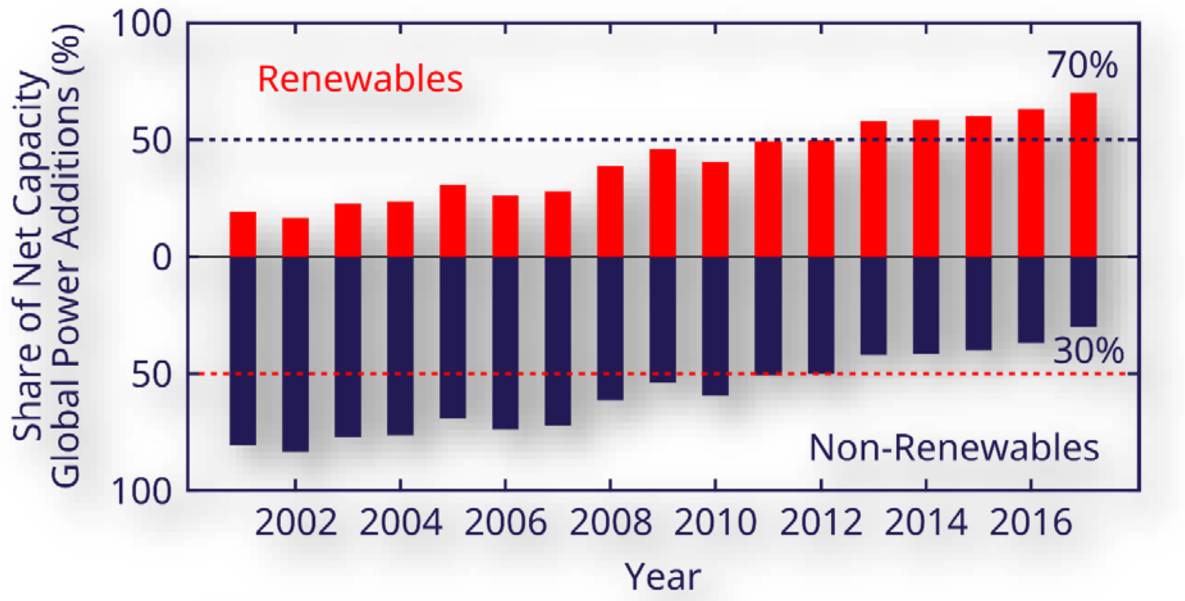
Power Converters for AC and DC electrical power systems: control and interconnection issues

Rosa Anna Mastromauro

Renewable Energy Sources & DPGS



Source: Chapter 01 in Renewable energy devices and systems with simulations in MATLAB and ANSYS, Editors: F. Blaabjerg and D.M. Ionel, CRC Press LLC, 2017

Distributed Power Generation Systems (DPGS)

Grid-connected mode

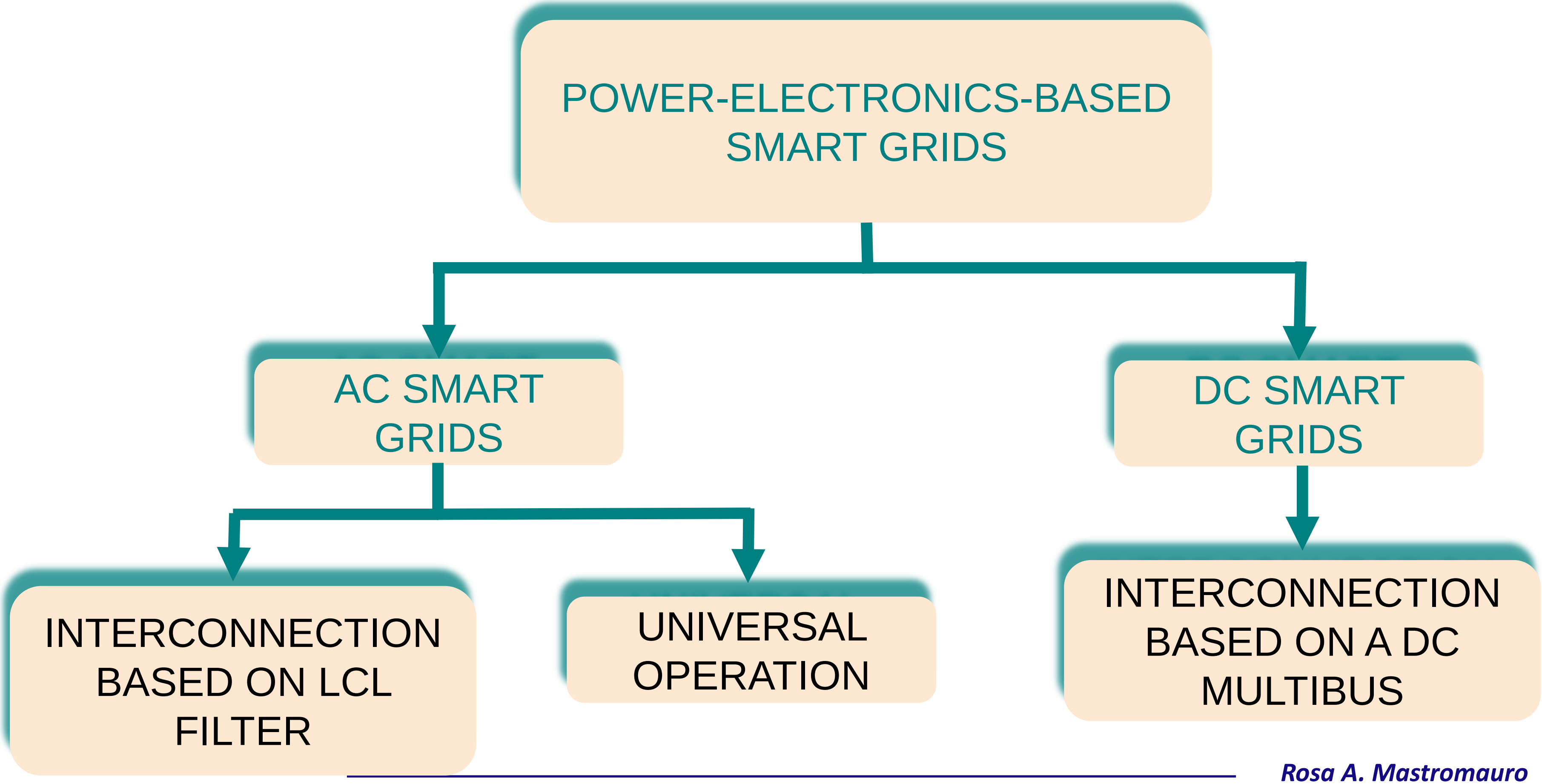
Islanding modes

No interruption in the load power supply

A **MICROGRID** is an electrical system that includes multiple loads and distributed energy resources that can be operated in parallel with main grid or as an electrical island.

In the Distributed Generation scenario, the **MICROGRID** concept has been introduced as a solution to provide high power quality and to improve the reliability of the traditional electrical power system.

A **MICROGRID** with INTELLIGENT features is a **SMART GRID** ....



DC & AC Microgrids

Problems in AC Microgrids:

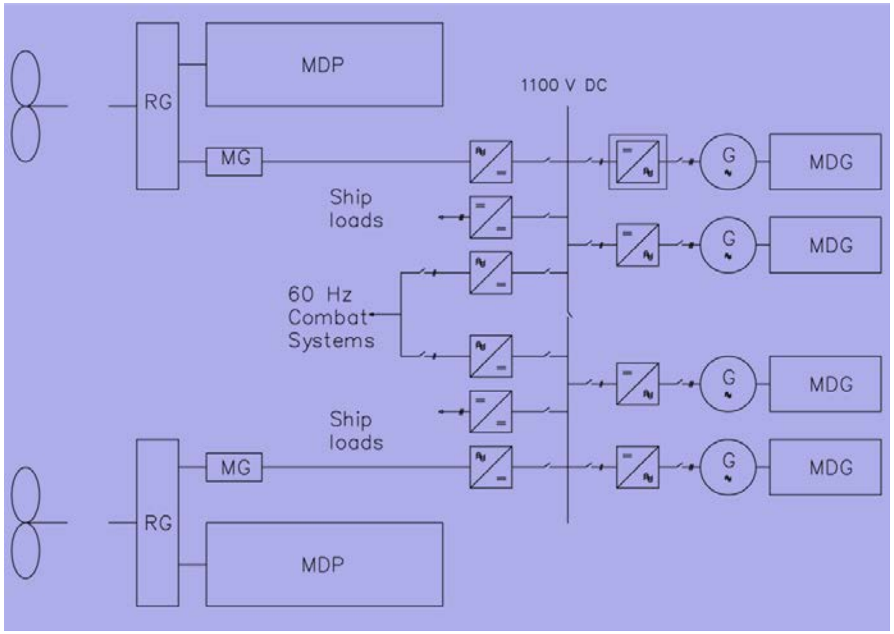
- Synchronization of distributed generators
- Inrush current (transformers, Induction motors, Induction generators)
- Three-Phase Unbalance (single-phase loads, single-phase generators such as PV)

Recent Trends

- Introduction of many Inverter loads (AC/DC and DC/AC conversions are included)
- Introduction of distributed generations with DC output (photovoltaic, fuel cell,variable speed type wind turbine, microturbine, gas engine)
- Needs for higher quality power

DC Smart Grids Applications:

- -48 V telecom systems, DC-link for UPS systems
- DC microgrids/nanogrids
- DC distributed power systems (DPS)
- Isolated systems: avionic, automotive, marine…

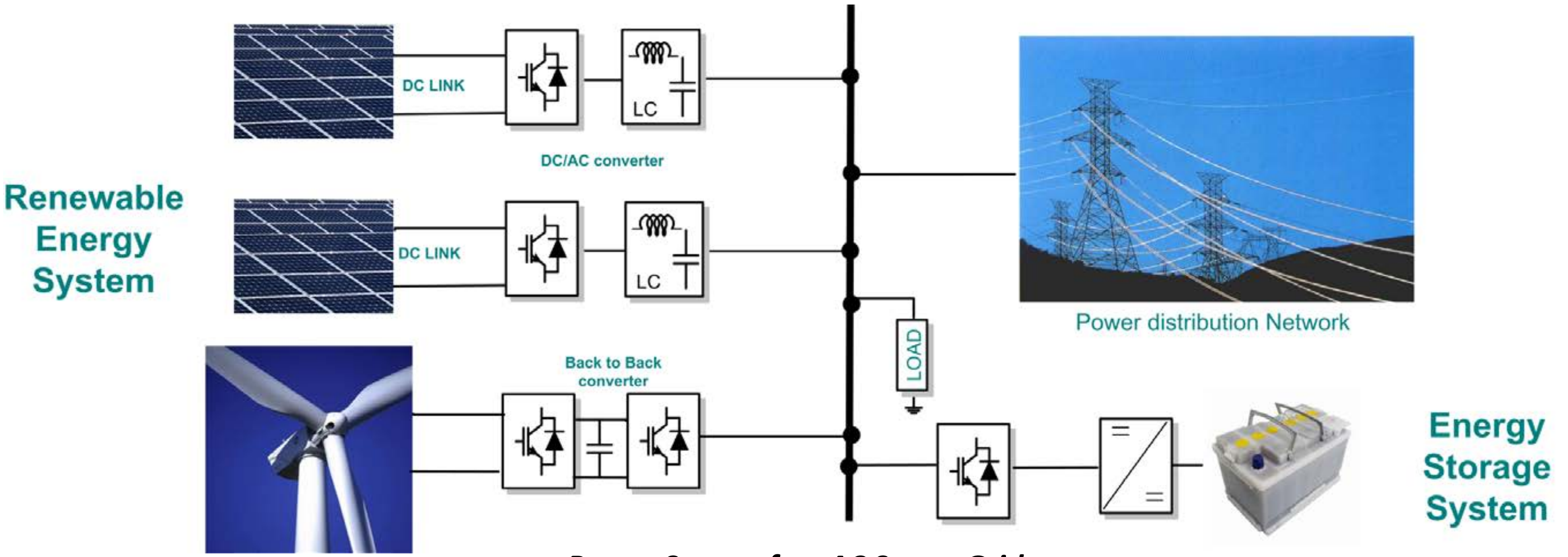


DC Smart Grids Advantages

- DC Smart Grids are a good solution for autonomous systems when trying to combine: PV systems with batteries

- DC Smart Grids can naturally interface:
  - DC sources: PV, fuel cells.
  - DC storage: supercapacitors, batteries
  - DC loads: LEDs, electronic loads

- DC Smart Grids are more efficient than AC Smart Grids ….. in general !



