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APEC 2011

Advanced Control Architectures for Intelligent Microgrids

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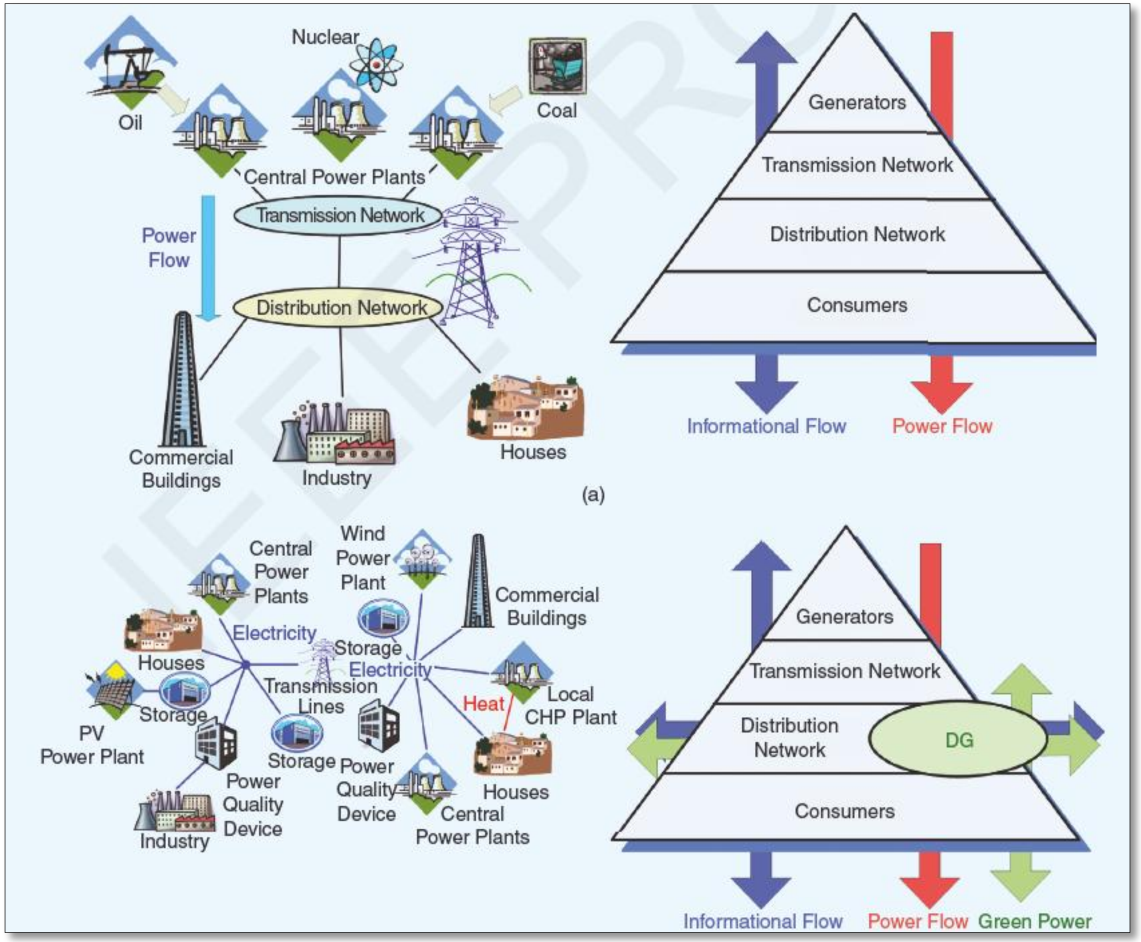
Outline

1 Microgrids systems
2 Control of VSIs for microgrids
3 Droop control and virtual impedance concept
4 Hierarchical control of microgrids
5 Power quality in microgrids
6 DC microgrids

Centralized vs Distribuited Power Systems

General advantages of the DPS:

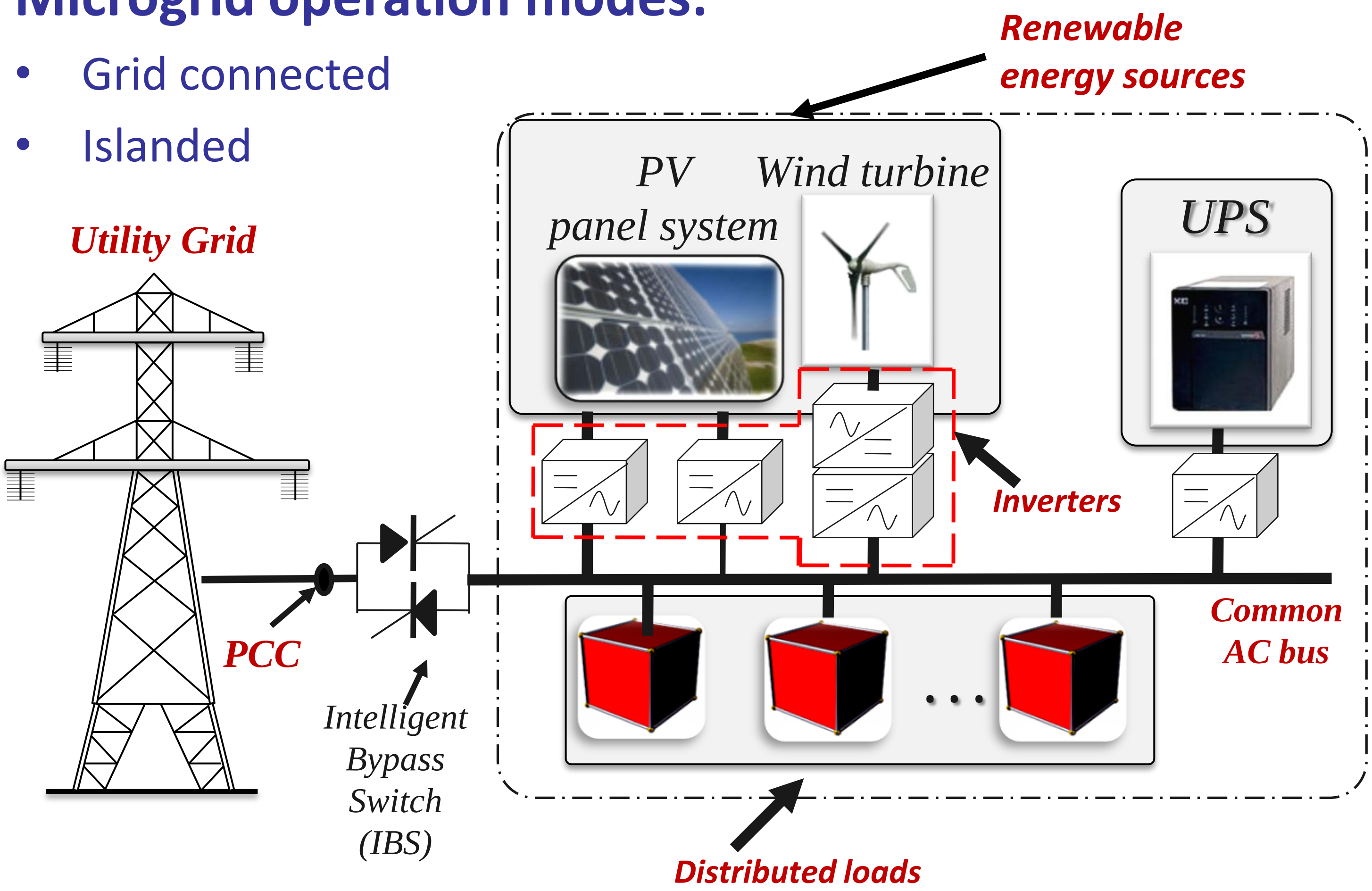
- Redundancy
- Modularity
- Fault tolerance
- Efficiency
- Reliability
- Easy maintenance
- Smaller size
- Lower design cost



Microgrid operation

Microgrid operation modes:

