy Systems

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4. μGrid control structures

4. μGrid control structures

4.1 Introduction

Primary Control, Sets references for the inner current and voltage control loops to halt deviations in the grid frequency and voltage amplitude. 'Virtual impedances' allow parallel operation of multiple power converters inverter. Inverters have an inherent trade of between P/Q sharing and f/V regulation.

Secondary Control, Ensures that the frequency and voltage errors are regulated to zero after changing load and/or generation conditions in the micro-grid. Also, include the ability of connecting and disconnecting to/from the main grid.

Tertiary Control, Sets the sharing of active and reactive power among the distributed generators to optimize the microgrid operation and match the P/Q requieremens from the main grid.

4. µGrid control structures

4.2 Grid-feeding converters

PRIMARY

Set P and Q according any MPPT, in any connection mode. But this reference can be set as references by the secondary control.

SECONDARY

Set the operation point of each inverter with the objective of minimizing the voltage and frequency deviations. In island mode establish the set of P and Q that intends to properly share the power generation into the microgrid.

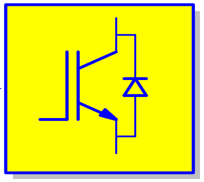
TERTIARY

Sets the optimal operation from an economic point of view.
- prime mover generation cost,
- prime mover availability,
- cost of purchasing energy.

Σ

P^*

Q^*



Grid-feeding

4. µGrid control structures

4.3 Grid-supporting converters

PRIMARY

combined with the virtual impedance, the amplitude, frequency and phase-angle of the reference voltage in the inner control loops

SECONDARY

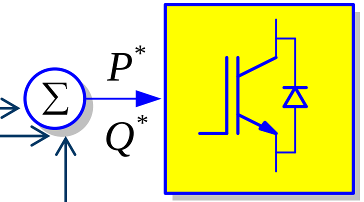
Adjusts the droop characteristic coefficients, k_P and k_Q in droop equations, to restore the microgrid voltage and frequency to their target values by changing the P^*_l and Q^*_l references. Also resynchronization services are included

$$f - f_O = -k_p(P - P_O)$$

$$V - V_O = -k_q(Q - Q_O)$$

TERTIARY

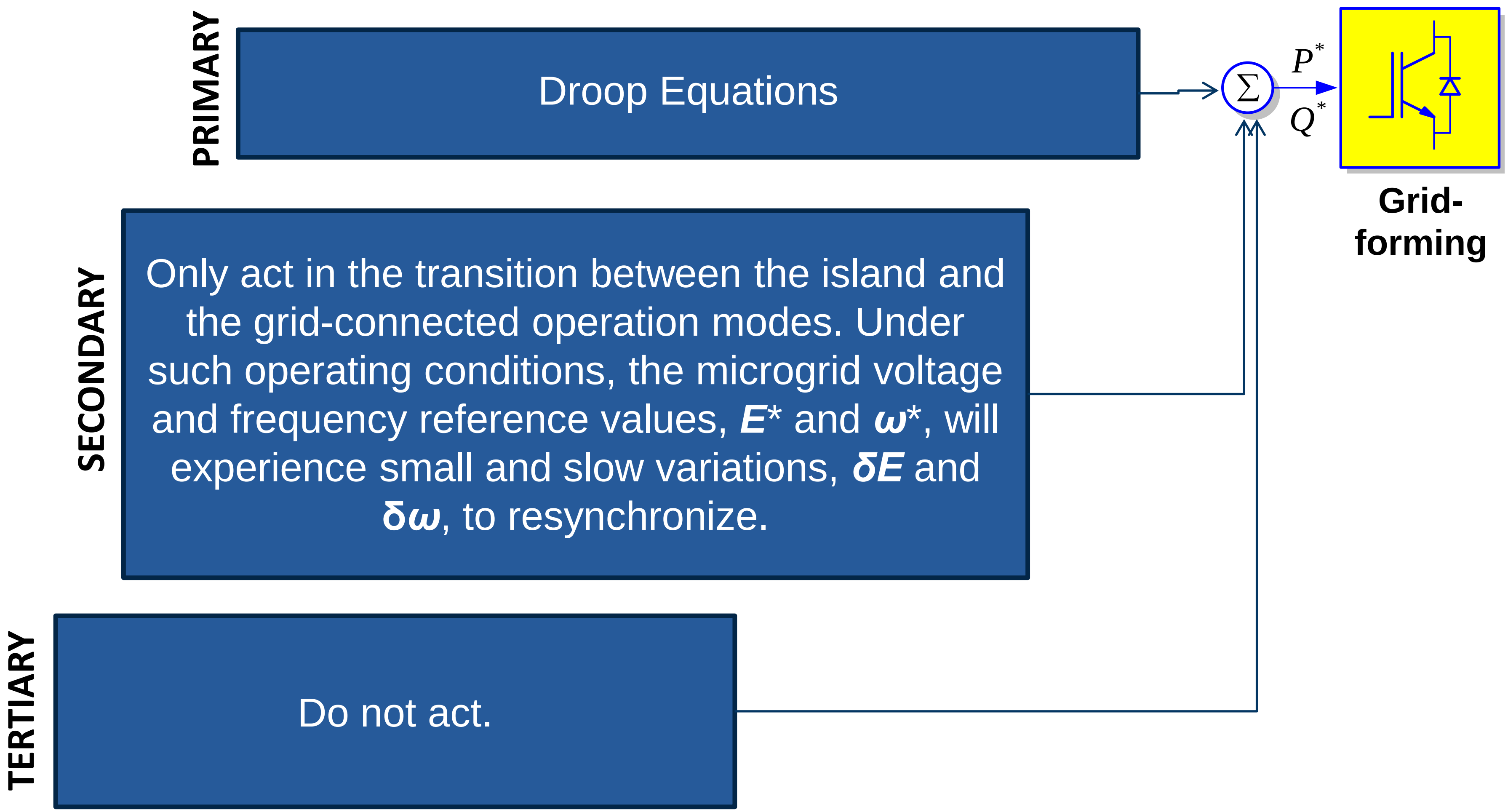
Restore the secondary control reserve, as well as to set the micro-grid voltage and frequency to their nominal values in case the secondary reserve is not effective enough