Power Stage of an AC Smart Grid

Rosa A. Mastromauro

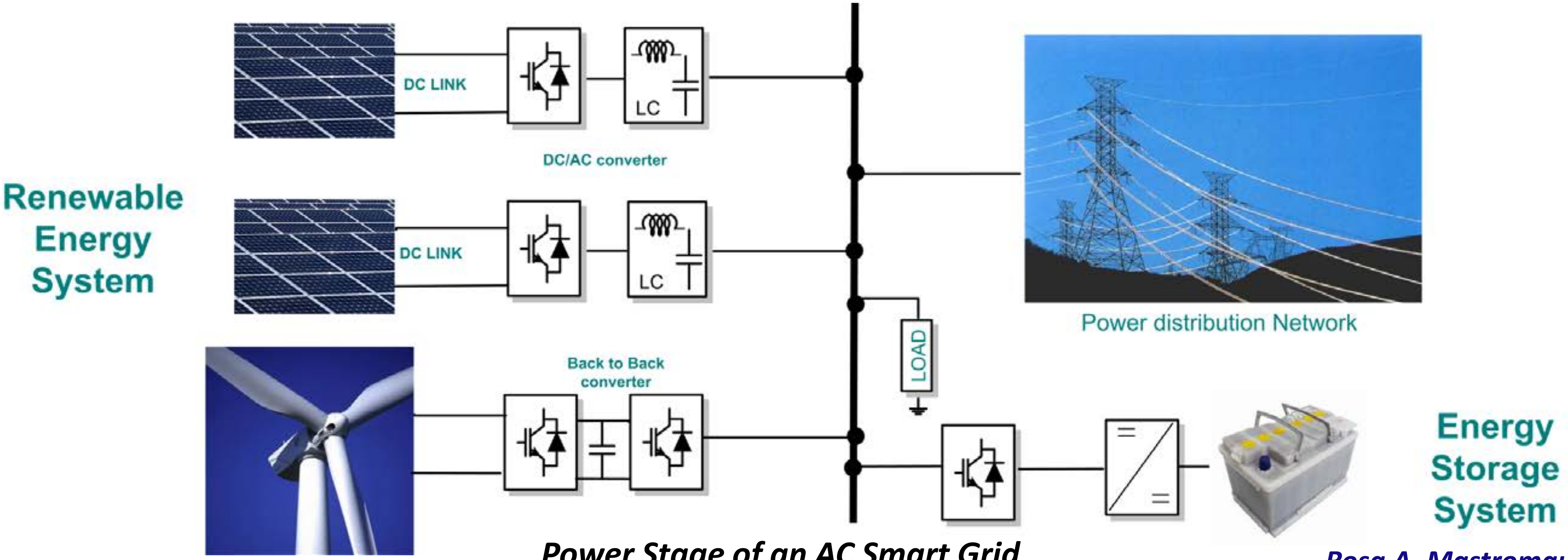
DC Smart Grids Advantages

- Fluctuation of generated power of distributed generators and load power can be compensated in the DC line by using energy storage devices

- Loads are not affected by voltage sag, voltage swell, three-phase voltage unbalance, and voltage harmonics

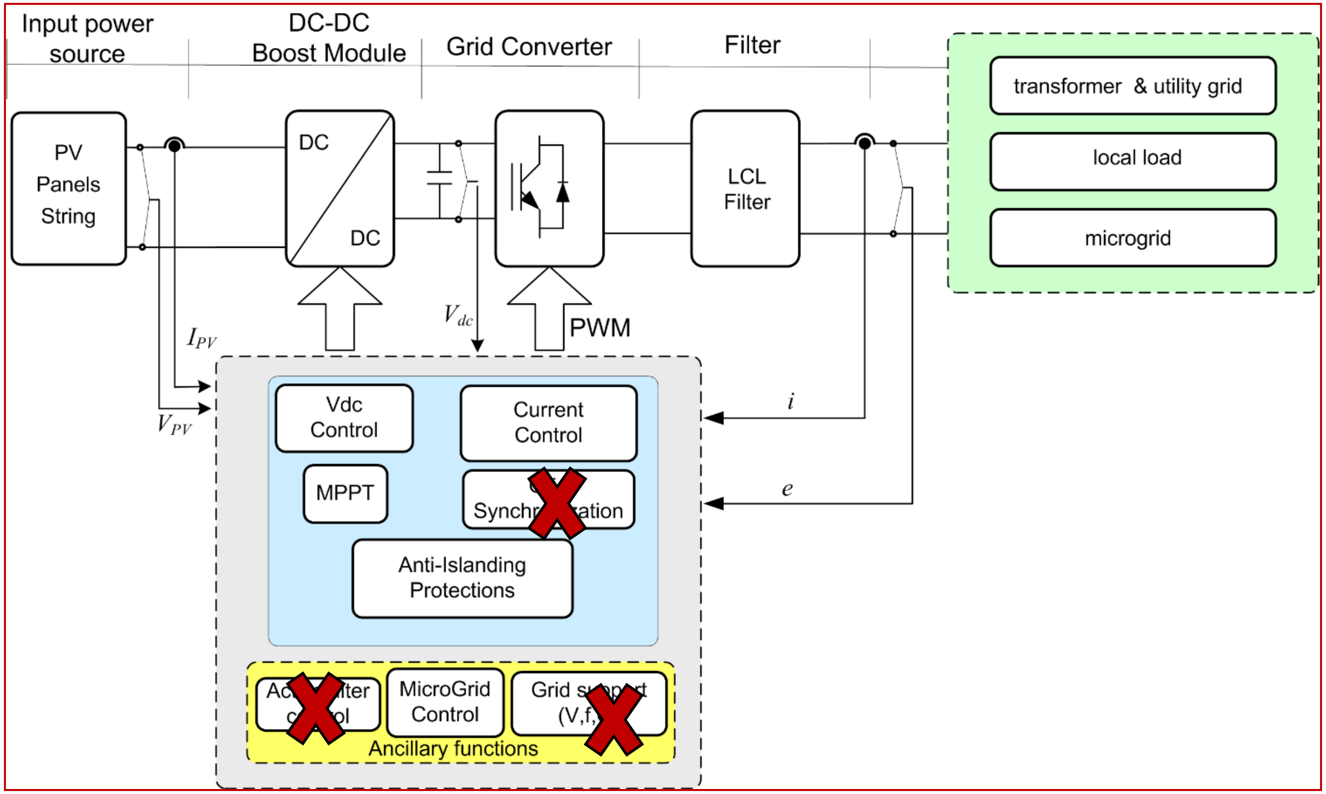
- Power quality is not affected by inrush current, single-phase loads and single-phase generators

- Synchronization of distributed generators are not necessary.



Power Stage of an AC Smart Grid

DPGS Control Features for AC and DC Power Systems



Complete control structure of a PV plant for integration into the AC power System

- Some of these control functions can be avoided in case of DC Smart Grids !

DC Smart Grids Voltage Levels

- 400V: This voltage level has been used in dc datacenters. This is relatively high voltage and hence highly effective grounding and protection techniques are required.

- 325V: It is equal to the peak of the AC phase voltage. Standard single phase power supplies with diode bridge input stage have DC-link voltage of 325 V. Hence, existing supplies are compatible with this DC voltage level.

- 230V: It has the same root mean square value as that of the existing AC system. Hence, the resistive loads (mostly heating) rated to operate with the existing AC system need not be modified, if this voltage level is used.

- 120V: It is an intermediate level between very low voltage and the existing AC system voltage.

- 48V: It is used in the telecom sector, hence supporting devices for this voltage level are available.

DC Smart Grids Challenges

- **Efficiency**: System efficiency depends on the power conversion stages between the sources and loads. As the power conversion stage and its efficiency depends on voltage levels, system efficiency also depends on DC bus voltage level.

- **Cost:** The cost of the power converters topologies depends on the voltage levels. Cabling size is decided by the current to be carried, which in turn depends on the system power and voltage level. Typically, converter and cabling costs increase with the reduction in voltage level. This limits the use of low DC voltage for high power application.

- **Safety:** Very low voltage (less than 50V) is considered safe for humans up to 3 seconds of direct contact. However, even for this voltage range, grounding practice is necessary for the protection of devices/equipments.

- **Protections:** circuit complexity (no zero-crossing detection);

- **Unclear pathway for moving from AC-centric power distribution to DC-inclusive distribution schemes.**

Smart Grids Control Strategies

Control Technique	Advantages	Disadvantages
Centralized	✓ Easy implementation ✓ Overall system supervision: wide range of capabilities are possible	✓ Limited flexibility ✓ Single point of failure ✓ Require redundancy on critical devices
Decentralized	✓ Do not require digital communication ✓ Highly flexible and expandable ✓ Simplicity of control	✓ Lack of global information ✓ Rely on accuracy of measurements (DBS, PLC) ✓ Voltage deviation (adaptive droop methods) ✓ Potential stability issue (adaptive droop methods)
Distributed	✓ Sparse communication ✓ Highly flexible ✓ Reconfigurable	✓ Communication coupled system dynamics ✓ High complexity for analytical performance analysis

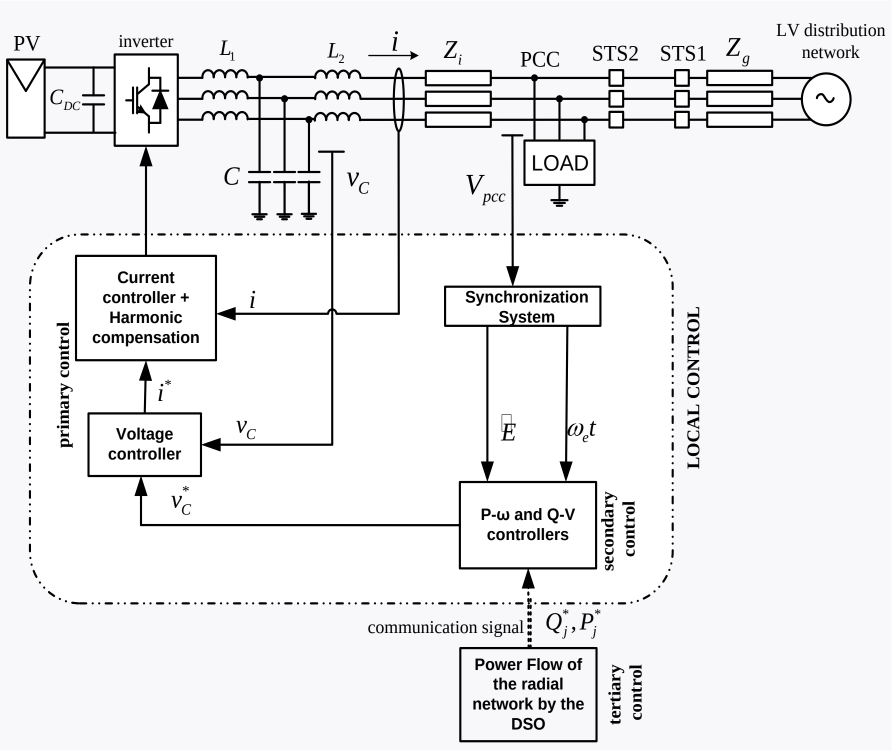
- **The power converter is the fundamental interface between the DPGS and the power system and the power converter control is the fundamental key for integration!!**