- Grid connected
- Islanded



Typical structure of a flexible microgrid

Microgrid operation

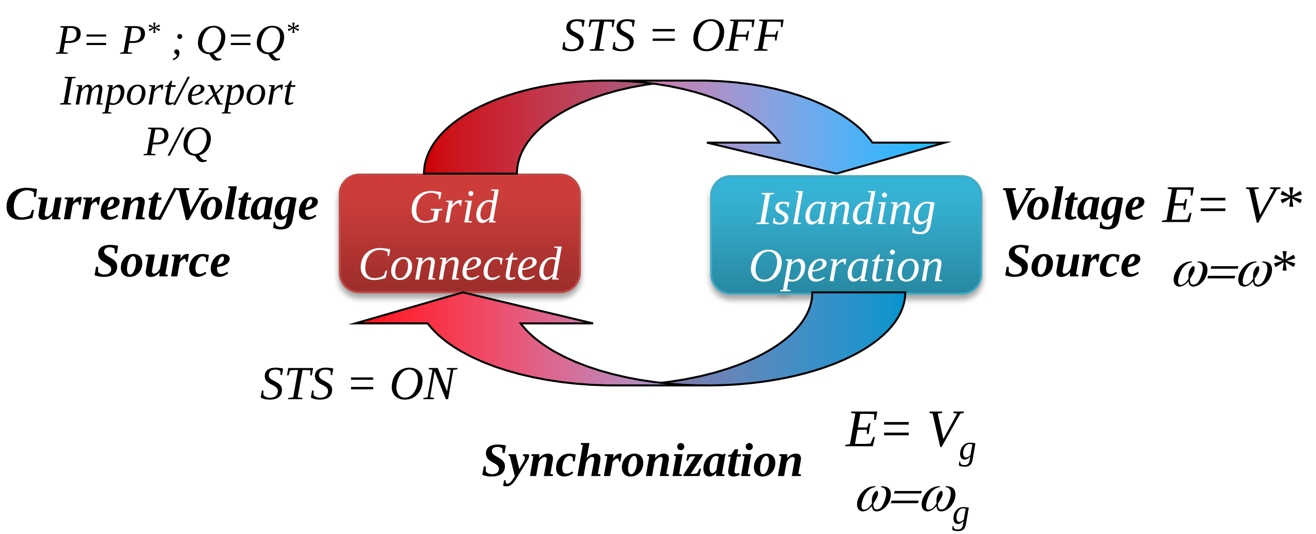
Microgrid operation modes

- Operation modes and transfers of the flexible microgrid and STS grid status supervisory
- Virtual inertias are often implemented through control loops known as droop method.
- Intelligent microgrids are required to integrate DG, DS, and dispersed loads into the future smart grid.
- Microgrids should be able to operate autonomously but also interact with the main grid.
- CSI units are normally used for PV or WT systems that require maximum power point tracker algorithms.
- VSI units are used for storage energy systems to support the voltage and frequency of the microgrid in island mode.

Microgrid operation

Islanded / Grid-connected operation

- Operation modes and transfers of the flexible microgrid and Static Transfer Switch (STS)

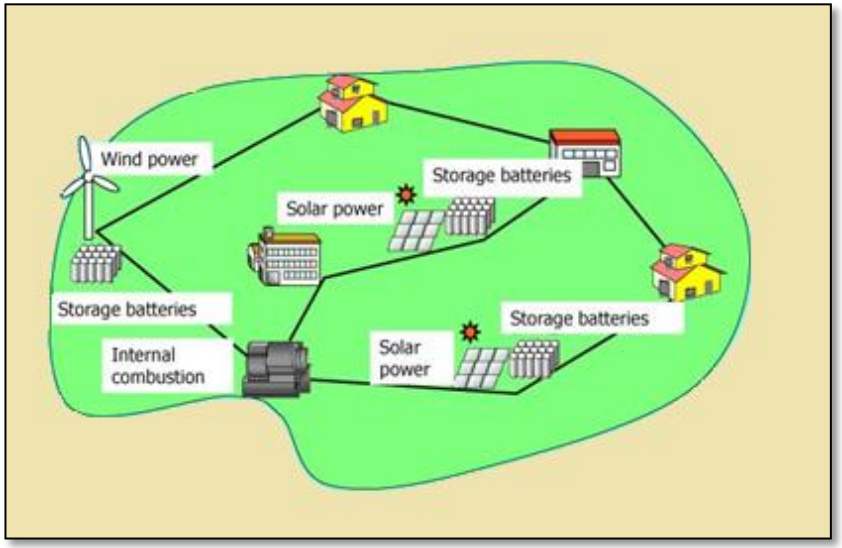


From grid-connected an islanded modes, it is necessary a smooth transition.
For both modes, the converters could work as voltage sources!

Microgrid operation

Islanded operation

- Preplanned islanded operation: If any events in the main grid are presented, such as long-time voltage dips or general faults, among others, islanded operation must be started.
- Nonplanned islanded operation: If there is a blackout due to a disconnection of the main grid, the microgrid should be able to detect this fact by using proper algorithms.



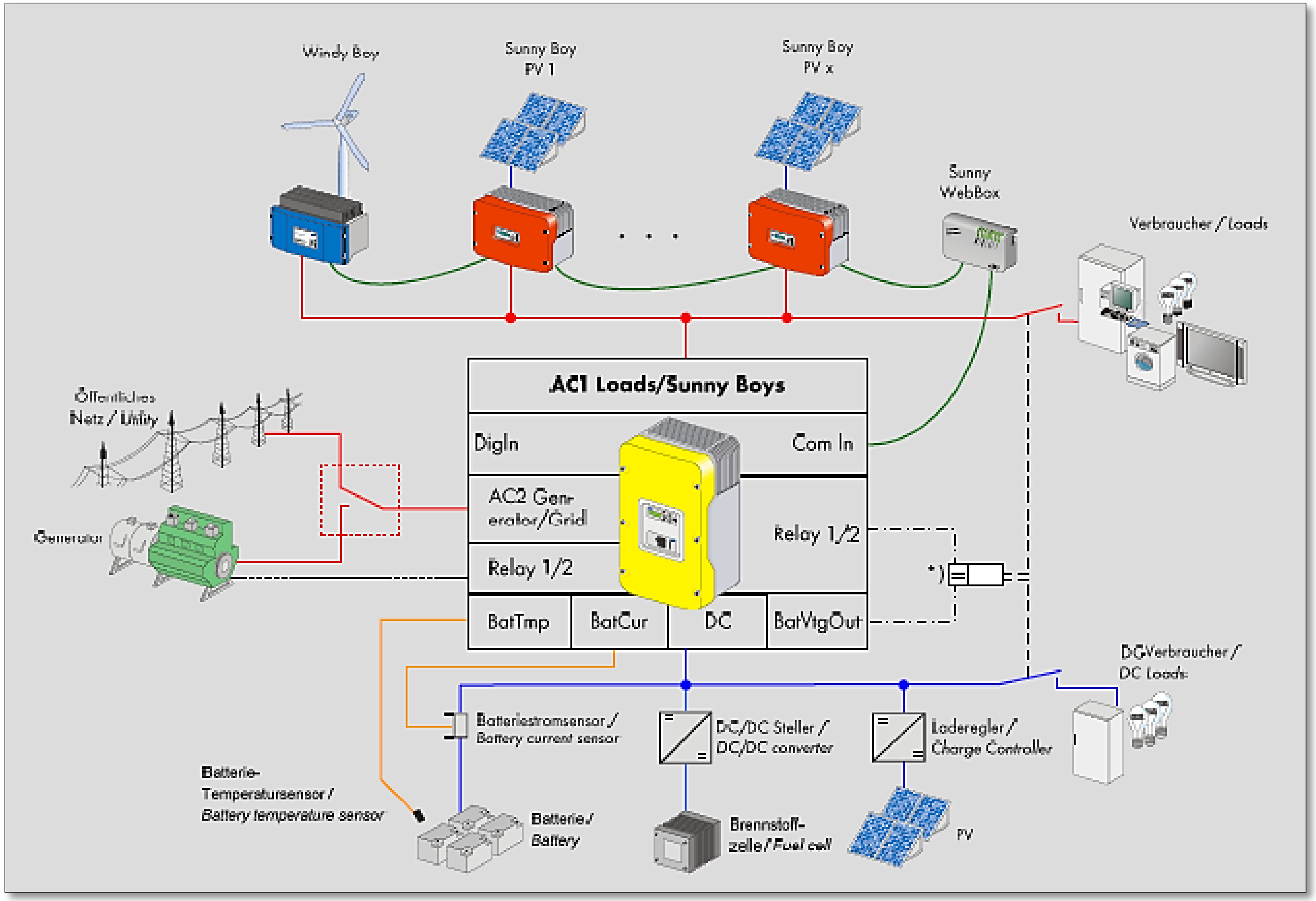
Microgrid operation

Islanded operation

- **Voltage and frequency management**: The system acts like a voltage source, controlling power flow through voltage and frequency control loops adjusted and regulated as reference within acceptable limits.
- **Supply and demand balancing**: In grid-connected mode, the frequency of the DG units is fixed by the grid. Changing the setting frequency, new active power set points that will change the power angle between the main grid and the microgrid can be obtained.
- **Power quality**: The power quality can be established in two levels. The first is reactive power compensation and harmonic current sharing inside the microgrid, and the second level is the reactive power and harmonic compensation at the PCC; thus, the microgrid can support the power quality of the main grid.