Grid-supporting

4. μGrid control structures

4.4 Grid-Forming



4. μGrid control structures

4.5 Energy Management

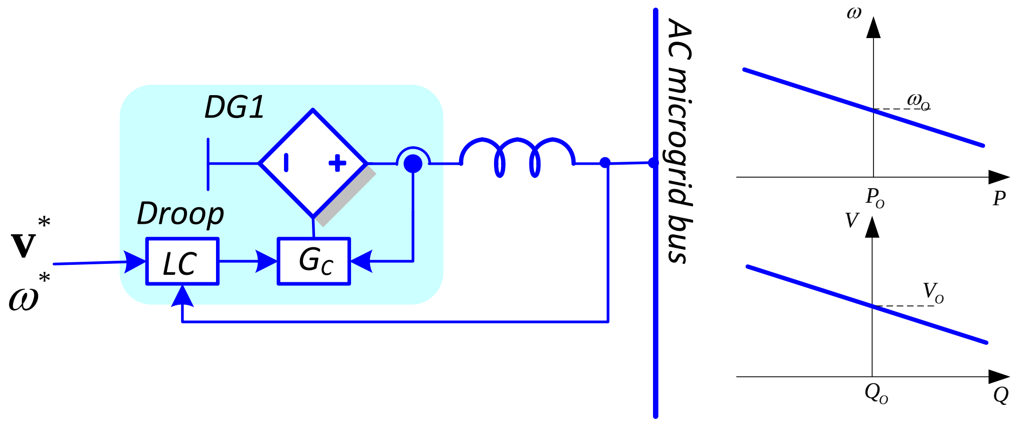
With a high penetration of distributed generation, different loads characteristics, power quality constrains, market participation strategies the required control and operational strategies of a microgrid are different from those of the conventional power systems.

- Dynamic characteristics of DER units, electronically coupled, different from large synchronous generators.
- Presence of single-phase loads/DER units
- High participation of “non-controllable” primary sources, wind and PV.
- Storage Systems participation
- Still a non-mature technology, so with a marginal costs variability.

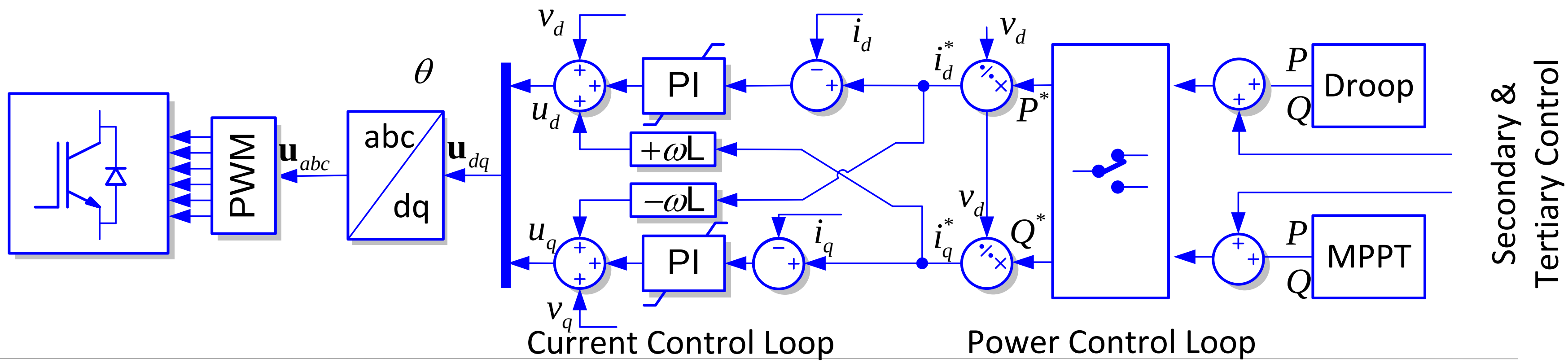
4. µGrid control structures

4.2 Energy Management at Primary Control

Control strategies for DG units within a microgrid are selected based on the required functions and possible operational scenarios. Primary control regulates the injected ***P*** and ***Q*** for **grid-supporting** functionalities.