Challenges

- ✓ The appearance of stability issues: careful tuning of parameters
- ✓ Increase in the number of converters
- ✓ Complexity of converter control strategies raises:
  - ✓ Coordination with the storage control
  - ✓ Converters topologies
- ✓ Necessity to develop a sophisticated Energy Management System

Hierarchical Control Strategy

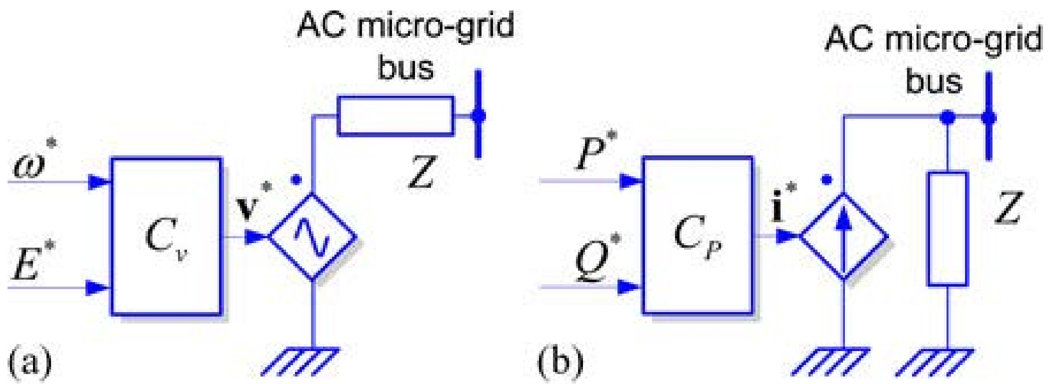
- ✓ Decreasing bandwidth with increasing of control levels
- ✓ Inner control loops as the basis
- ✓ DC bus voltage and power sharing control, e.g. droop method
- ✓ Secondary control for error cancellation
- ✓ Coordinated control of different energy resources
- ✓ Tertiary control for optimal operation



Power Converter Primary Control

- Traditionally the Distributed Power Generation Systems (DPGS) are current controlled in grid-connected mode and they deliver a pre-specified amount of active power into the distribution network.

- Differently in stand-alone operation mode, or forming a microgrid, the DPGS are voltage controlled and are responsible for both voltage and power control, in this case the DPGS converters are grid-forming.

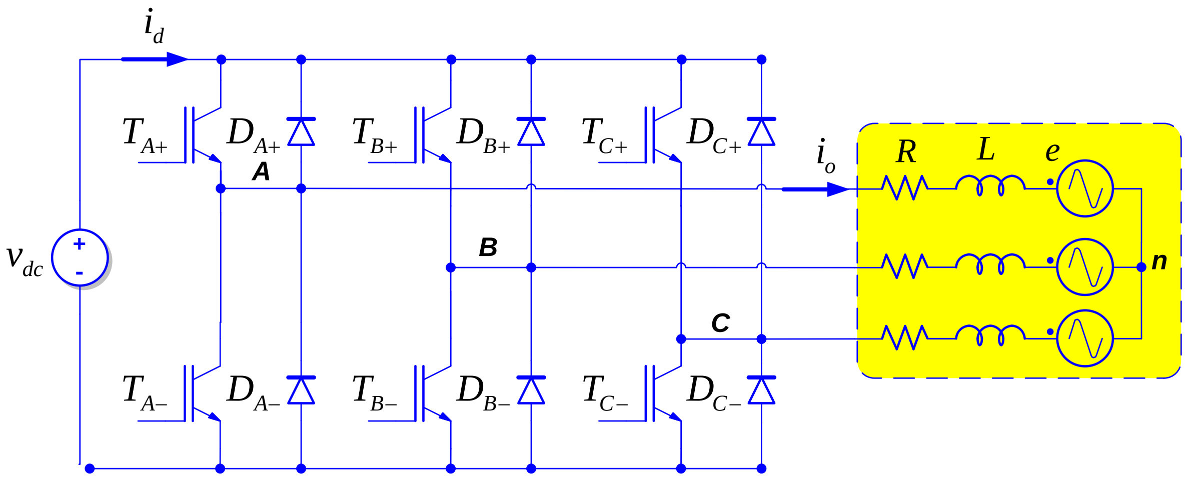


GRID-FORMING **GRID-FEEDING**

It usually operates in islanded mode

It cannot operate in island mode

Simple Model of a Grid-Feeding Converter



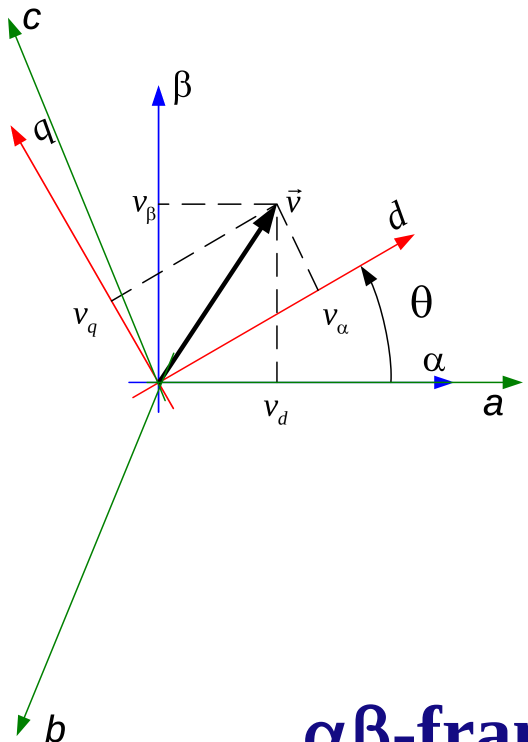
converter switching function

$$\overline{p}(t) = \frac{2}{3}\left(p_a(t) + \alpha \cdot p_b(t) + \alpha^2 \cdot p_c(t) \right)$$

AC voltage equation

$$\frac{\mathrm{d}\overline{i}(t)}{\mathrm{d}t} = \frac{1}{L}\left[-R\overline{i}(t) - \overline{e}(t) + \overline{p}(t) v_{dc}(t) \right]$$

Use of a Synchronous Frame



$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}\begin{bmatrix} p_a \\ p_b \\ p_c \end{bmatrix}$$

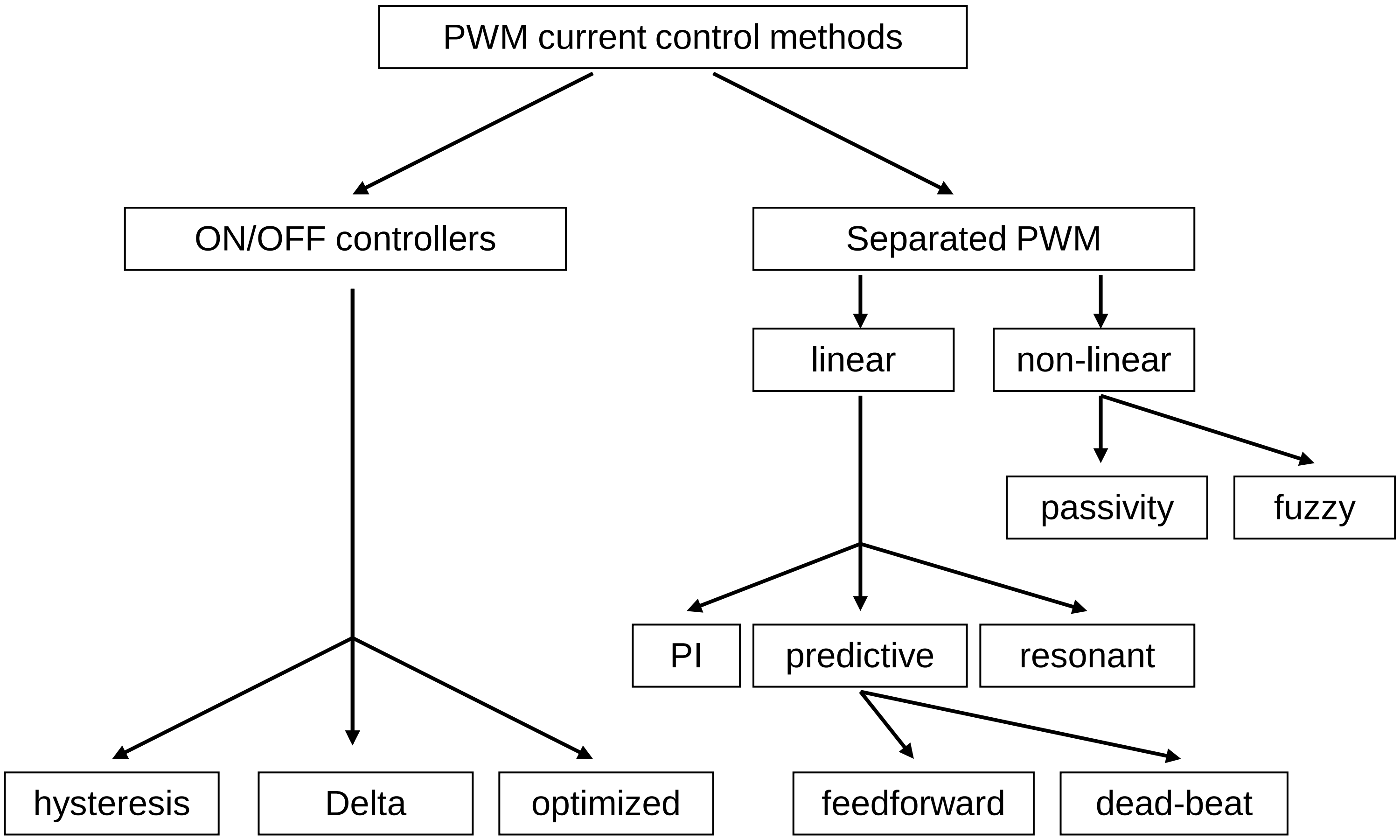
$$\begin{bmatrix} p_d \\ p_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} p_a \\ p_b \\ p_c \end{bmatrix}$$

αβ-frame

$$\begin{cases} \dfrac{di_\alpha(t)}{dt} = \dfrac{1}{L}\left[-Ri_\alpha(t) - e_\alpha(t) + p_\alpha(t)v_{dc}(t)\right] \\ \dfrac{di_\beta(t)}{dt} = \dfrac{1}{L}\left[-Ri_\beta(t) - e_\beta(t) + p_\beta(t)v_{dc}(t)\right] \end{cases}$$

dq-frame

$$\begin{cases} \dfrac{di_d(t)}{dt} - \omega i_q(t) = \dfrac{1}{L}\left[-Ri_d(t) - e_d(t) + p_d(t)v_{dc}(t)\right] \\ \dfrac{di_q(t)}{dt} + \omega i_d(t) = \dfrac{1}{L}\left[-Ri_q(t) - e_q(t) + p_q(t)v_{dc}(t)\right] \end{cases}$$