Microgrid Configurations

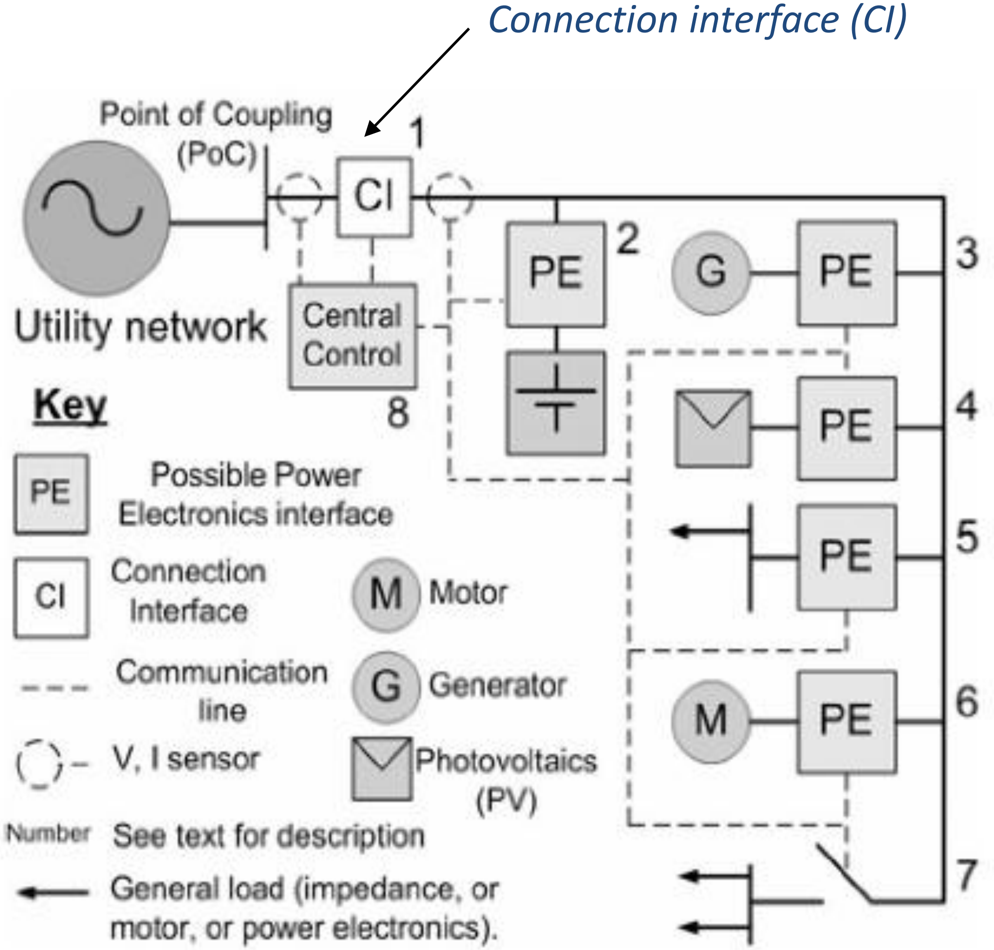
- **AC-DC Hybrid Microgrid**
  Hierarchy of loads



Source: SMA

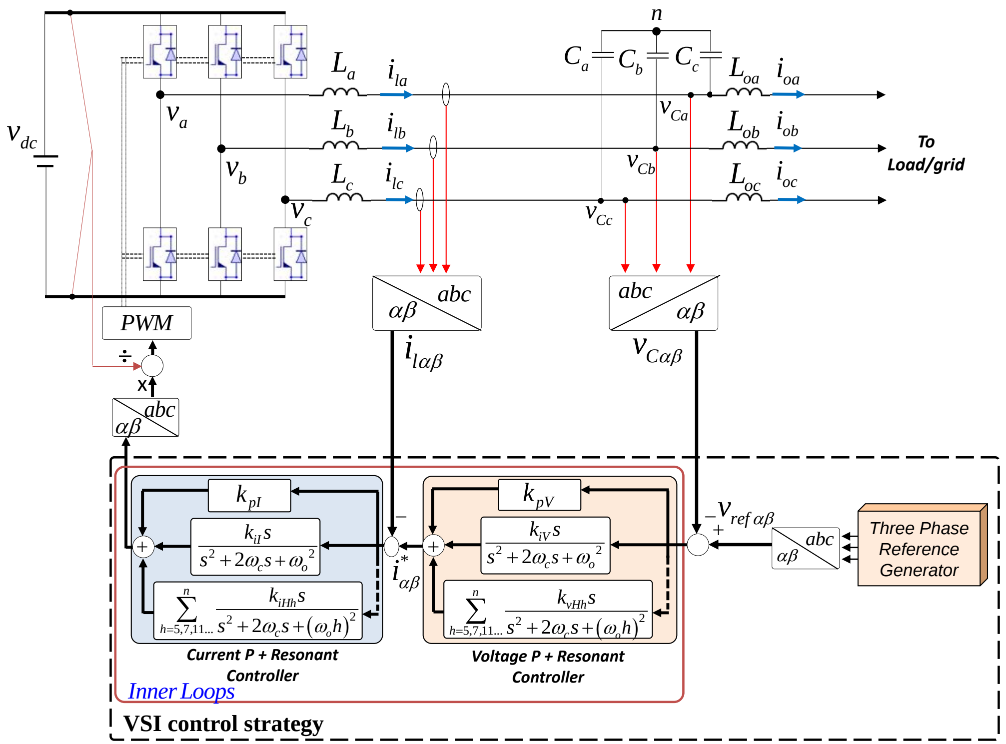
Microgrid Configurations

Connection interface (CI)



Inner control loops

Power stage and control of a 3 phase VSI with LCL filter

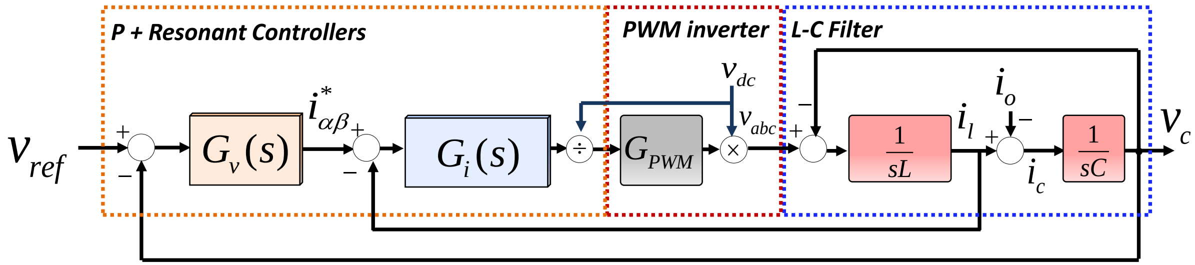


$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3}\cdot\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\cdot\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Alpha-beta transformation

Inner control loops

Block diagram of the closed-loop VSI.



$$V_c = \frac{G_v(s)G_i(s)G_{PWM}}{LCs^2 + \left(Cs + G_v(s)\right)G_i(s)G_{PWM} + 1} V_{ref} - \frac{1/Cs}{LCs^2 + \left(Cs + G_v(s)\right)G_i(s)G_{PWM} + 1} i_o$$

Voltage tracking

Output impedance

Voltage control loop

$$G_v(s) = k_{pV} + \frac{k_{rV}s}{s^2 + \omega_o^2} + \sum_{h=5,7,11} \frac{k_{hV}s}{s^2 + (\omega_o h)^2}$$

Current control loop

$$G_i(s) = k_{pI} + \frac{k_{rI}s}{s^2 + \omega_o^2} + \sum_{h=5,7,11} \frac{k_{hI}s}{s^2 + (\omega_o h)^2}$$

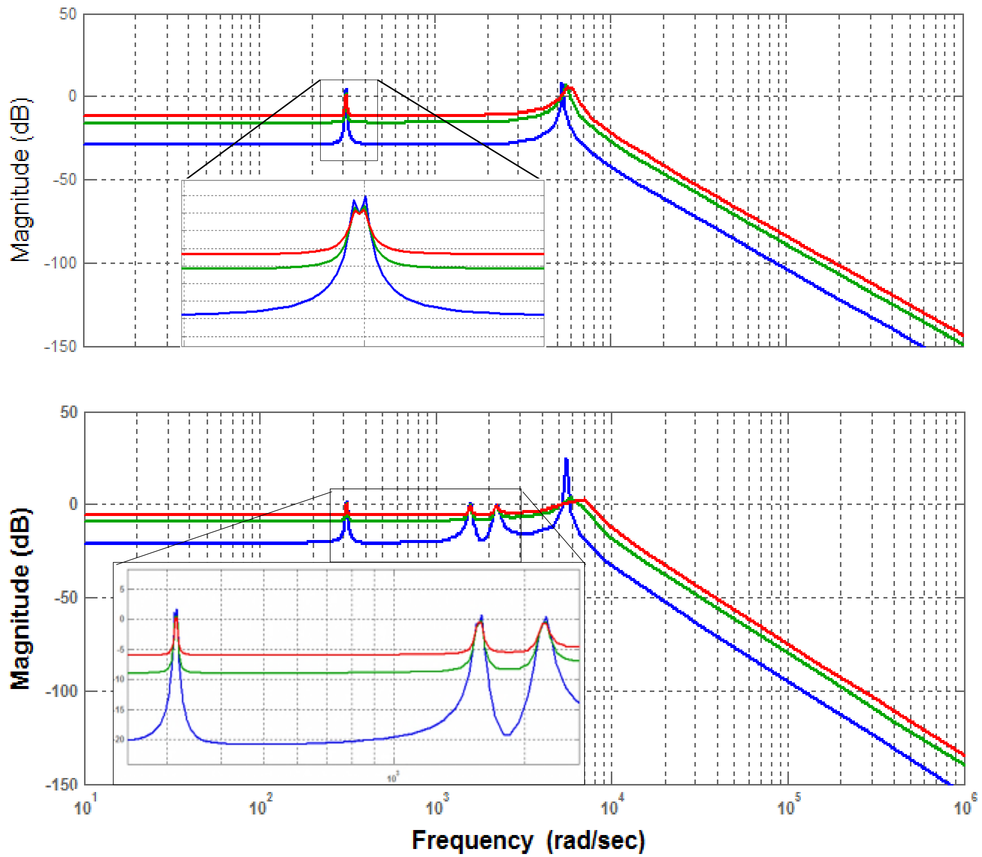
Computation delay $G_{PWM} = \dfrac{1}{1 + 1.5T_s}$