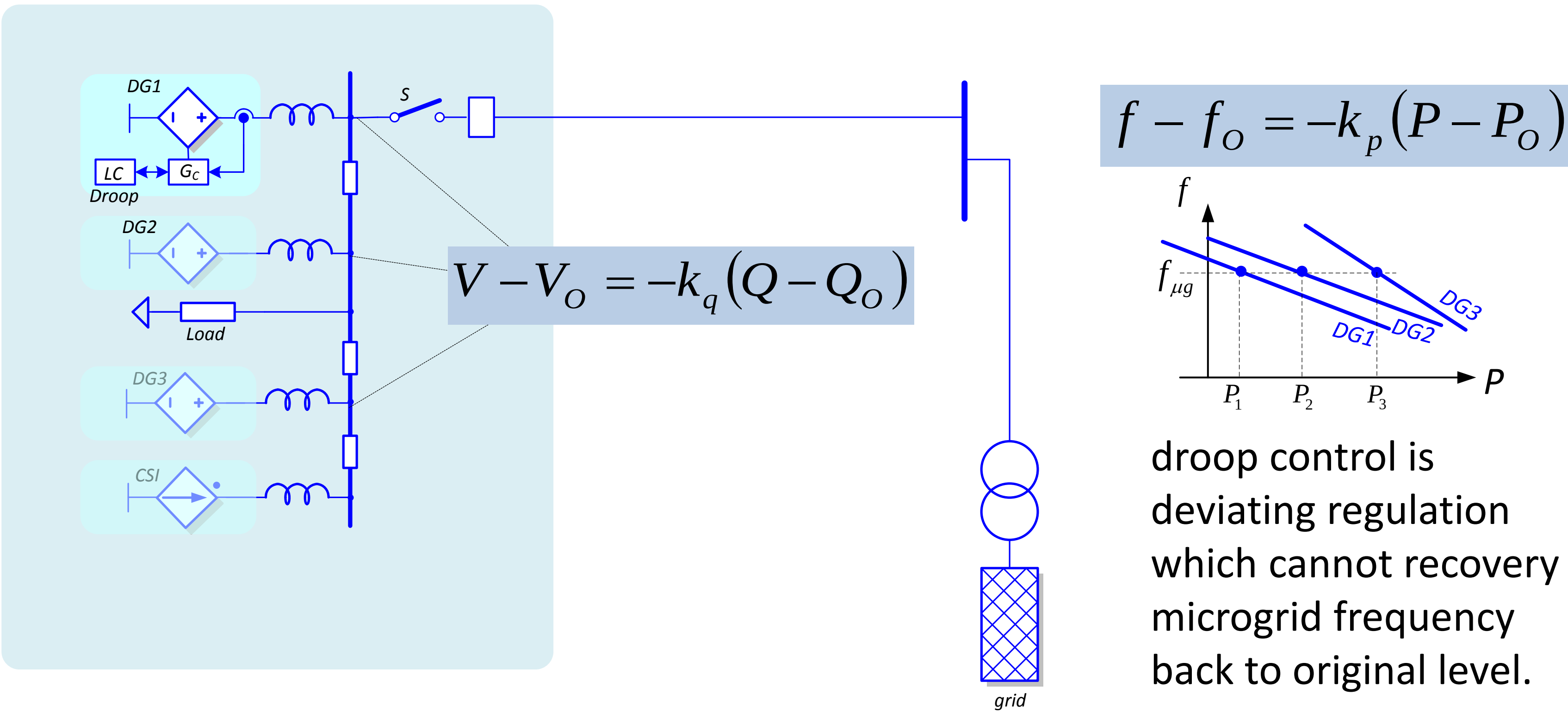
In **grid-feeding** mode, this will be controlled by a MPPT algorithm in order to maximize the power injected from the primary sources. However, this **P** and **Q** references can be can be modified by secondary and tertiary controllers.



4. μGrid control structures

4.3 Energy Management at Primary Control

Each one of the DG units gets its own **local control** with the objective of feed the grid or give **voltage support** through the injection of an specific active and reactive power to the grid without communication with other DG.