PWM current control methods
ON/OFF controllers
Separated PWM
linear
non-linear
passivity
fuzzy
PI
predictive
resonant
hysteresis
Delta
optimized
feedforward
dead-beat

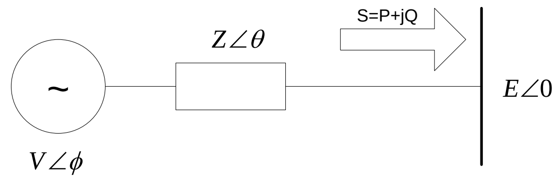
Grid-Forming Converter: Droop Control

Active power

$$P = \left(\frac{EV}{Z}\cos\phi - \frac{V^2}{Z} \right)\cos\theta + \frac{EV}{Z}\sin\phi\sin\theta$$

Reactive power

$$Q = \left(\frac{EV}{Z}\cos\phi - \frac{V^2}{Z} \right)\sin\theta + \frac{EV}{Z}\sin\phi\cos\theta$$

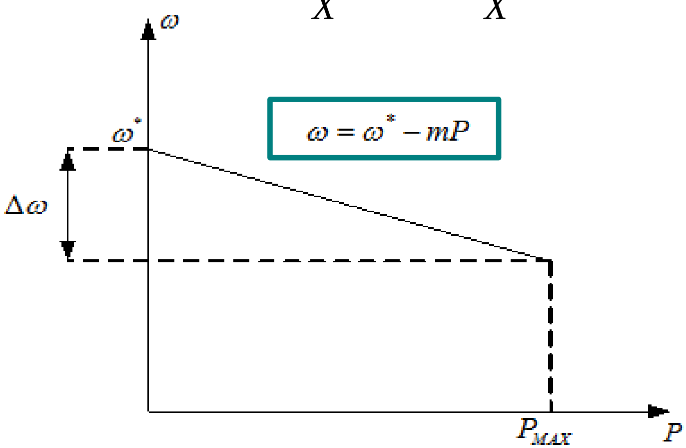


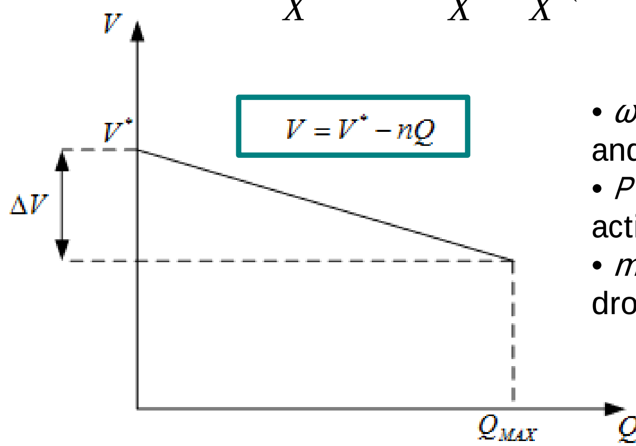
- V is the amplitude of the converter output voltage;
- *E* is the amplitude of the voltage at the point of the connection with the grid;
- Φ is the converter voltage angle;
- *Z* and are the magnitude and the phase of the line impedance.

Assuming that the output impedance is purely inductive and the angle Φ is small the amplitude and the frequency of the control voltage can be expressed as it follows:

$$P = \frac{EV}{X}\sin\phi \approx \frac{EV}{X}\phi$$

$$Q = \frac{EV}{X}\cos\phi - \frac{E^2}{X} \approx \frac{E}{X}(V - E)$$





- ω^* and V^* are the rated frequency and voltage;
- P^* and Q^* are the set points for active and reactive power;
- m_p and n_q are the proportional droop coefficients.

In case of a low voltage smart grid the **line resistance** cannot be neglected.

Active power

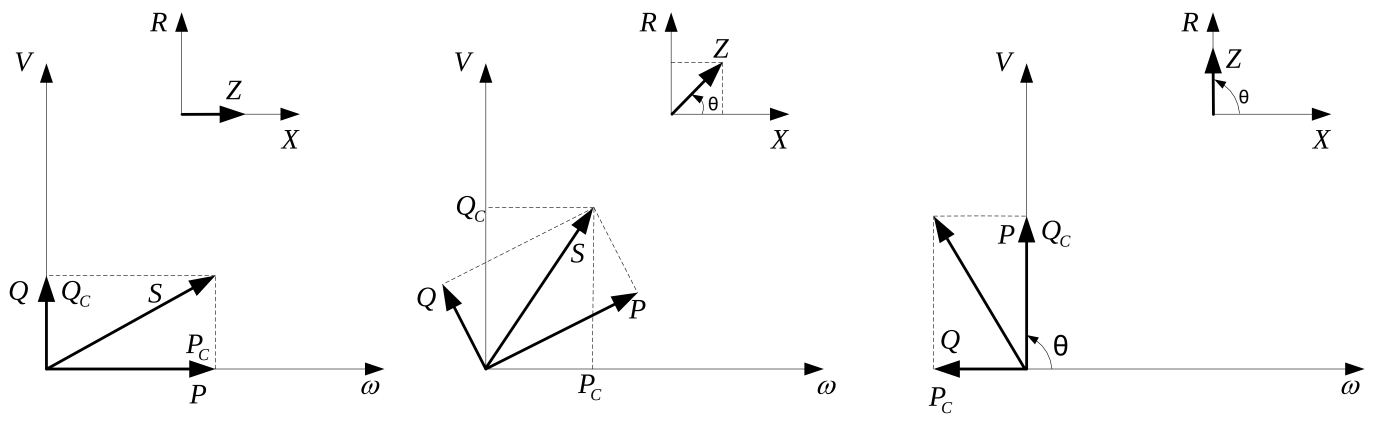
$$P = \frac{E}{X}(V - E) \Rightarrow V = V^* - n(P - P^*)$$

Reactive power

$$Q = \frac{EV}{X}\phi \Rightarrow \omega = \omega^* - m(Q - Q^*)$$

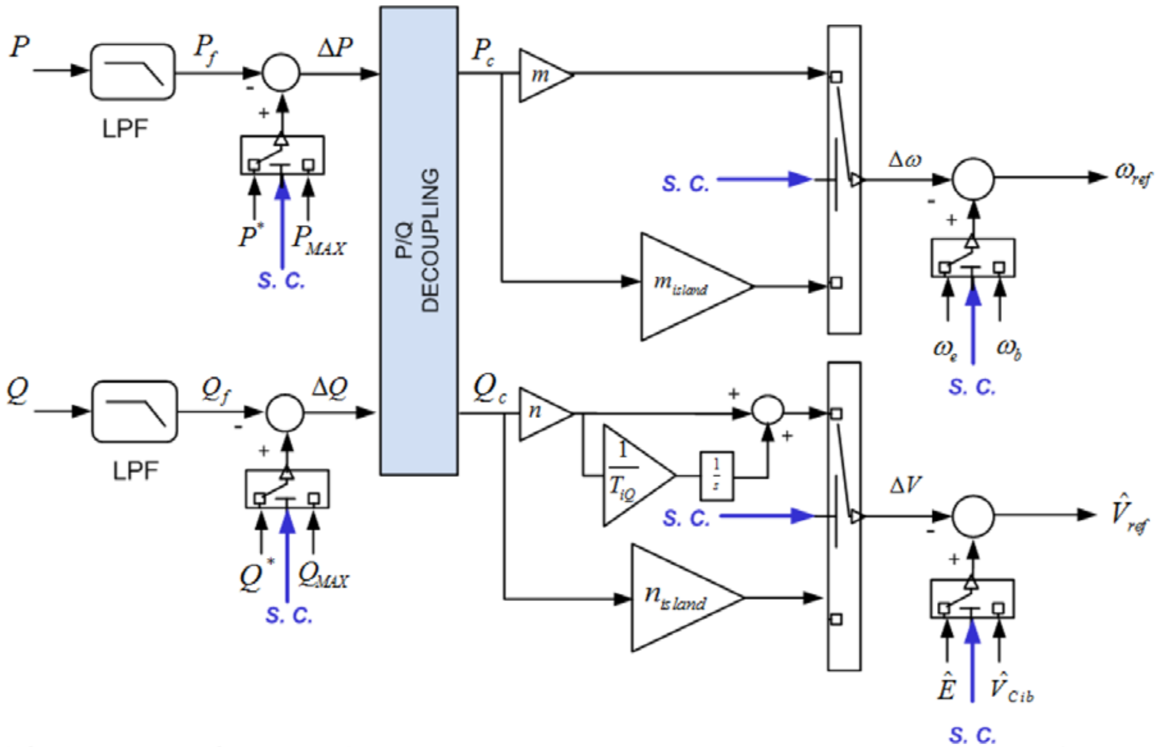
Transformation matrix T

$$\begin{bmatrix} P_C \\ Q_C \end{bmatrix} = Z \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix}$$



(a) (b) (c)

Grid-Forming Converter: Droop Control



Power Control in Grid-Connected Operation Mode

$$\hat{V} = \hat{E} - n\left[(Q - Q^*) + \frac{1}{T_{iq}} \int_{-\infty}^{t} (Q - Q^*)dt \right]$$