Inner control loops

Bode diagram of the tracking voltage transfer function Gv(s)

P+R

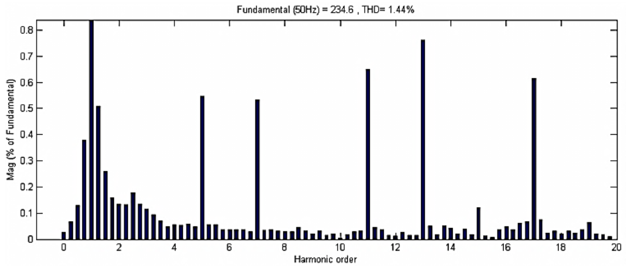
P+R+H

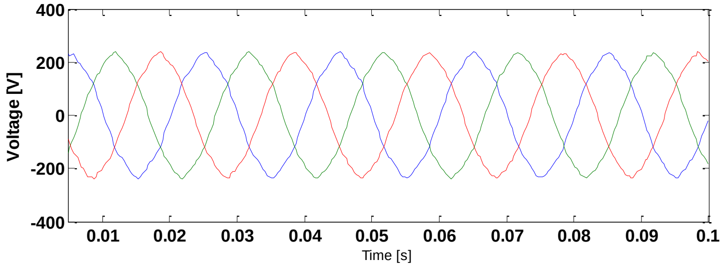


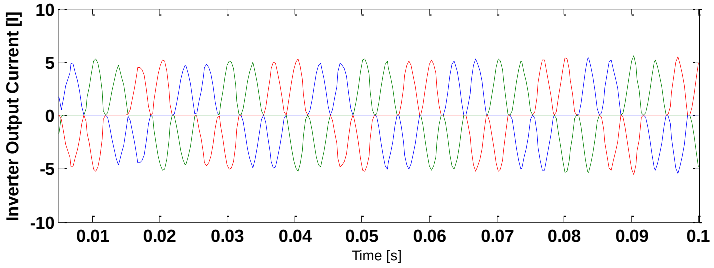
Objective: closed-loop band pass filter characteristics with 0dB, 0º

Inner contro loops

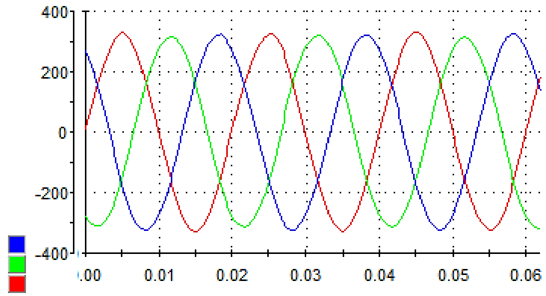
Results

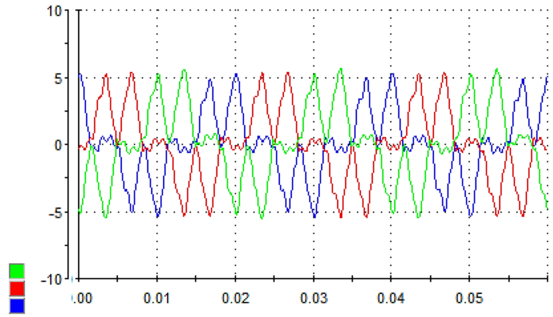






abc-Voltages

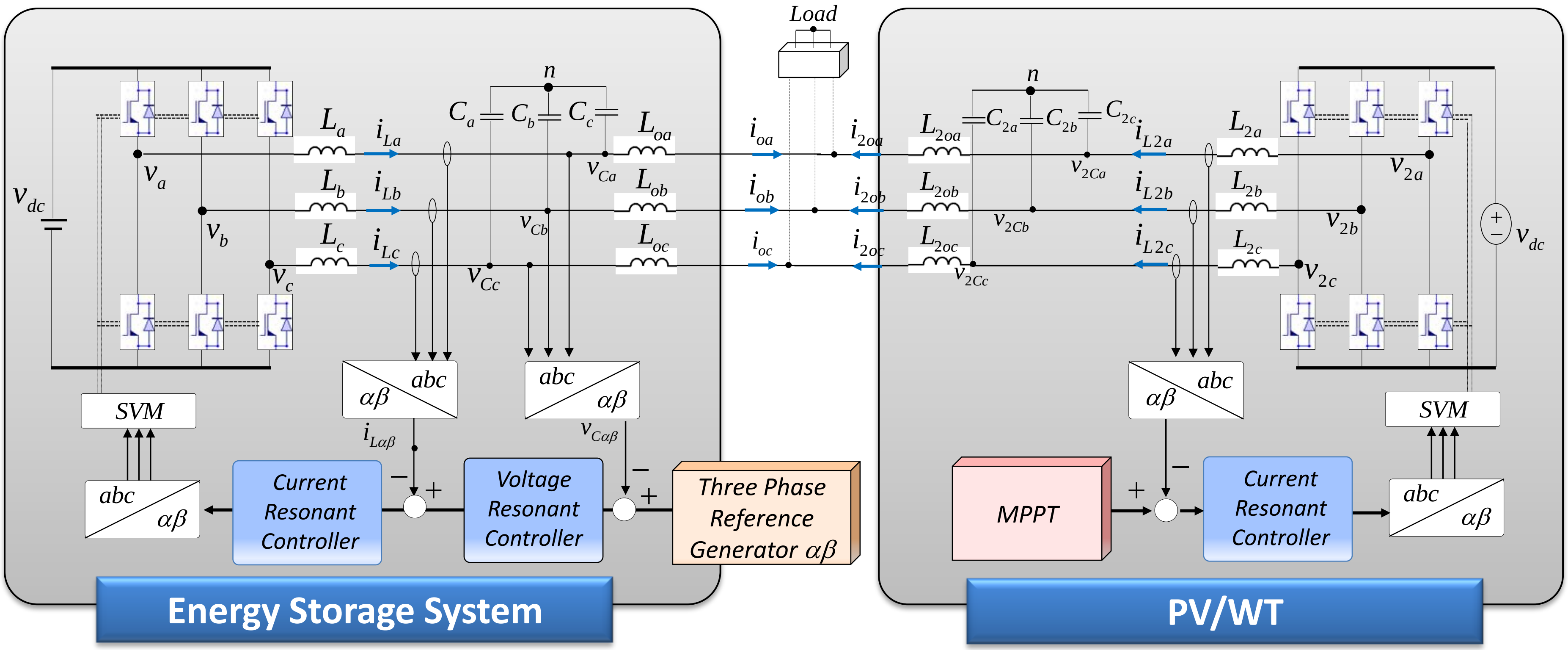




abc-Currents

Control of parallel converters

Master-slave control

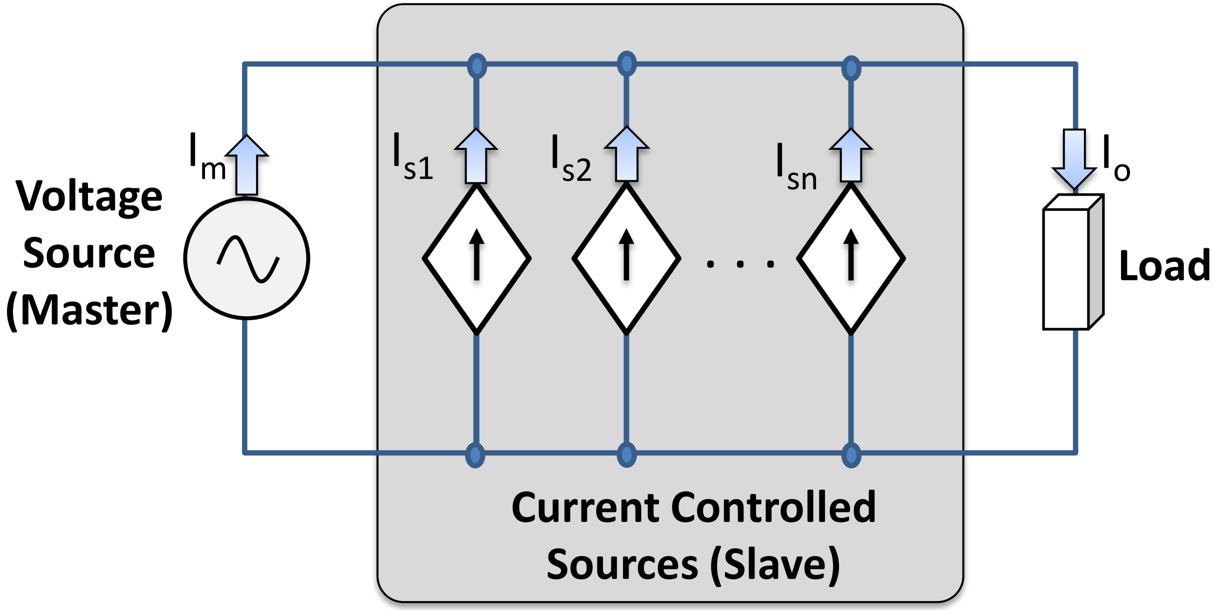


- Voltage source: grid forming units
- Current source: MPPT units. WT and PV

In this system is not necessary current sharing!