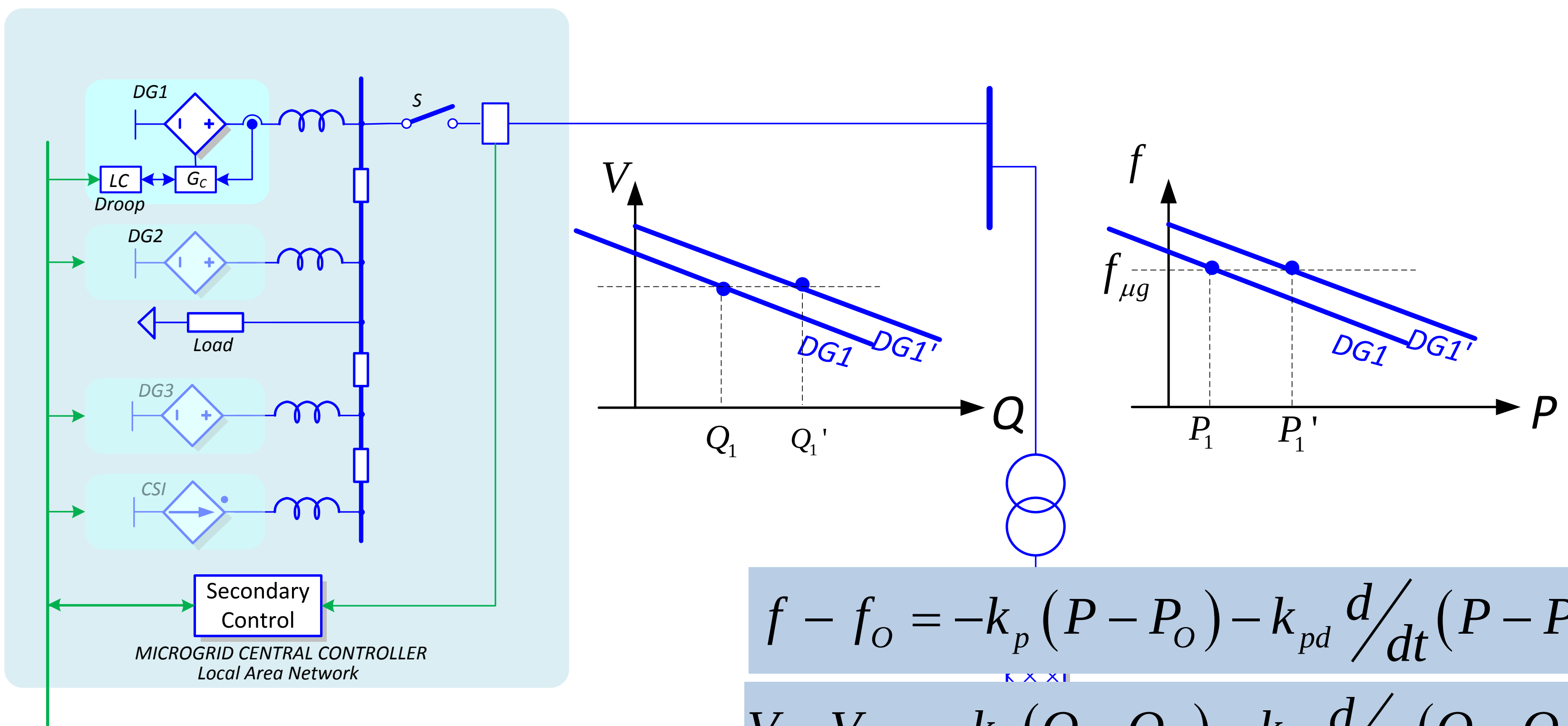


droop control is deviating regulation which cannot recovery microgrid frequency back to original level.

4. µGrid control structures

4.4 Energy Management at Secondary Control

The purpose of the secondary control is to maintain constant the *V* and *f* in the output of the each DG unit, minimizing the average of all deviations.



$$f - f_O = -k_p\left(P - P_O\right) - k_{pd}\,{}^{d}\!/_{dt}\left(P - P_O\right)$$

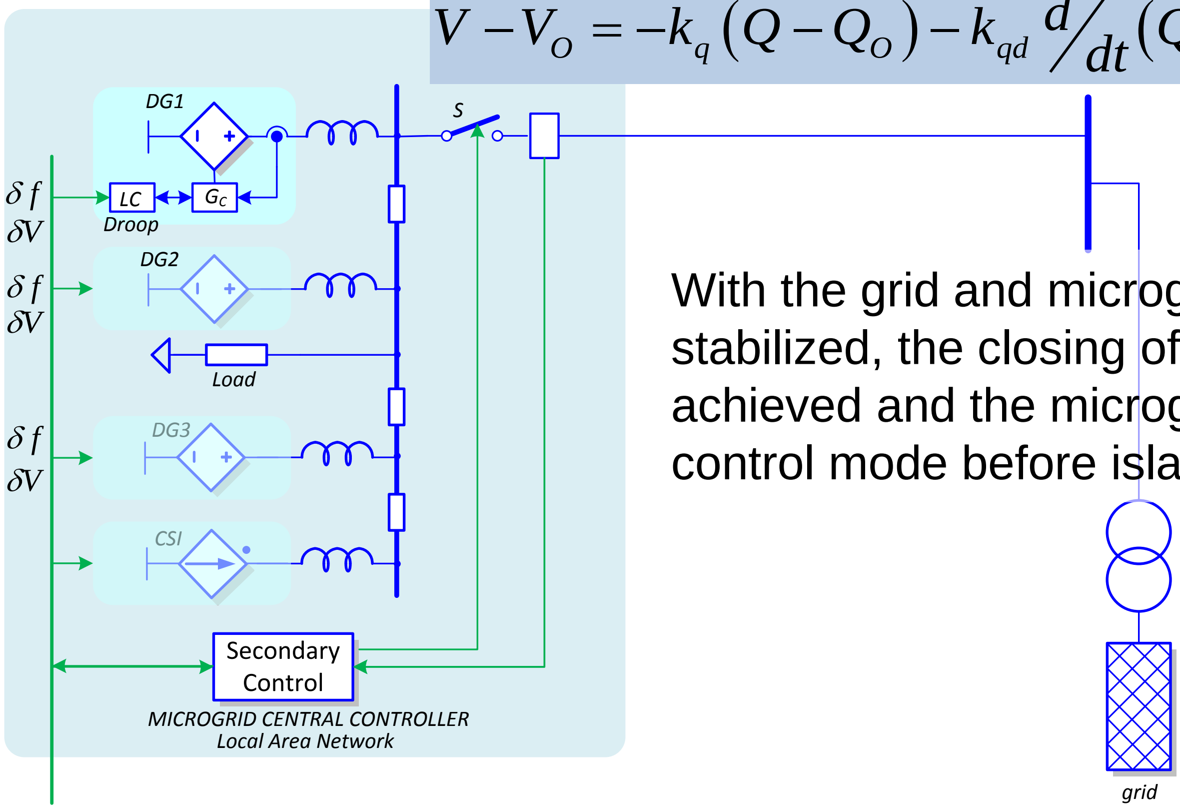
$$V - V_O = -k_q\left(Q - Q_O\right) - k_{qd}\,{}^{d}\!/_{dt}\left(Q - Q_O\right)$$

4. μGrid control structures

4.4 Energy Management at Secondary Control

$$f - f_O = -k_p\left(P - P_O\right) - k_{pd}\, {d}/{dt}\left(P - P_O\right) - \delta f_{synch} \cdot G_{synch}(s)$$

$$V - V_O = -k_q\left(Q - Q_O\right) - k_{qd}\, {d}/{dt}\left(Q - Q_O\right) - \delta V_{synch} \cdot G_{synch}(s)$$