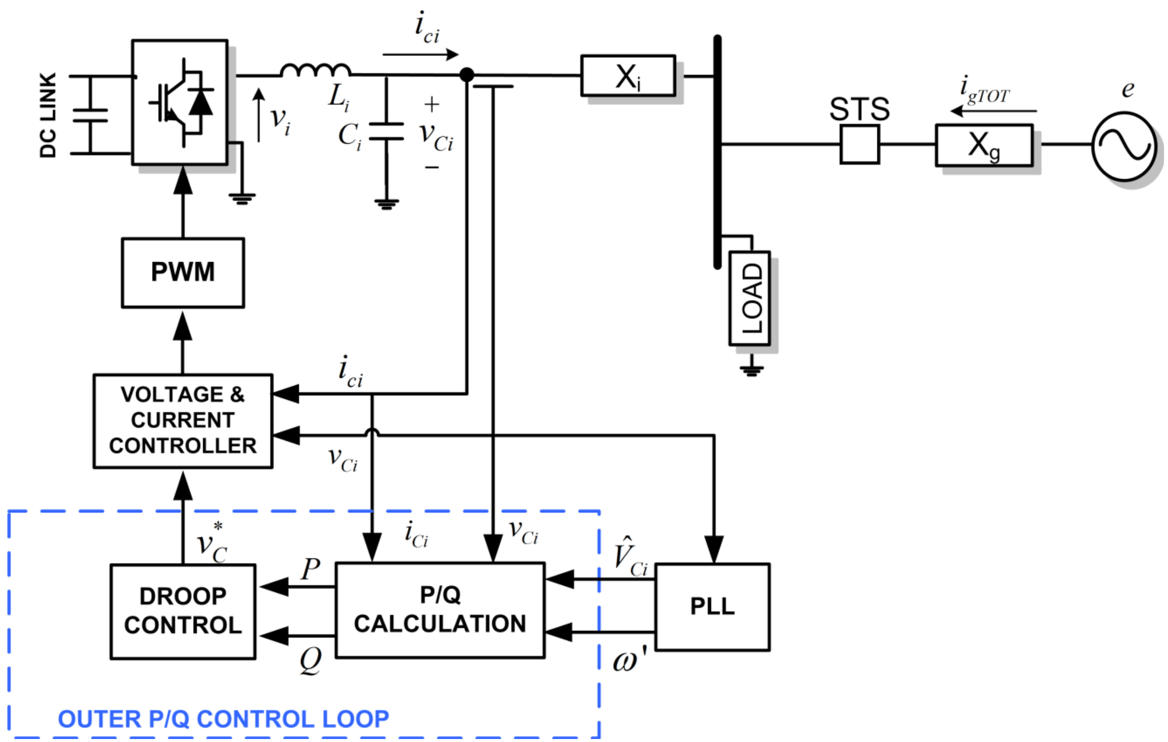
$$\omega = \omega^* - m(P - P^*)$$

Power Control in Stand-Alone Operation Mode

$$\omega = \omega_b - m_{island}(P - P_{MAX})$$

$$\hat{V} = \hat{V}_{Cb} - n_{island}(Q - Q_{MAX})$$

Droop Control: Results



Normal operation mode

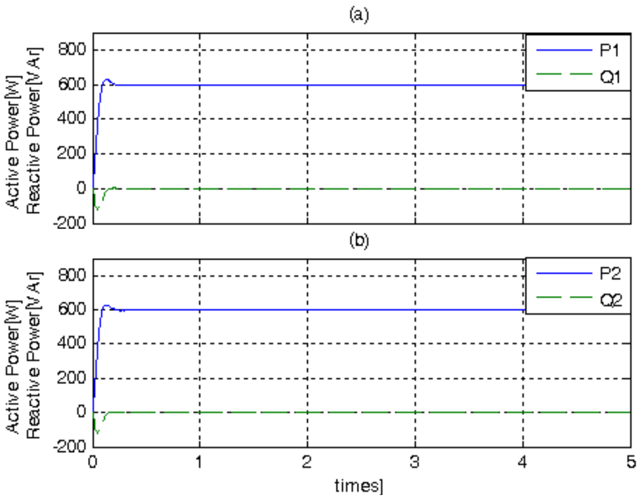
Short duration interruption

Outage of an inverter

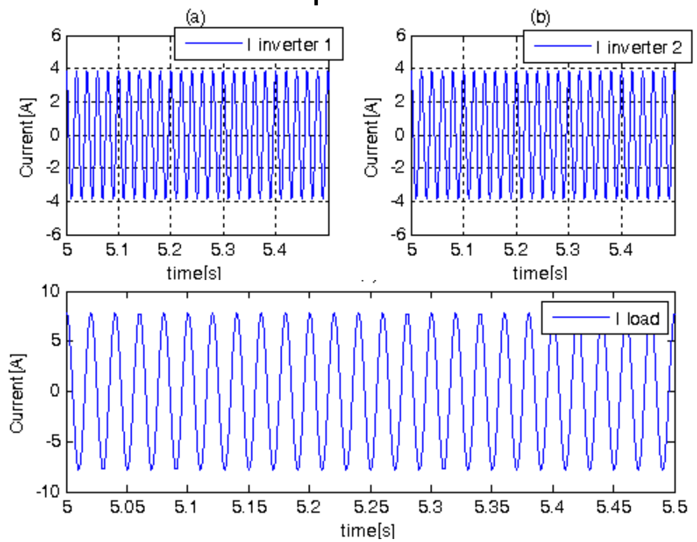
Voltage sag

Results: Normal Operation Mode

Active and reactive powers of inverters

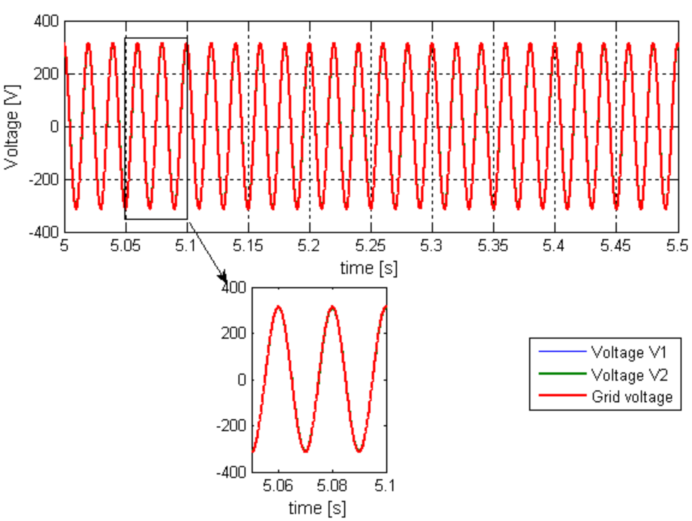


output current

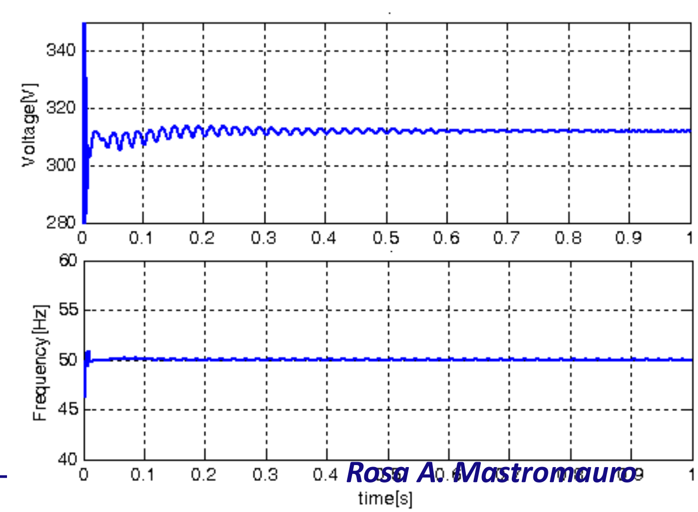


Tested regards the grid-connected operation mode. With the droop control, the inverters can share power (active and reactive power) required by the load without using a communication system.

Grid voltage and inverters output voltage



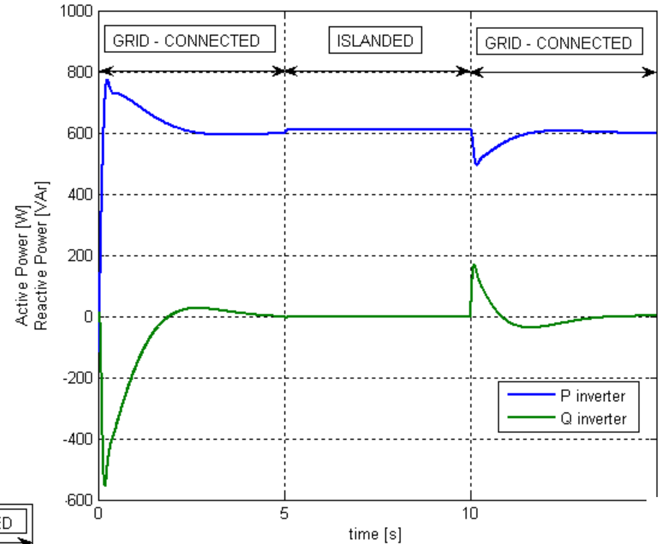
Voltage amplitude and Frequency



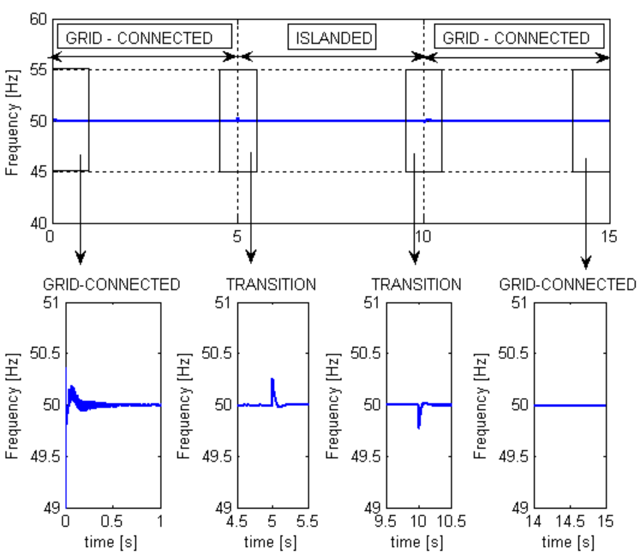
Rosa A. Mastromauro

Results: Short Duration Grid Interruption

Active and reactive power outputs of the DPGS system

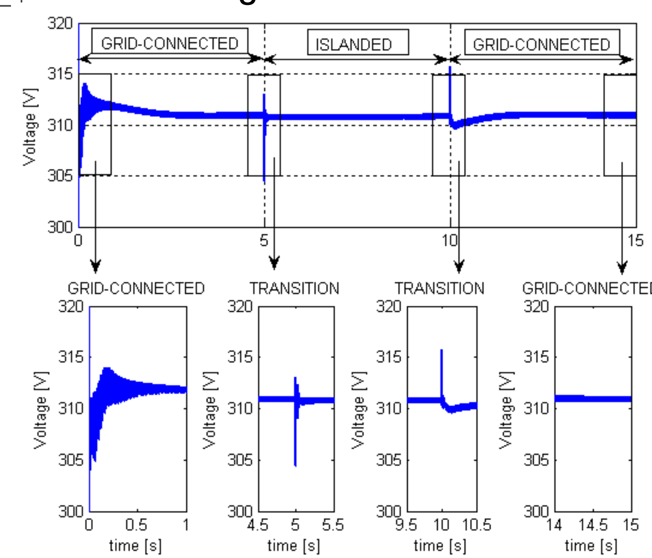


Frequency of the converter



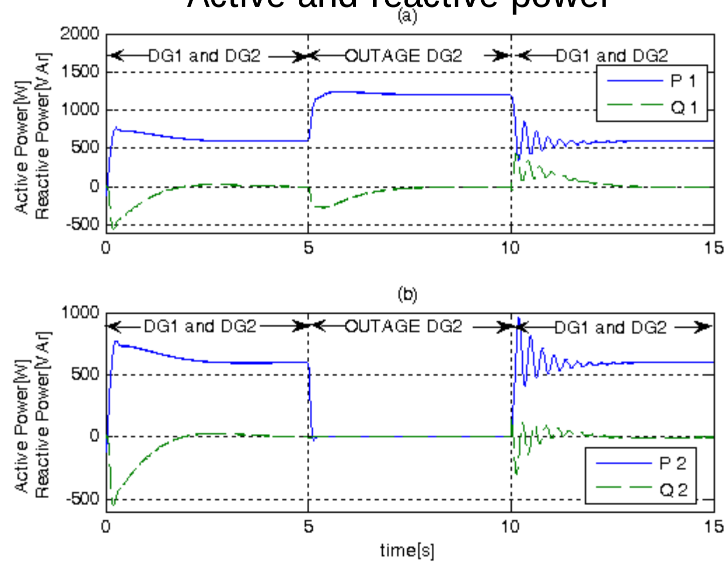
A short duration grid interruption occurs at time t=5s and the DPGS system switches from grid-connected to islanded mode operation. At t=10s the micro-grid switches from islanded to grid-connected mode.