Control of parallel converters

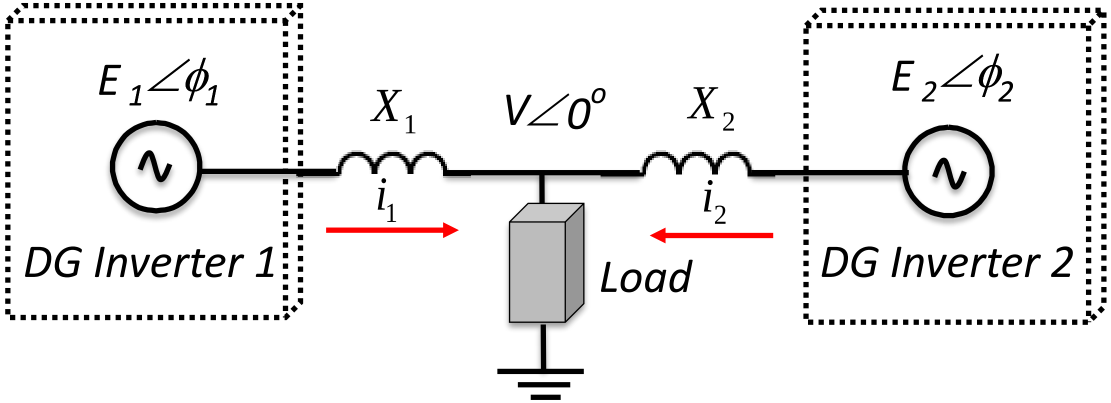
Master-slave control



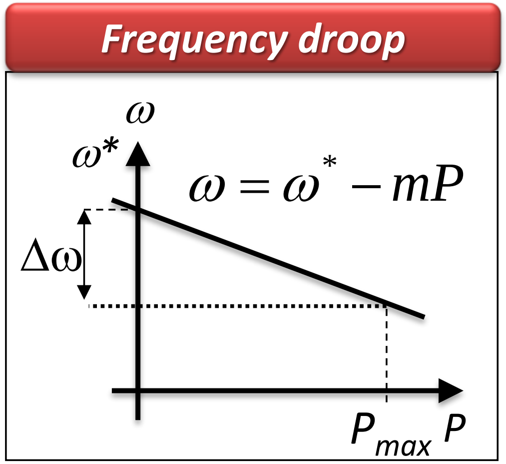
Woo-Cheol Lee "A Master and Slave Control Strategy for Parallel Operation of Three-Phase UPS Systems with Different Ratings"

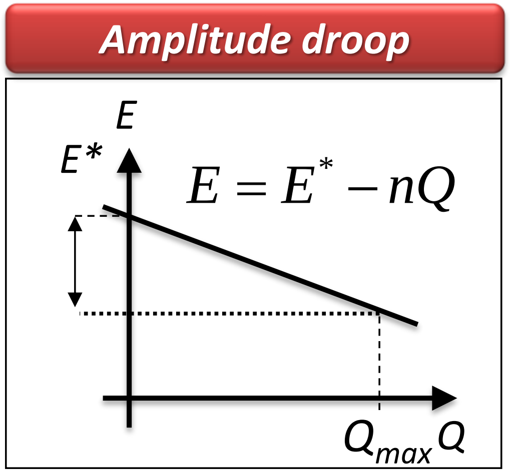
Droop control for AC MGs

Droop control of AC systems



Active power $P = \frac{VE}{X}\sin\phi$ **Reactive power** $Q = \frac{EV\cos\varphi - V^2}{X}$





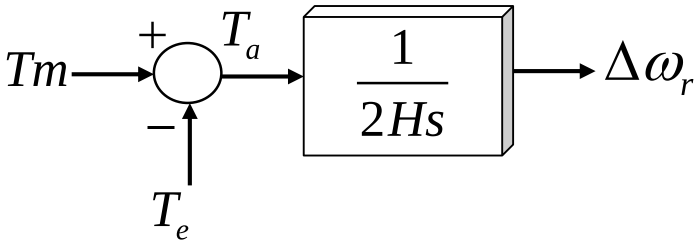
Droop control for AC MGs

Inertias in power systems

- **Synchronous generator**

Equation of motion: $J\frac{d\omega}{dt} = T_m - T_e$

Inertia constant: $H = \frac{stored\ energy}{rating\ power} = \frac{E}{P}[s]$ with $E = \sum \frac{1}{2} J\omega^2$



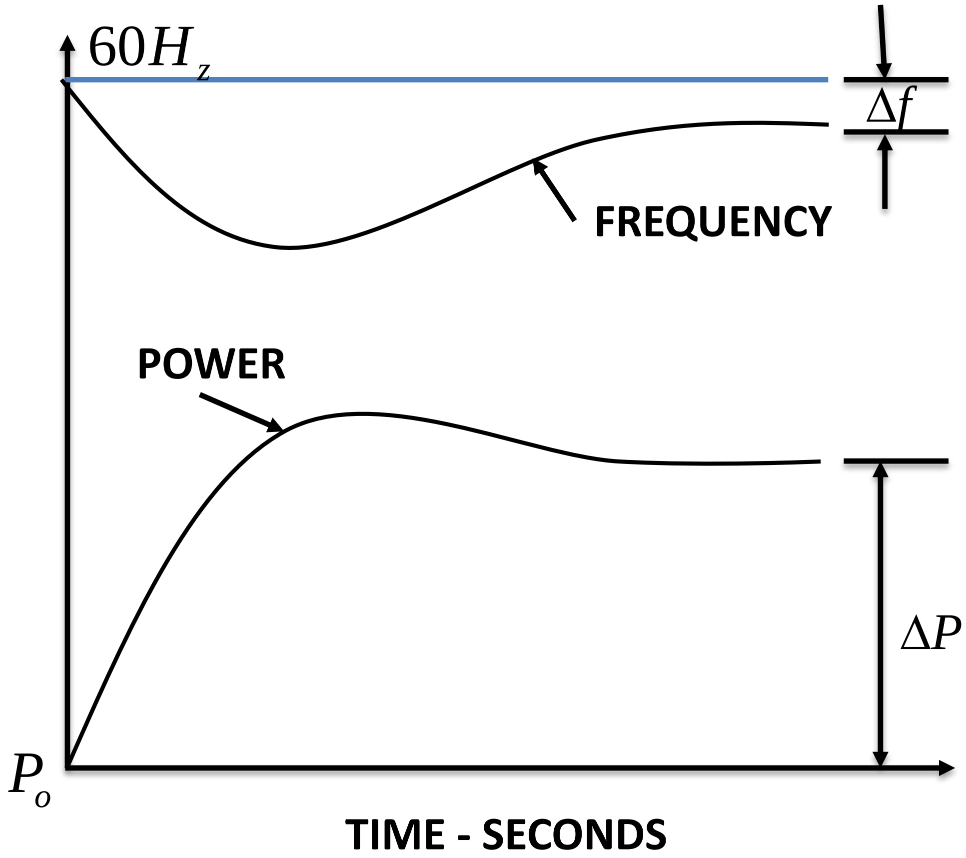
s	*Laplace Operator*
Tm	*Mechanical torque (pu)*
T_e	*Electrical torque(pu)*
T_a	*Accelerating torque (pu)*
H	*Inertia constant (MW-Sec/MVA)*
$\Delta\omega_r$	*Rotor speed deviation (pu)*

P. Kundur

Droop control for AC MGs

Inertias in power system

- **Synchronous generator transient response**

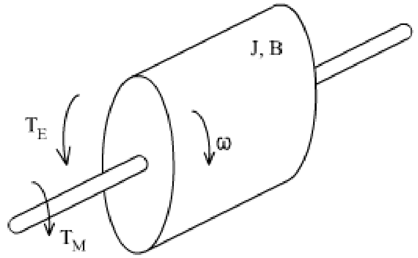


There is a dynamic and a static droop. The static droop coeficient is ΔP/Δf.