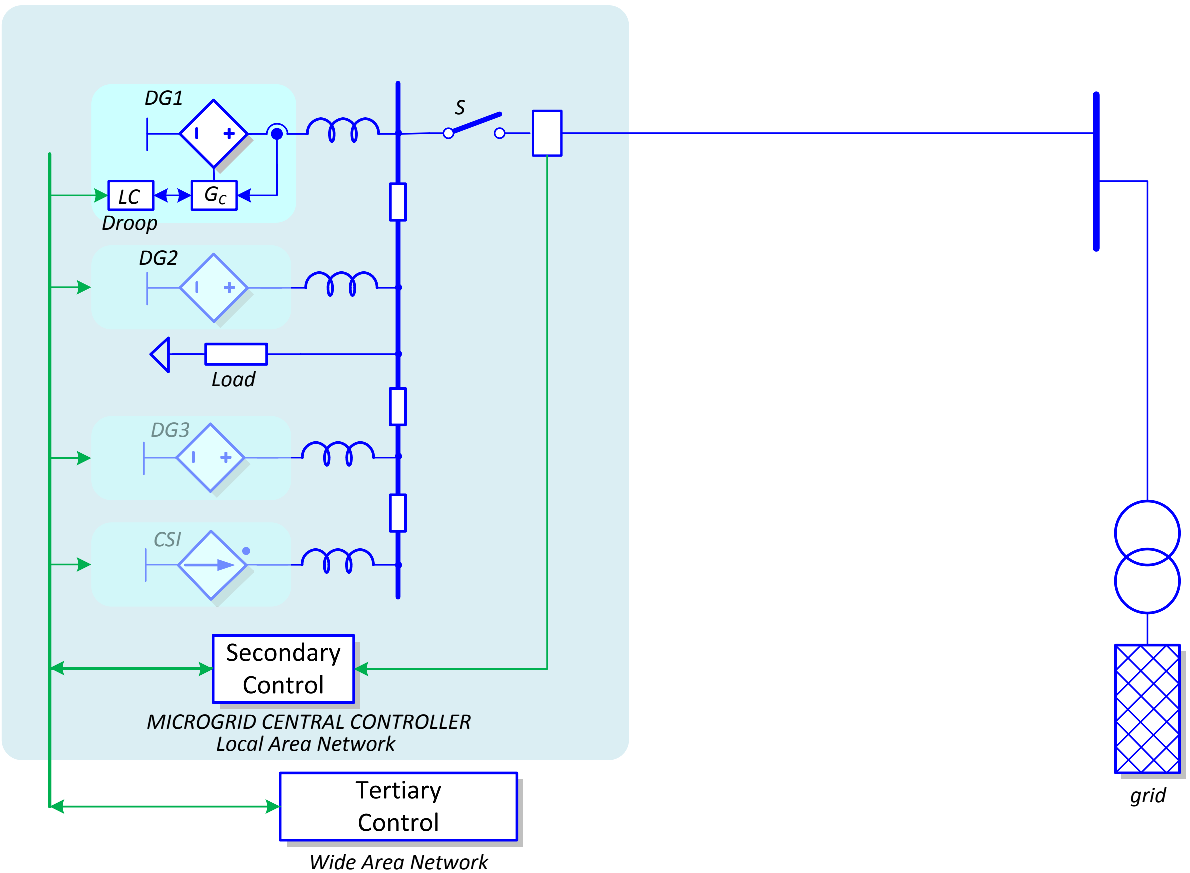


With the grid and microgrid synchronized and stabilized, the closing of the grid switch, S, is achieved and the microgrid is recover to the control mode before island.

4. µGrid control structures

4.5 Energy Management at Tertiary Control

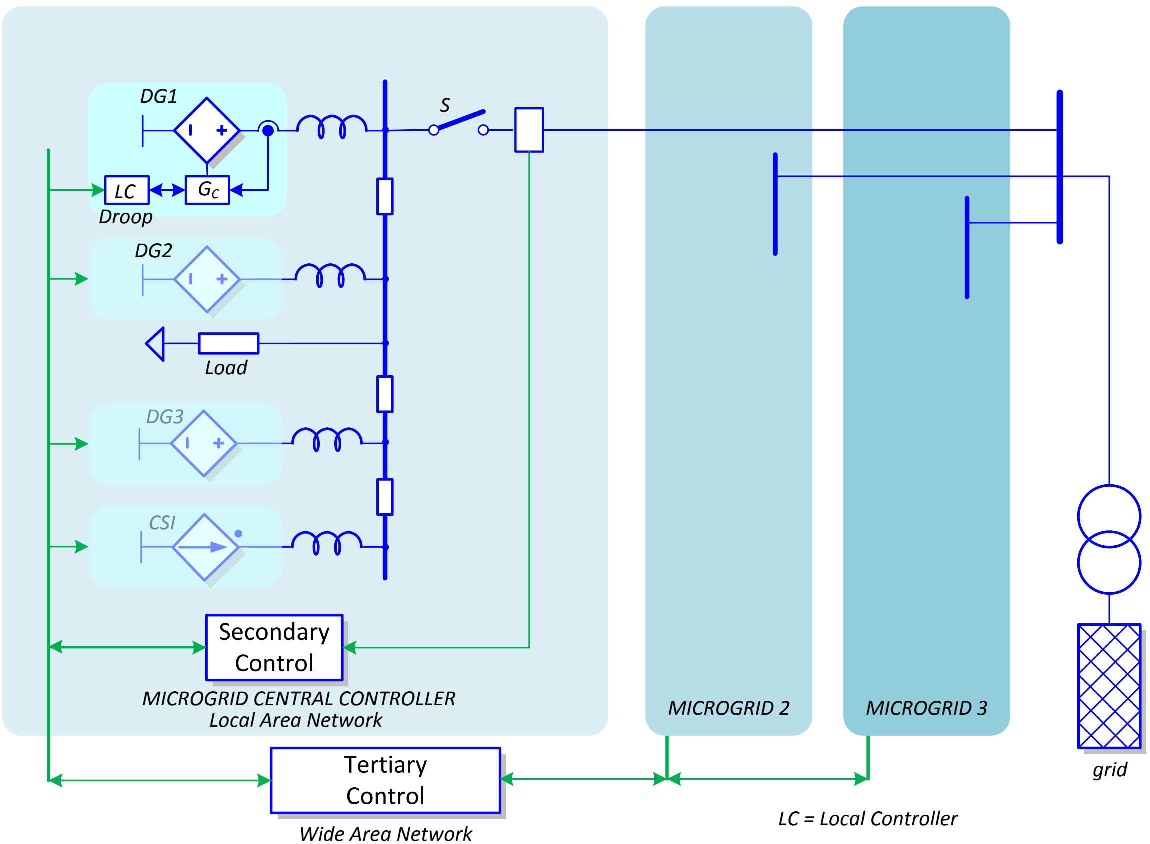
In a high level, the tertiary control replace the secondary in order to improve the economics