Voltage of the converter

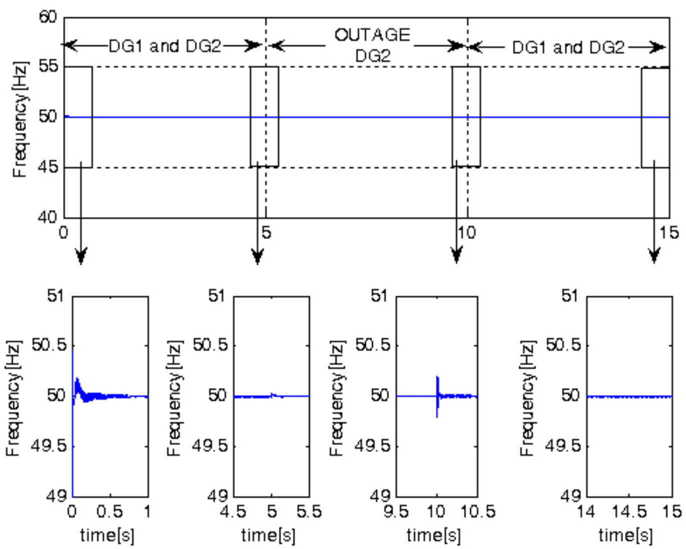


Results: Outage of an Inverter

Active and reactive power

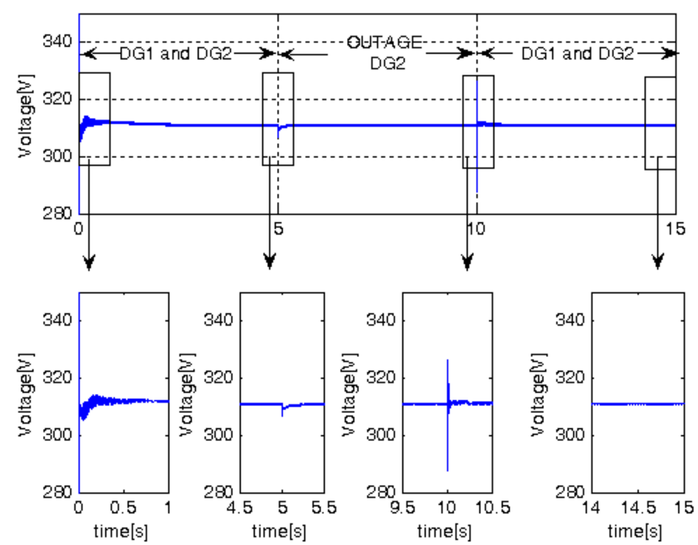


Frequency on common bus



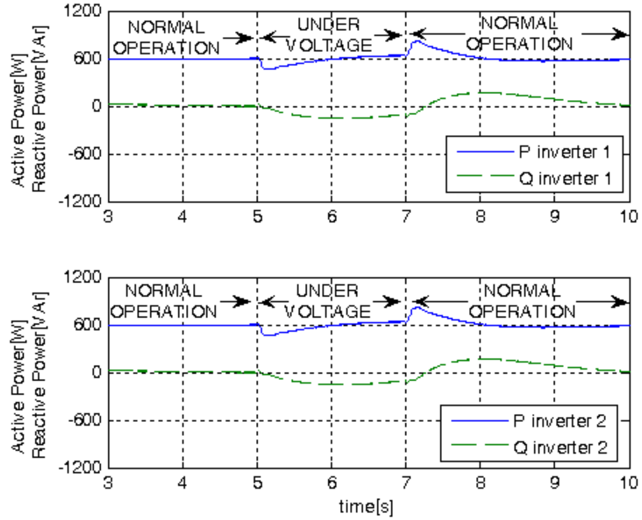
From t=5s to time t=10s the inverter 2 is affected by a disservice, while the inverter 1 has to cope with the total load power demand

Voltage on common bus

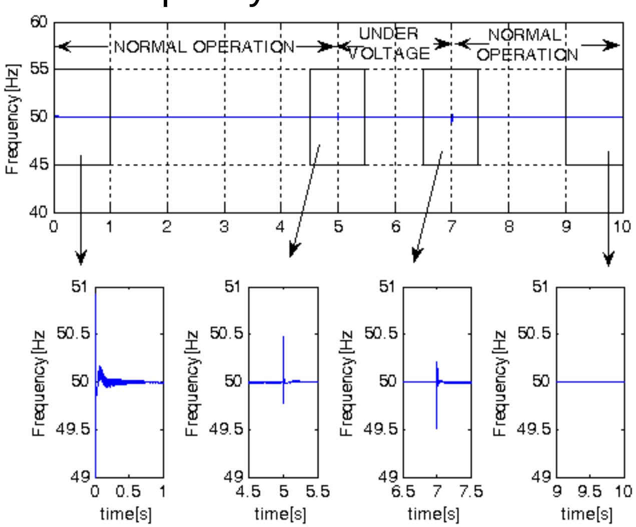


Results: Voltage Sags

Active and reactive power



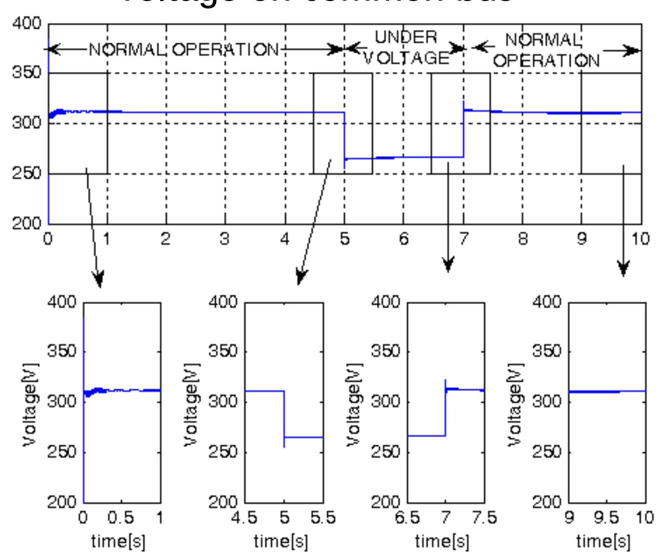
Frequency on common bus



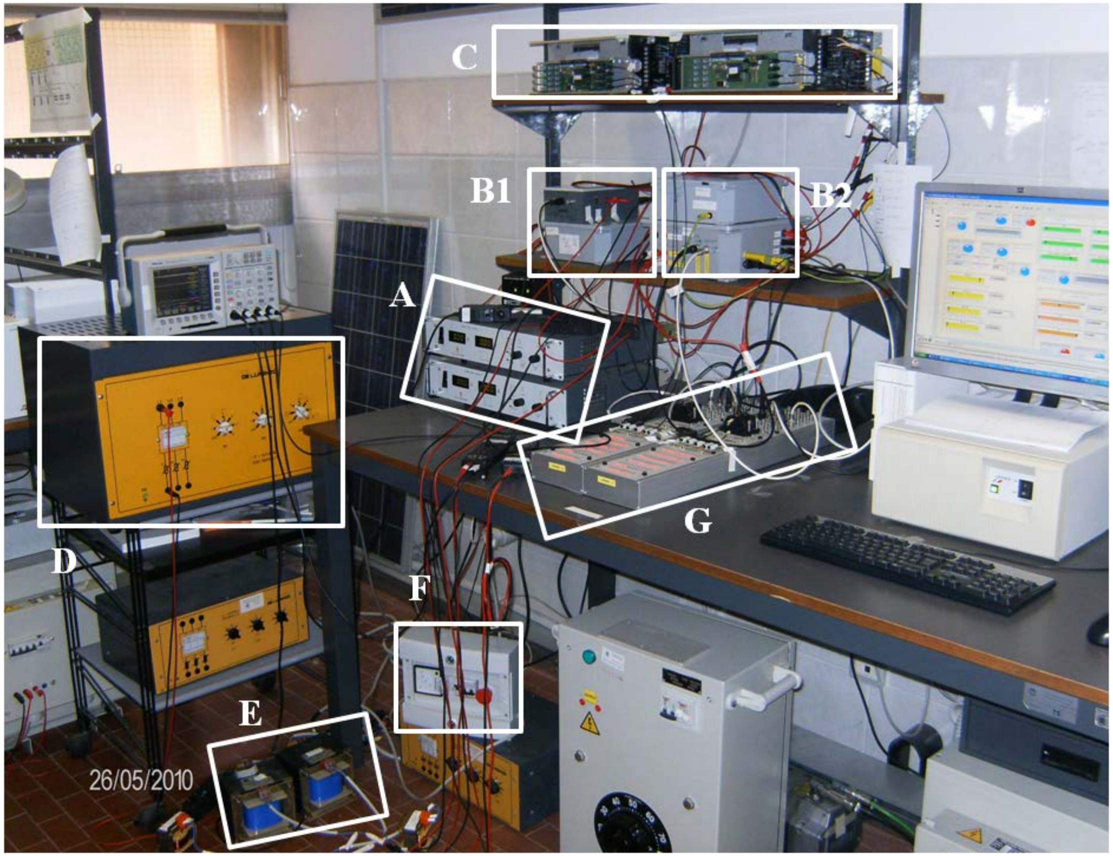
During voltage sag, the inverters are able to share active and reactive power required by the load following the references set by the droop control algorithm.

Droop control maintains the frequency constant on common bus, but the voltage amplitude decreases because references in the droop control come from the PLL.

Voltage on common bus



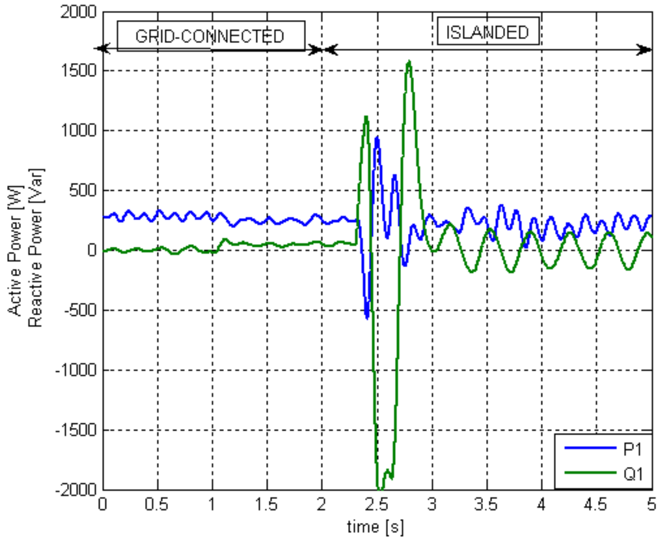
Experimental Setup



The laboratory setup:
A - two DC power supplies;
B1- filter 1 + current and voltage acquisition boards (system 1);
B2 - filter 2 + current and voltage acquisition boards (system 2);
C - two inverters;
D - load;
E - isolation transformer;
F - static transfer switch (STS);
G - two 1103 dSpace boards

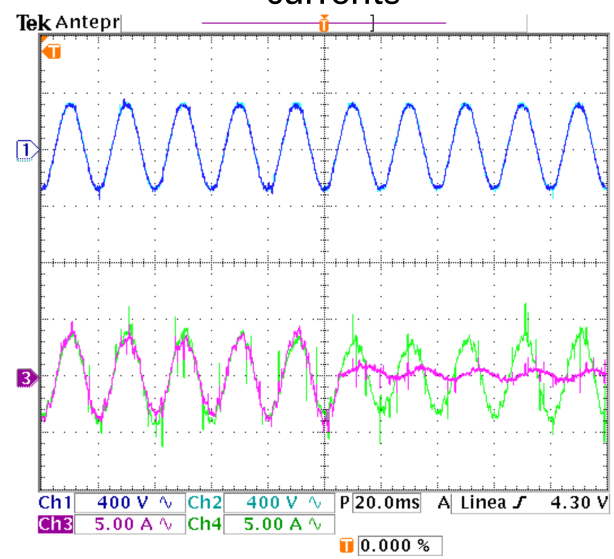
Experimental Results: Outage of an Inverter

transition from grid-connected to stand-alone operation

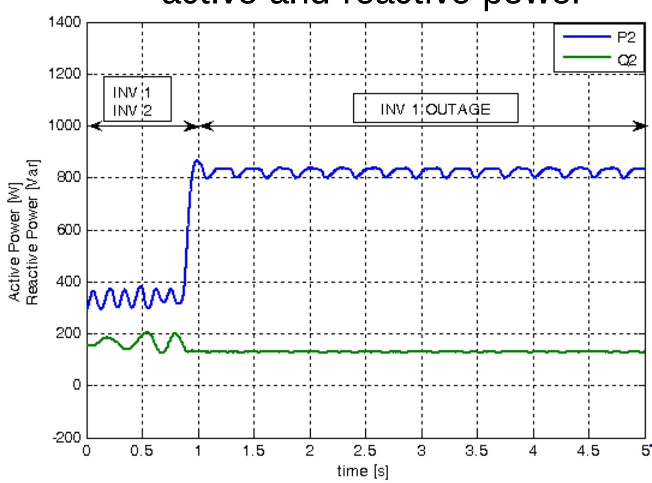


Inverters currents (CH3 and CH4), grid-voltage (CH1) and voltage at the common bus (CH2) considering grid-connected operation mode and inverter 1 is affected by a disservice