Virtual synchronous generators

Synchronous Machine

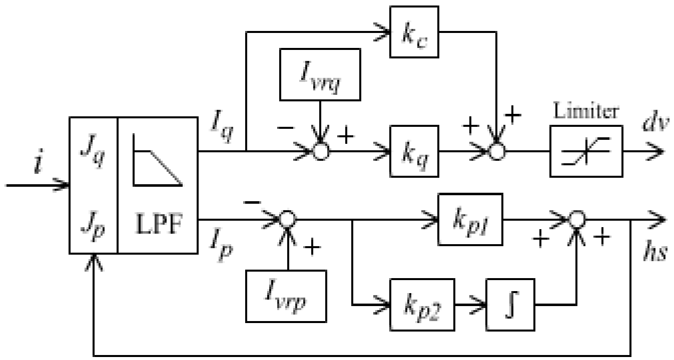
$$J \frac{d}{dt} \omega = T_m - (T_e + B\omega)$$ Synchronous Machine Motion Equation



Representation of a synchronous machine

- Inverters that mimic synchronous converters
- Kawamura’s approach (2005)

Independent Control

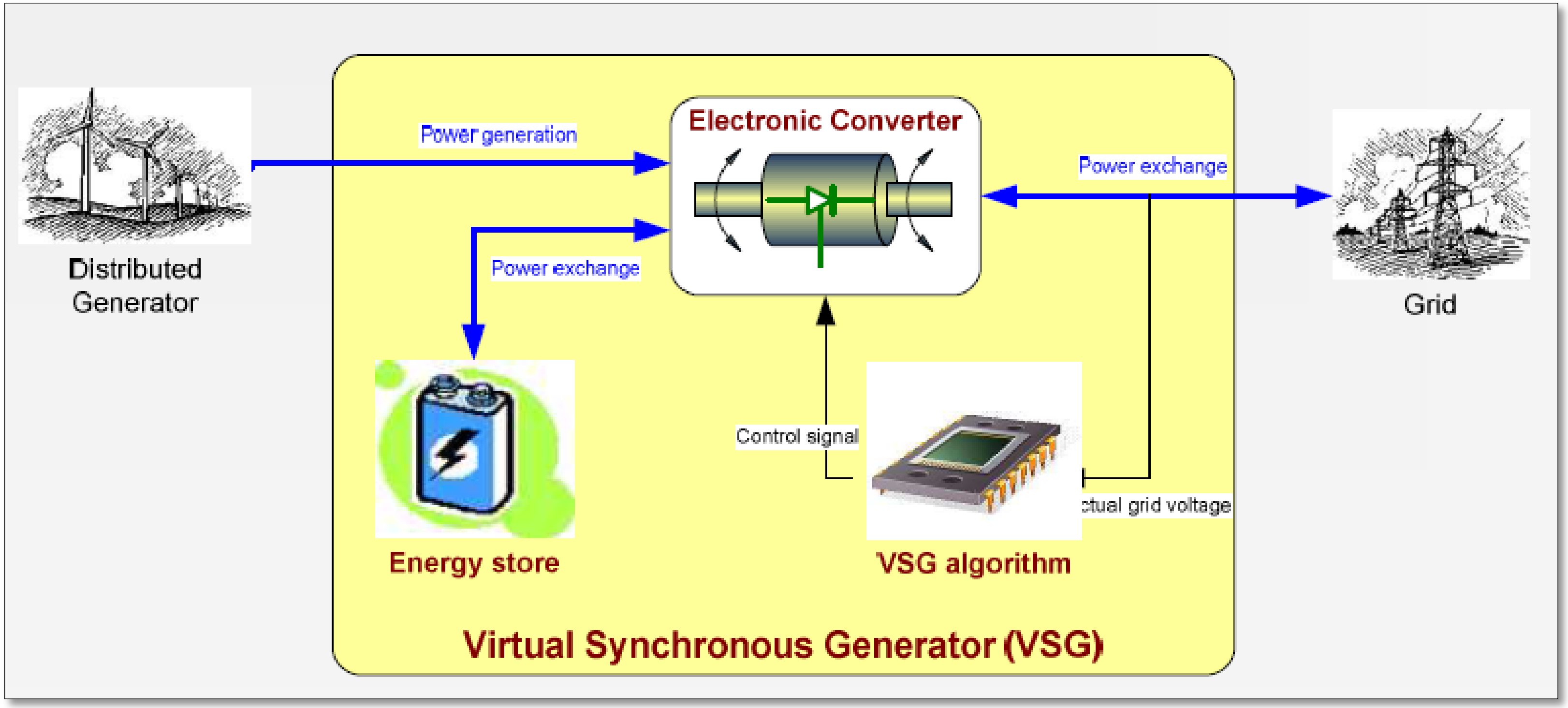


To determine *dv* and *hs* (amplitude variation and phase angle, respectively), the controller computes the active and reactive components (I_p and I_q, respectively) of the output current *i*.

High Reliability and High Performance Parallel-Connected UPS System with Independent Control

Eduardo Kazuhide Sato

Virtual synchronous generators



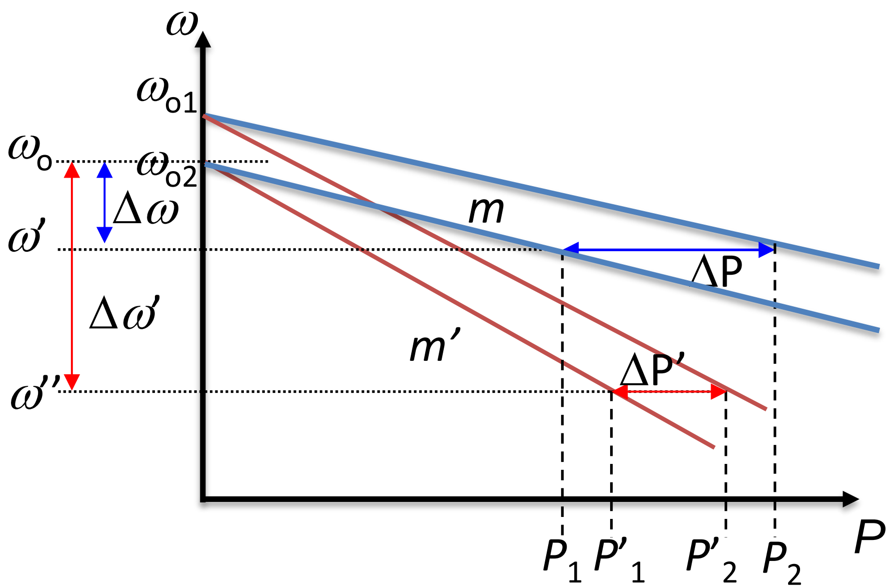
Inertias means not only load-dependent frequency (droops), but also local storage energy system.

European Project VSYNC: http://www.vsync.eu

Droop control of AC systems

- **Trade-off power sharing / amplitude - frequency regulation**

$$\omega = \omega^* - mP \qquad E = E^* - nQ$$

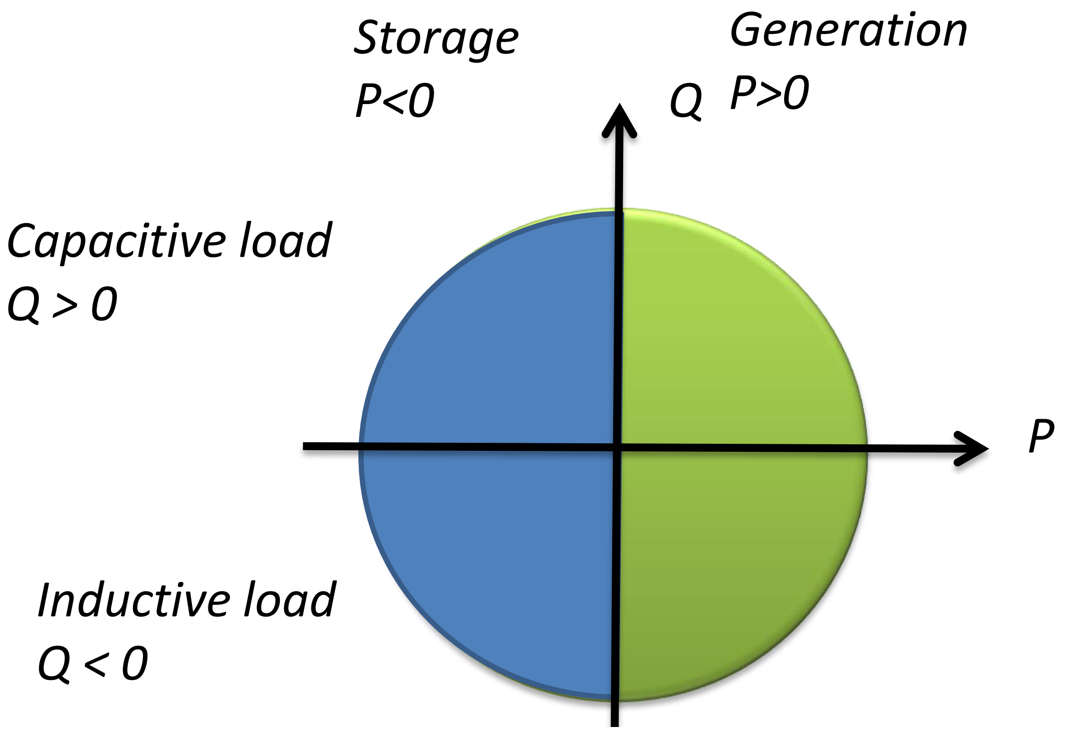


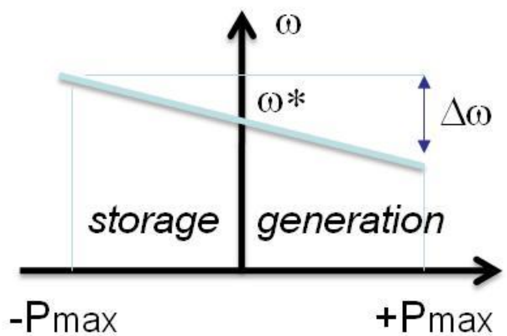
$$\Delta\omega_{max} = 2\% \qquad \Delta E_{max} = 5\%$$

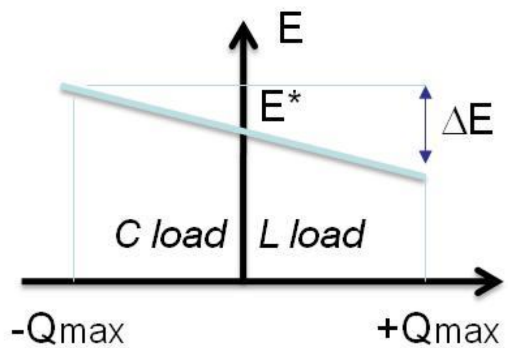
Phase droops are not feasible since the initial phase of each inverter is different!