4. µGrid control structures

4.5 Energy Management with Microgrids Operation

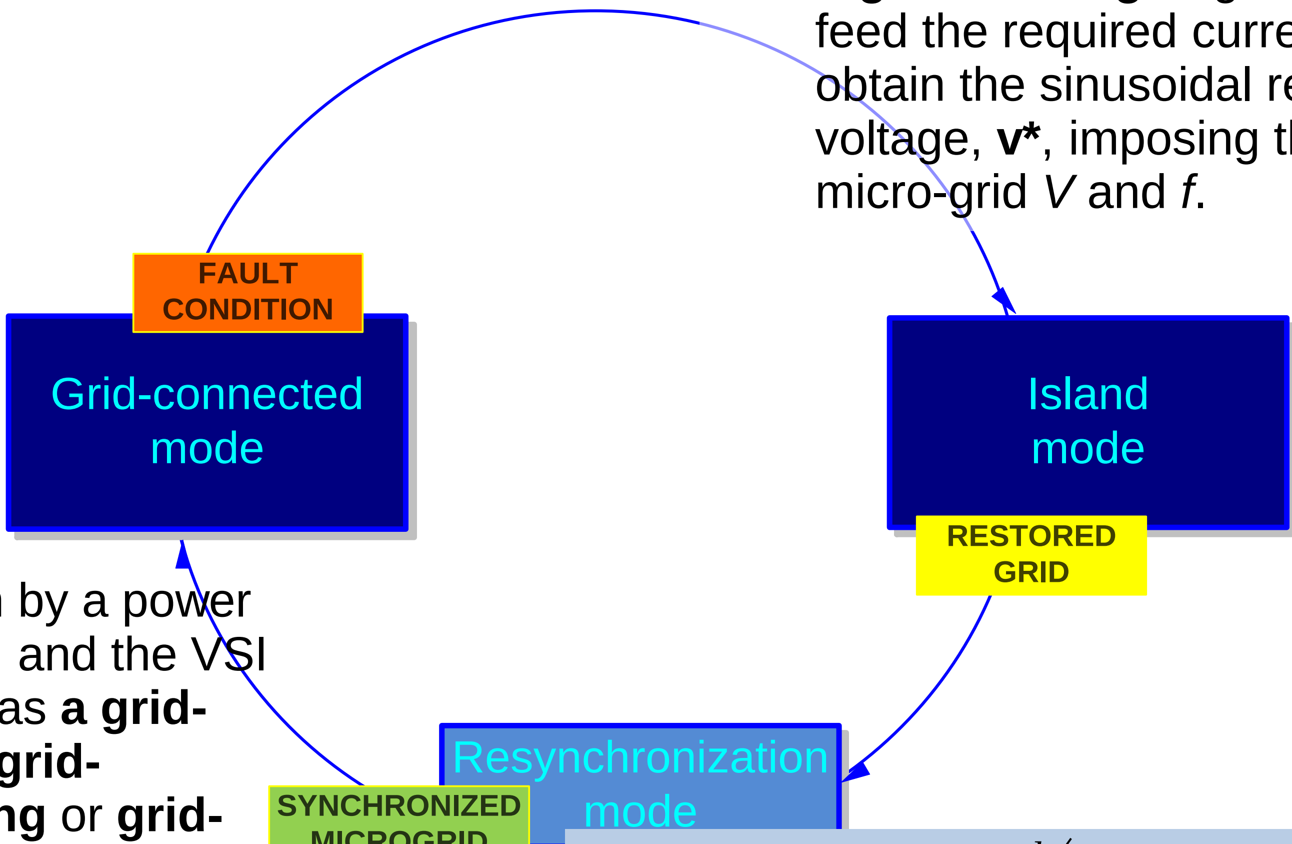
Additionally, the tertiary control regulates the coordination between neighboring micorgrids, in clusters



4. μGrid control structures

4.6 Energy Management with Microgrids Operation – Secondary Control

A **grid-forming** or grid-supporting feed the required current, **i***, to obtain the sinusoidal reference voltage, **v***, imposing thus the micro-grid *V* and *f*.



i* is given by a power controller, and the VSI operates as **a grid-feeding, grid-supporting** or **grid-tracking** converter.