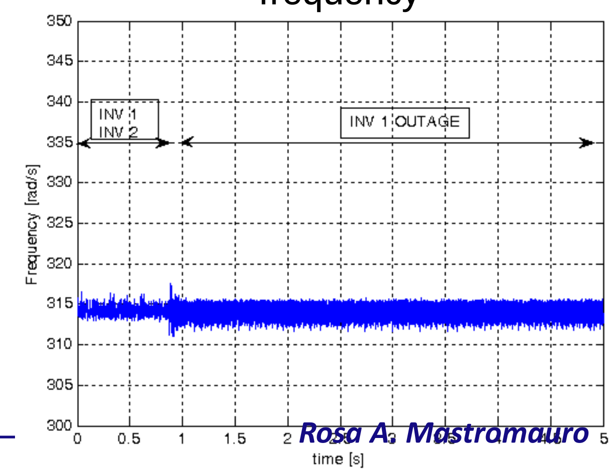
currents



active and reactive power



frequency



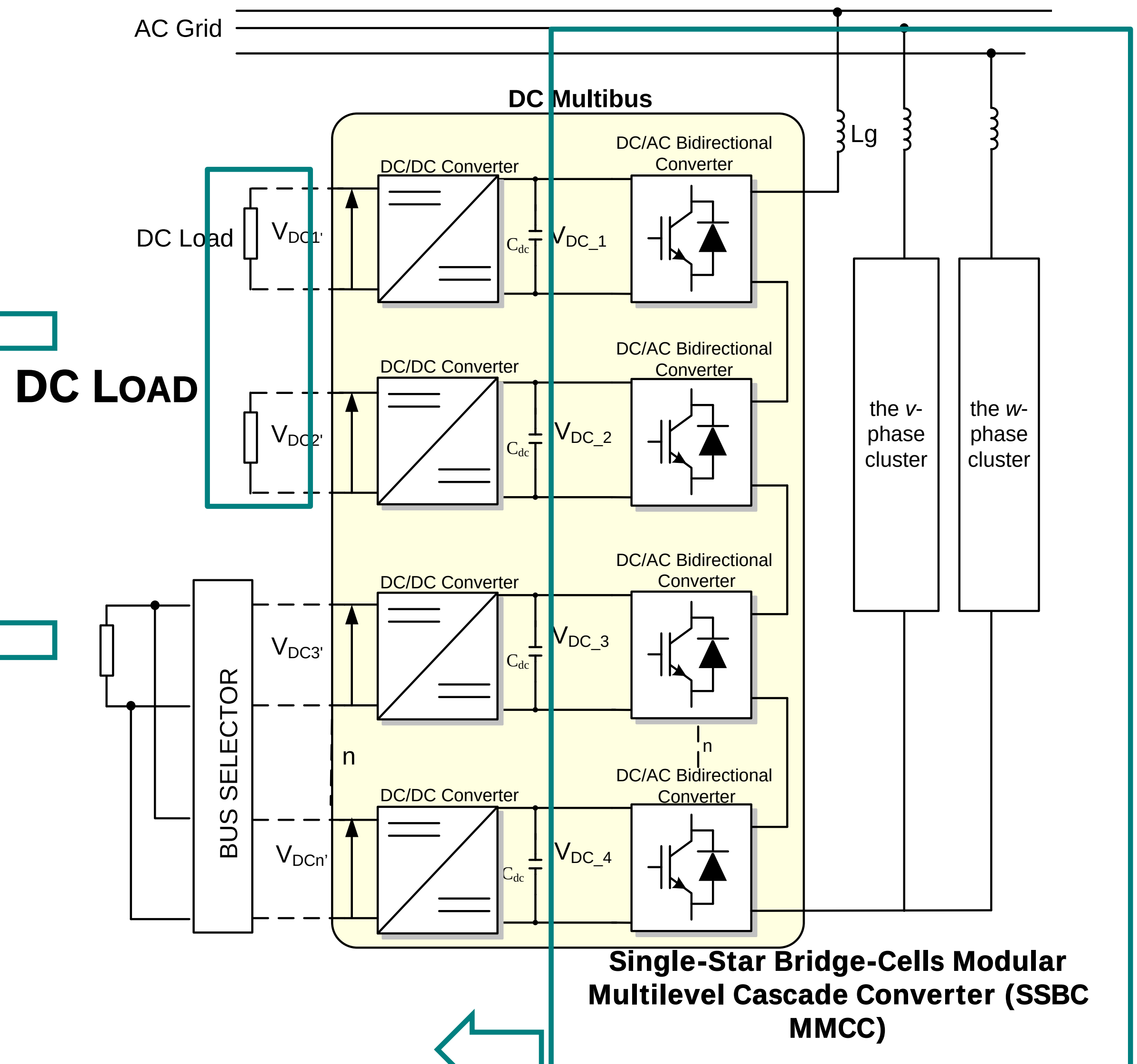
Power-Converter-Based DC Multibus for DC Smart Grids

Main components:

- Distributed generation sources
- Energy storage systems
- Critical and non-critical loads

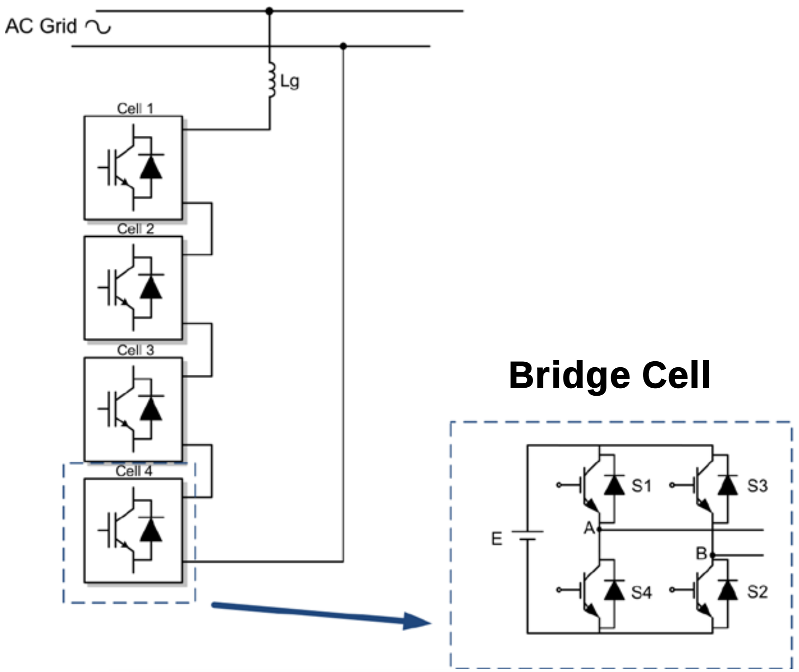
The DC Multibus provides:

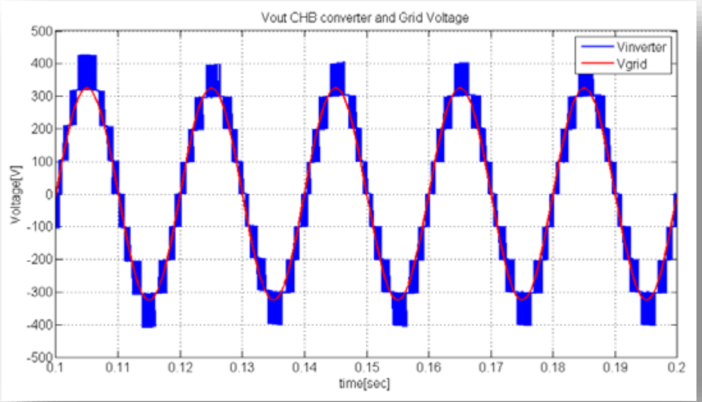
- Different DC voltage levels
- Redundancy



Interface between DC Smart Grid and main grid

DC Multibus based on the Single-Star Bridge-Cells (SSBD) Modular Multilevel Cascade Converter (MMCC)





Advantages of SSBC MMCC

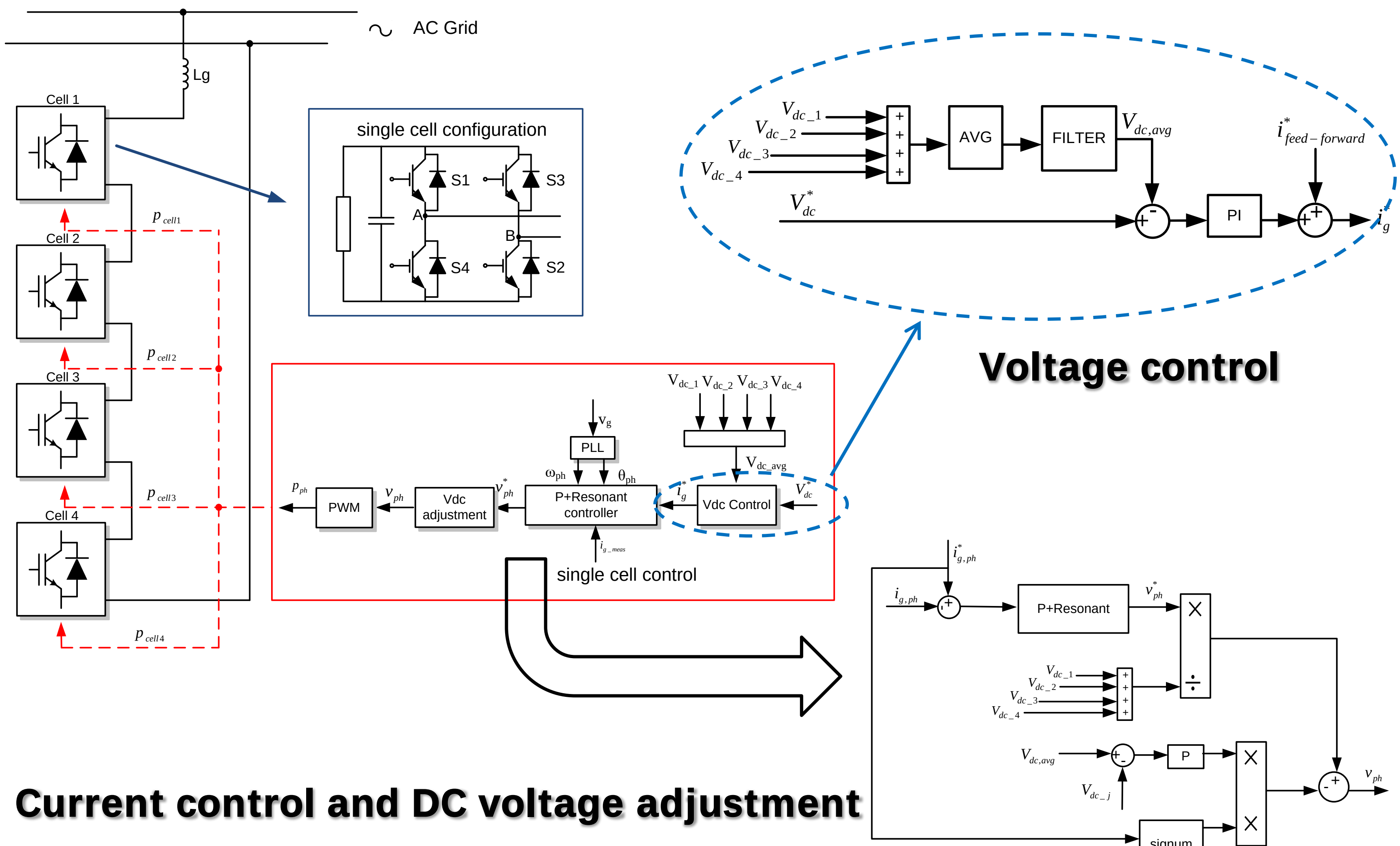
- Modularity and reliability;
- High power with high voltages;
- Multiple DC outputs;
- Low harmonic distortion;
- Bi-directional;
- Low switching losses;
- Small input filters.