Droop control for AC MGs

Droop control of AC systems



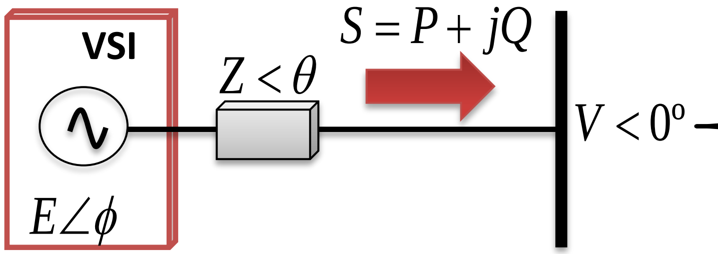




Droop control for AC MGs

Generalized droop control

- **Study of P/Q flow in function of the output impedance**



$$\begin{cases} P = \dfrac{EV}{Z}\cos(\theta-\phi) + \dfrac{V^2}{Z}\cos\theta \\ Q = \dfrac{EV}{Z}\sin(\theta-\phi) - \dfrac{V^2}{Z}\sin\theta \end{cases}$$

By using the Park transformation, the droop method functions become

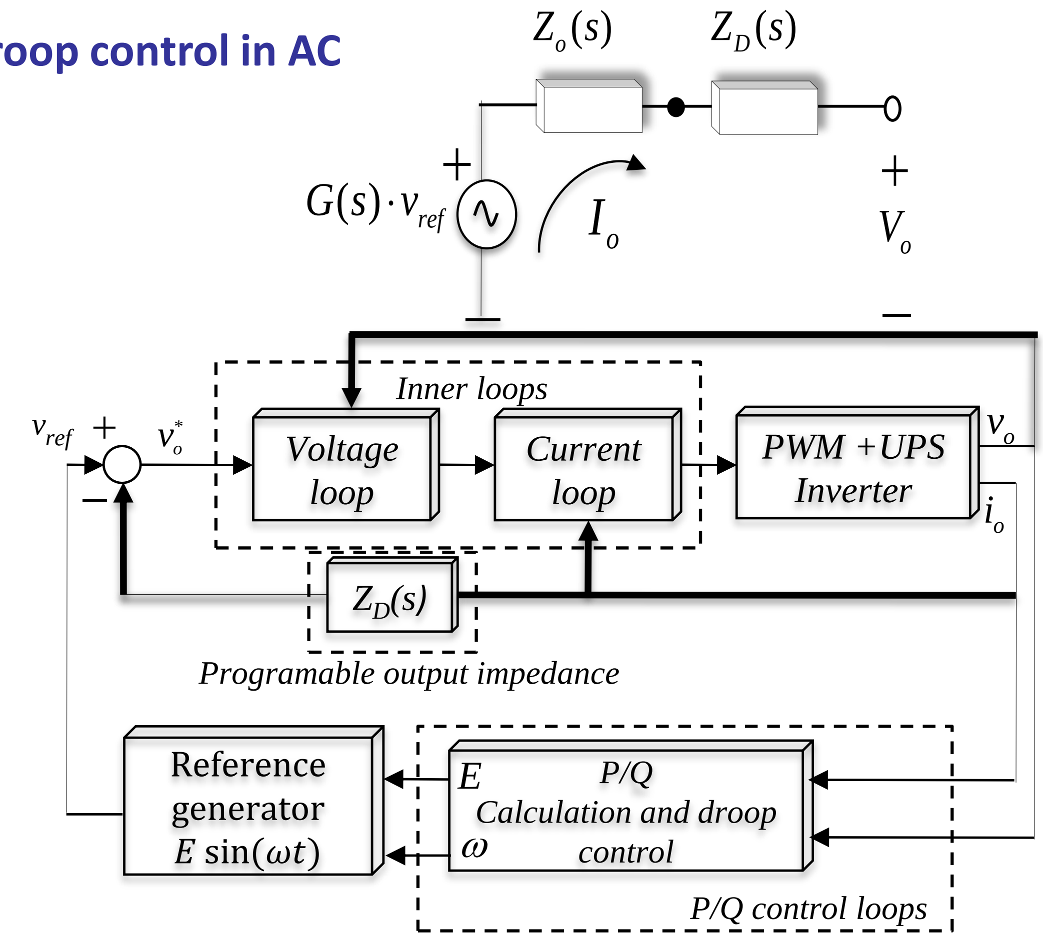
$$\omega = \omega^* - m(P\sin\theta - Q\cos\theta)$$
$$E = E^* - n(P\cos\theta + Q\sin\theta)$$

The R – V virtual resistance in a DC microgrid can be see as Q – V droop in an inductive AC microgrid. The ω – P droop is added to synchronize the system.

Virtual Impedance

Virtual Impedance concept

- **Droop control in AC**



Objective: fix the output impedance

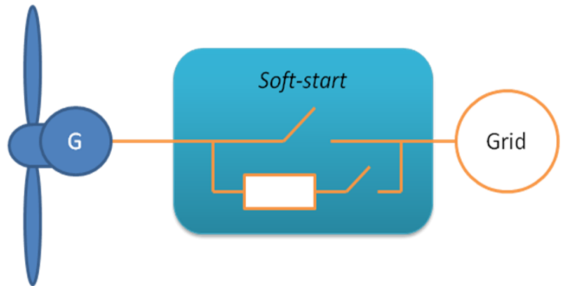
Virtual Impedance

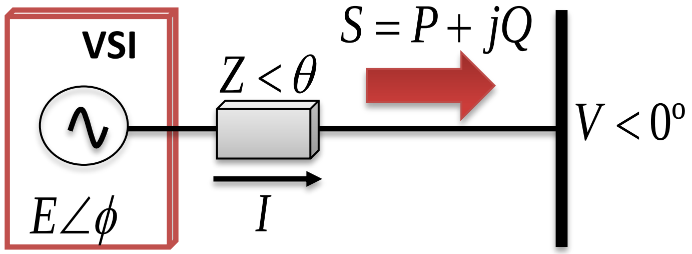
Soft-start operation

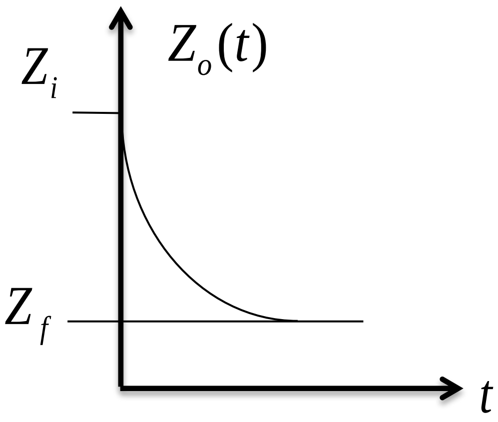
$$I_p \approx \frac{E}{\omega L_D} \Delta\varphi$$

$\Delta\varphi$ → Initial PLL error

ωL_D → Output impedance







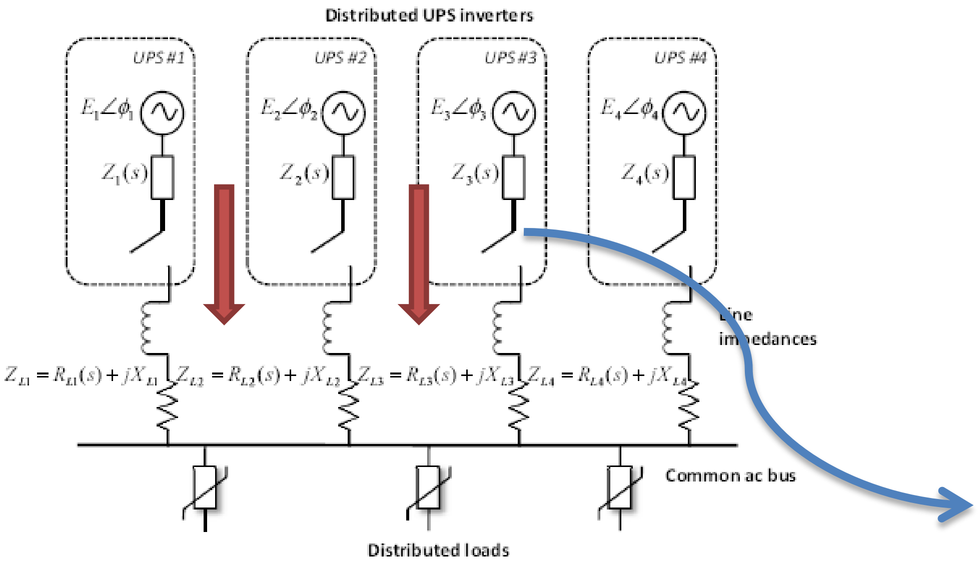
$$L_D^* = L_{Df}^* + (L_{Do}^* - L_{Df}^*) \cdot e^{-t/T_{ST}}$$