$$f - f_O = -k_p\left(P - P_O\right) - k_{pd}\,{}^{d}\!/_{dt}\left(P - P_O\right) - \delta f_{synch}\cdot G_{synch}(s)$$

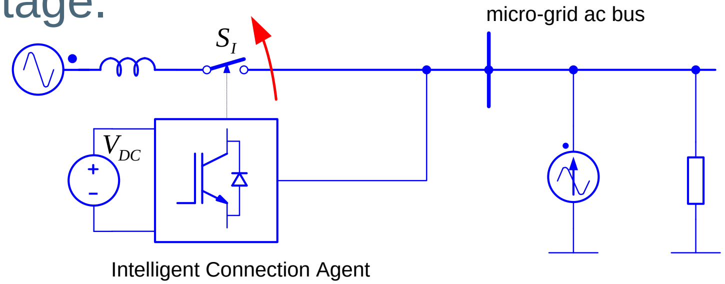
$$V - V_O = -k_q\left(Q - Q_O\right) - k_{qd}\,{}^{d}\!/_{dt}\left(Q - Q_O\right) - \delta V_{synch}\cdot G_{synch}(s)$$

4. µGrid control structures

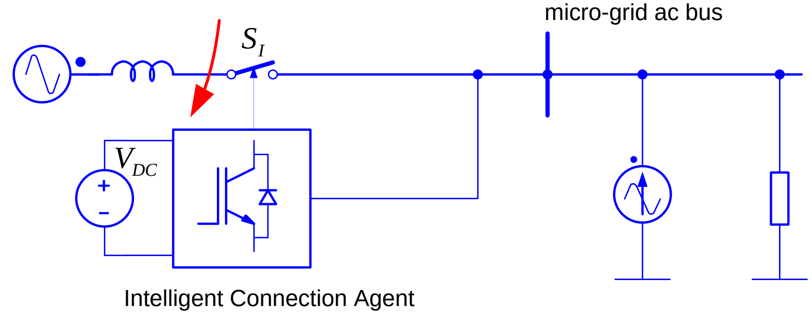
4.6 Energy Management with Microgrids Operation

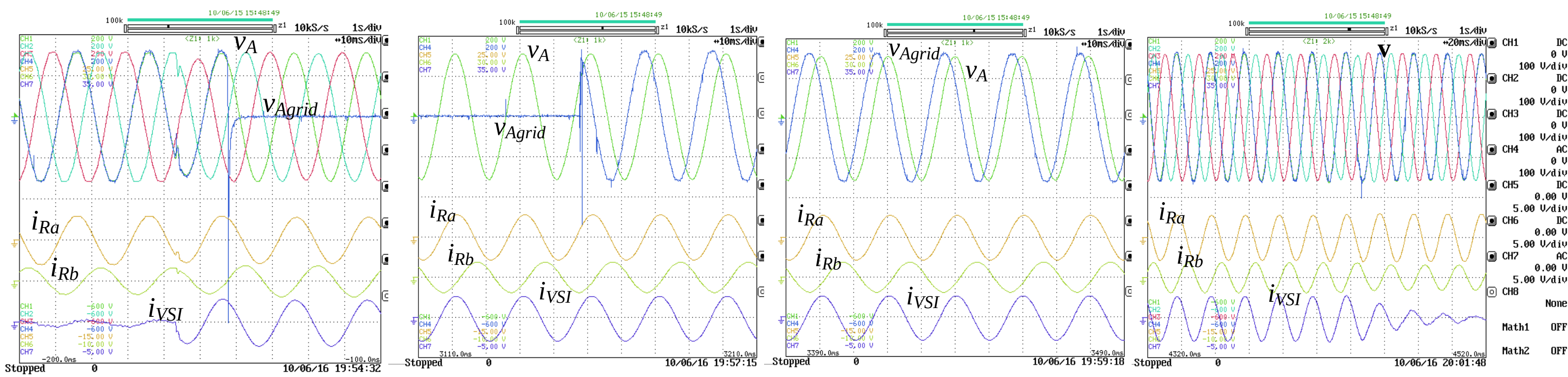
Microgrid synchronization

The resynchronization process starts when the main grid voltage is restored with a slow resynchronization process with the grid voltage.