Drawbacks of the SSBC MMCC

- Large numbers of components;
- Control of V_{dc}.

9 levels Voltage

Control of the single cell of the SSBC MMCC

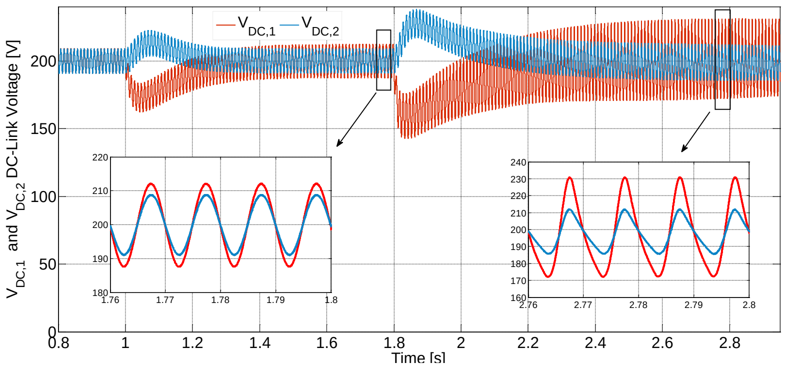


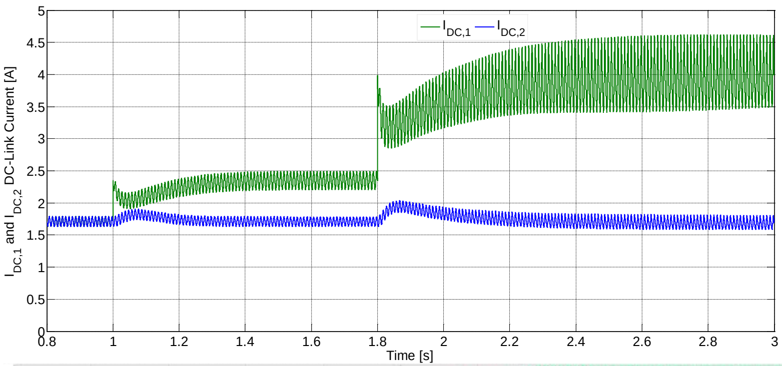
Voltage control

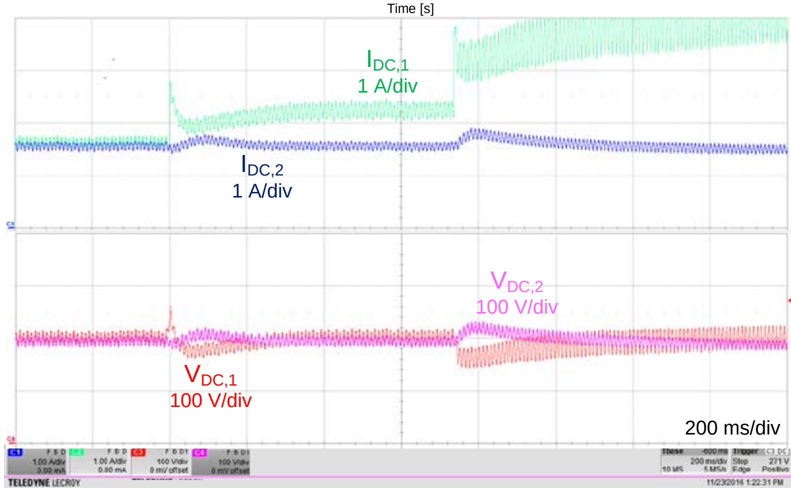
Current control and DC voltage adjustment

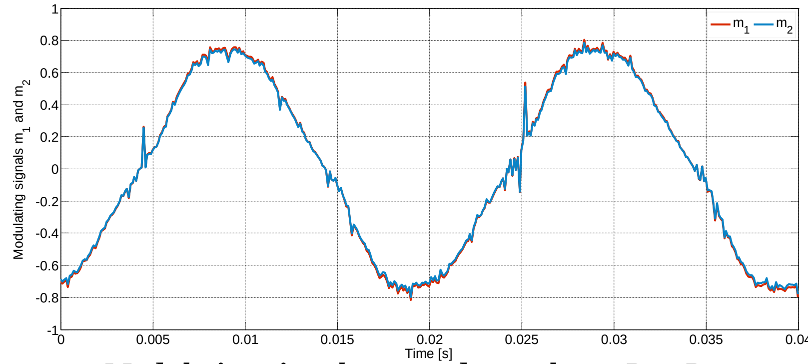
Rosa A. Mastromauro

SSBC MMCC Voltage Balance Results

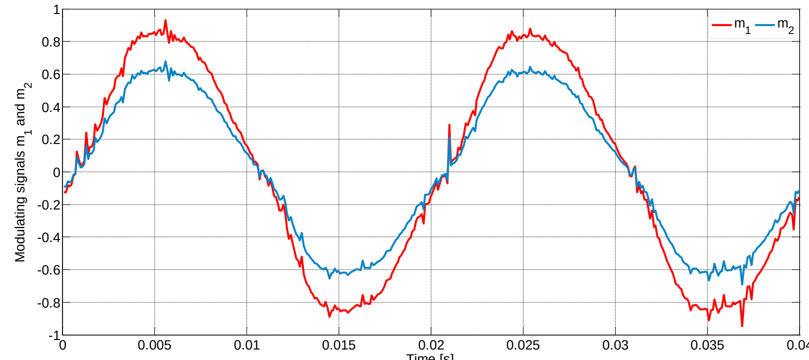




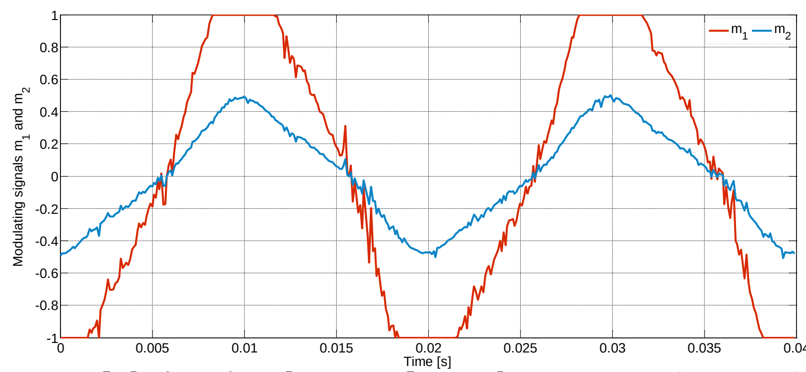




Modulating signals, m_1 and m_2, when : $P_1 = P_2$

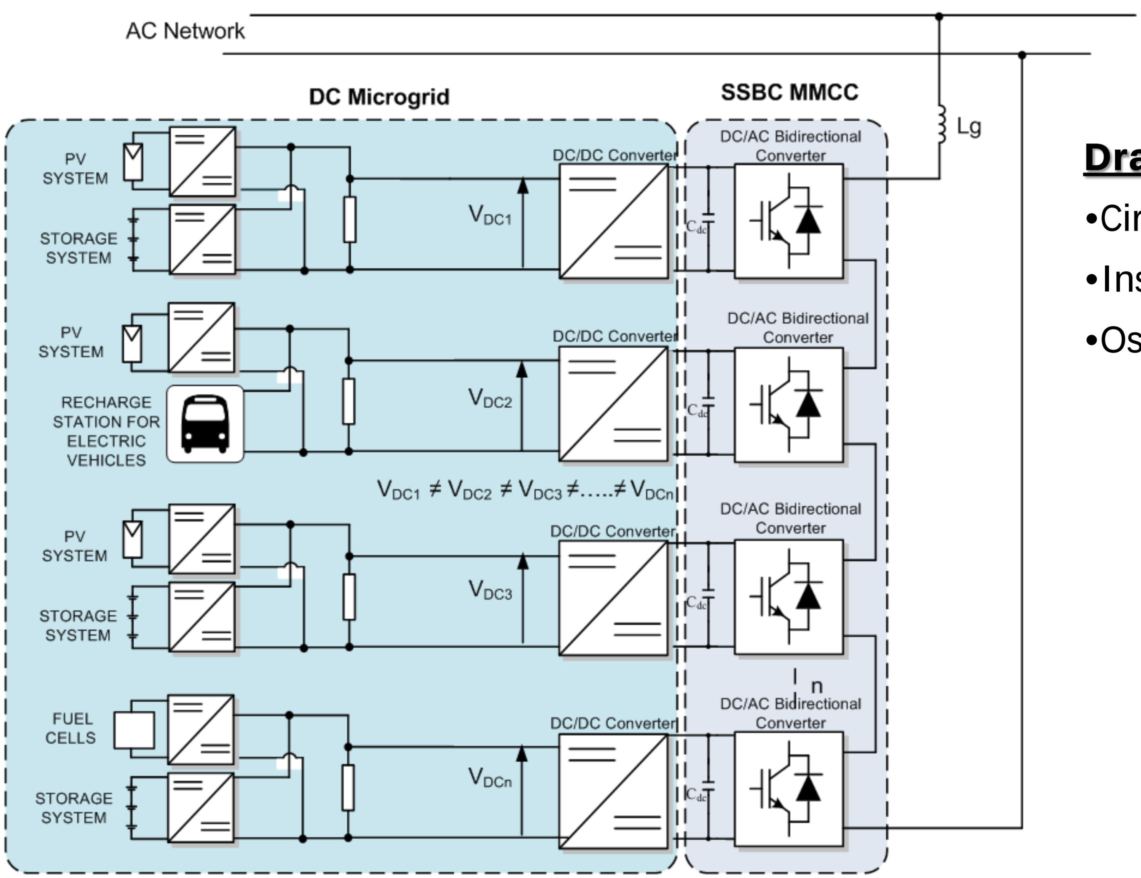


Modulating signals, m_1 and m_2, when: $P_1 \neq P_2$ (ΔP=30%)



Modulating signals, m_1 and m_2, when: $P_1 \neq P_2$ (ΔP=50%)

Management of the DC Multibus Fed by the SSBC MMCC Converter and DC Sources together



Drawbacks to be solved:

- Circulating currents
- Instability
- Oscillations

DC DROOP CONTROL