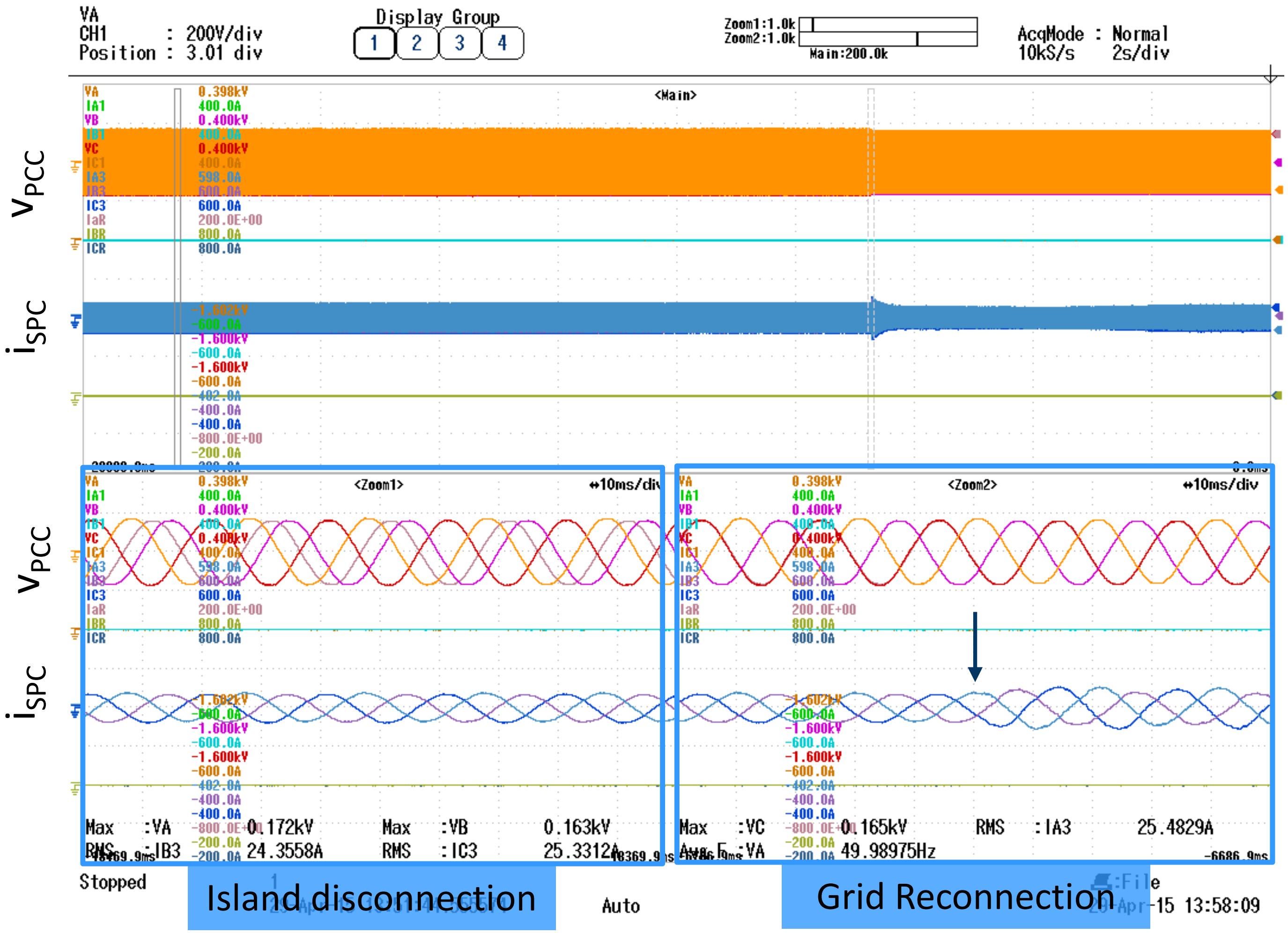
Once the error between the grid and the micro-grid voltage becomes below a certain value





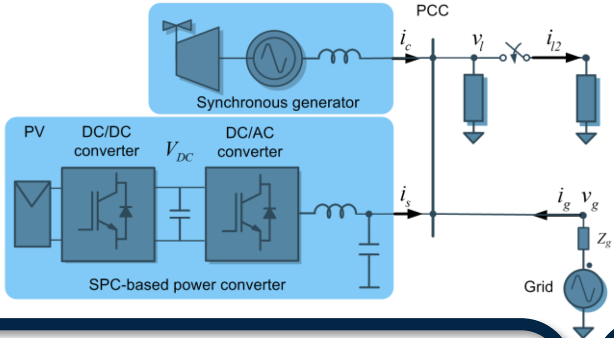
5. Synchronous Services in μGrid

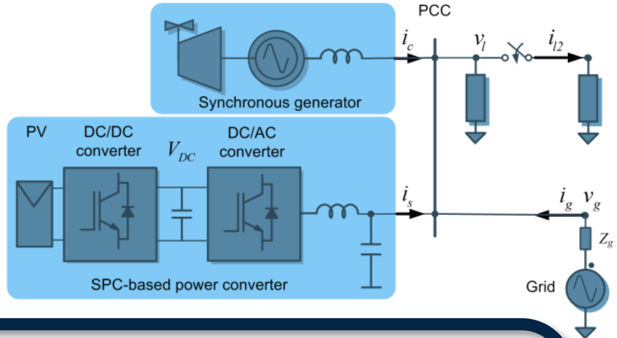
5.9 The SPC beyond the grid-codes requirements – Island Mode



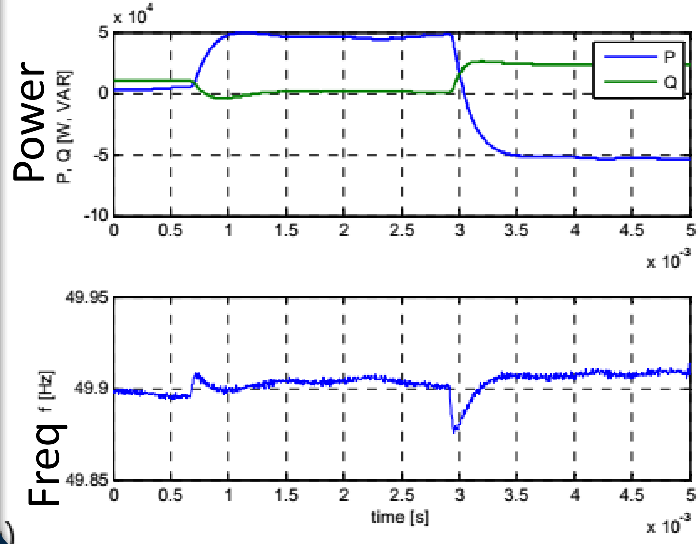
5. Synchronous Services in µGrid

5.8 The SPC beyond the grid-codes requirements – Power Oscillation Damping





Power reference step from 0 to 50 kW, and from 50 to -50 kW.



Power reference change from 0 to 40 kW.