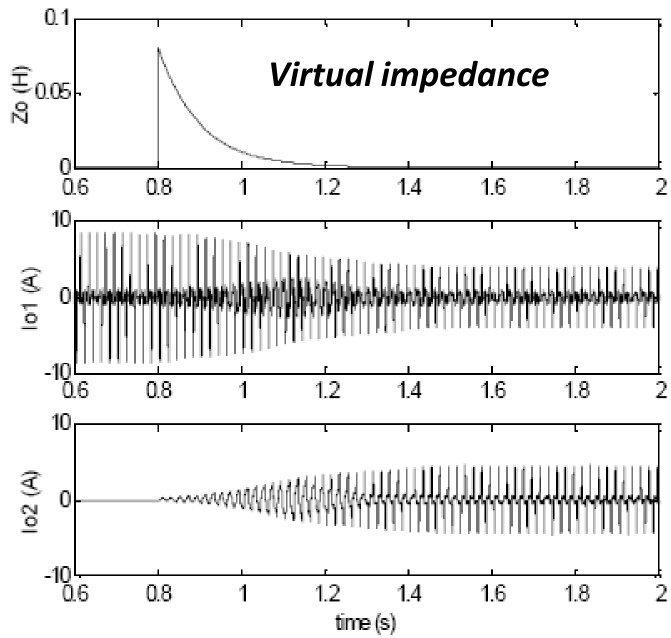
The virtual output impedance is a control variable.
Increasing the output impedance can reduce the initial current peak at the connection

Virtual Impedance

Hot-swap capability

4 DG units microgrid





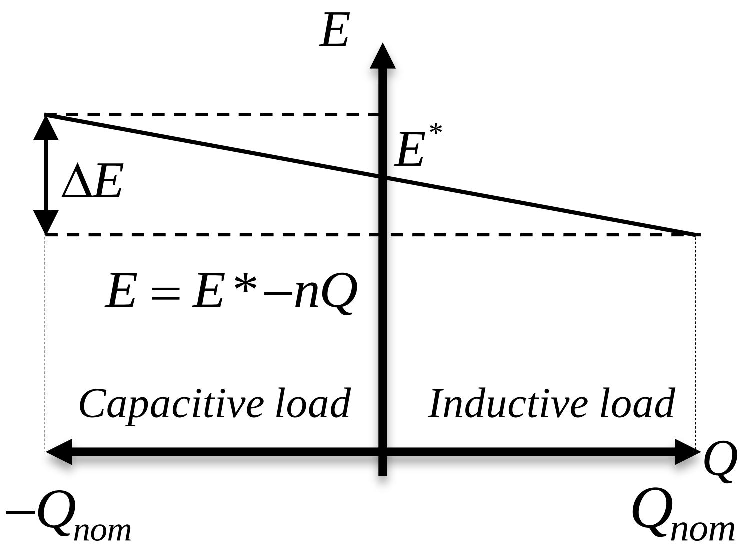
Output currents

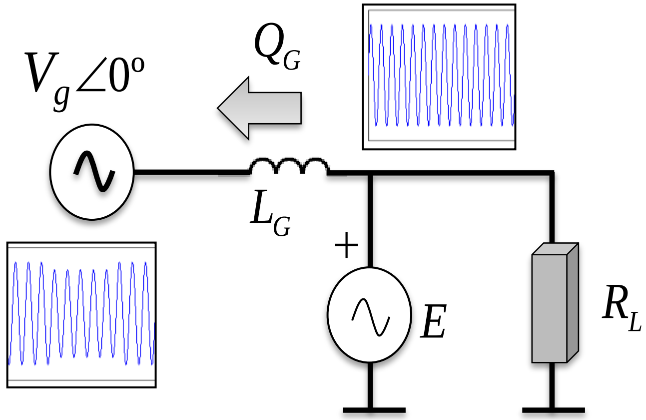
Before the connection,
a PLL have to synchronize the DG with the MG.
A the connection the virtual impedance is high to reduce the initial current peak.

This capability allow us to connect DGs without stop the microgrid, for mantainance reasons.

Low voltage ride-through

- Reactive power control of a grid-connected DG.



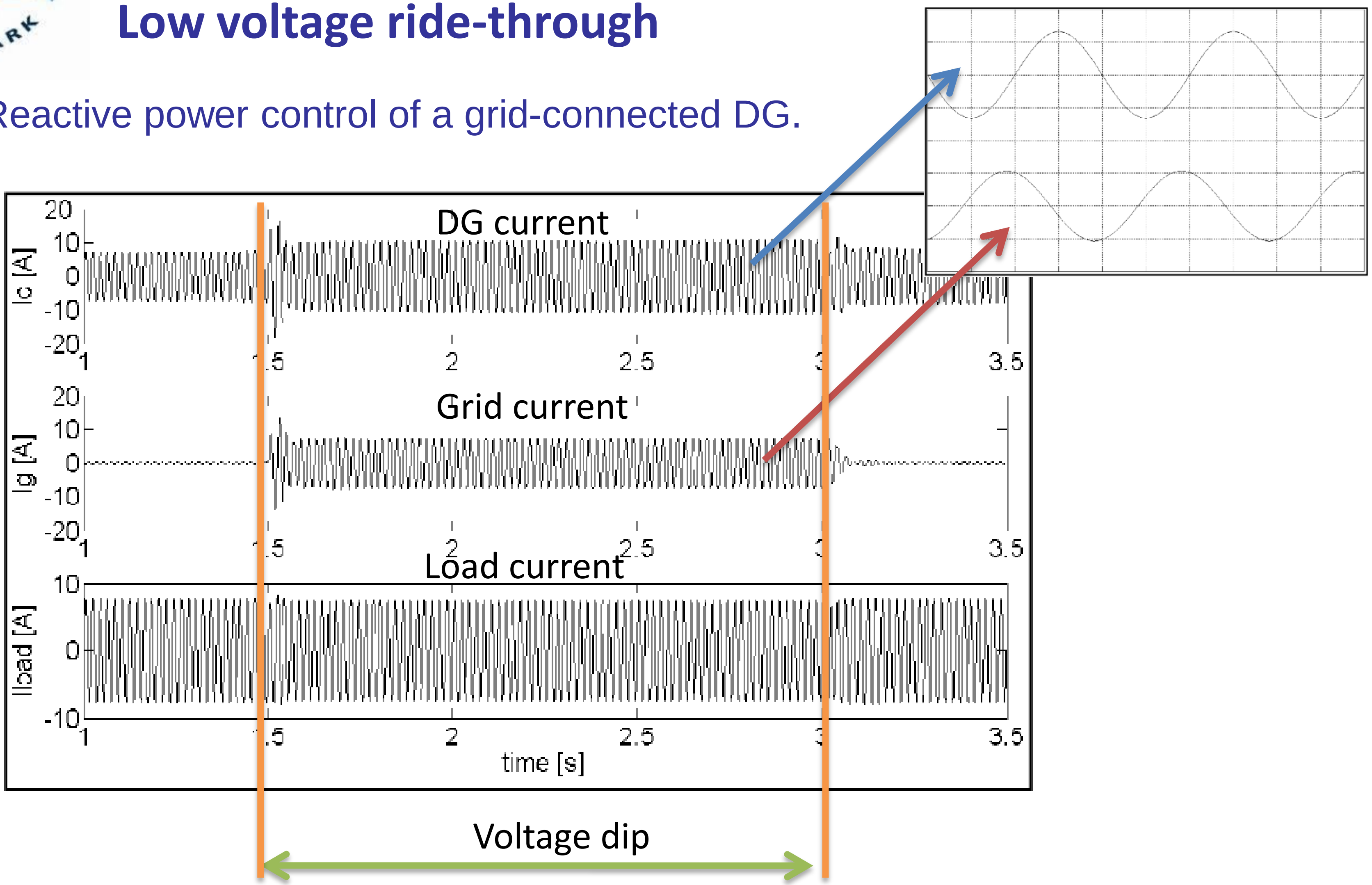


Trade-off during voltage dips: 1) voltage follower (Q=0) 2) stiff voltage source (Q high)

Low voltage ride-though

Low voltage ride-through

- Reactive power control of a grid-connected DG.

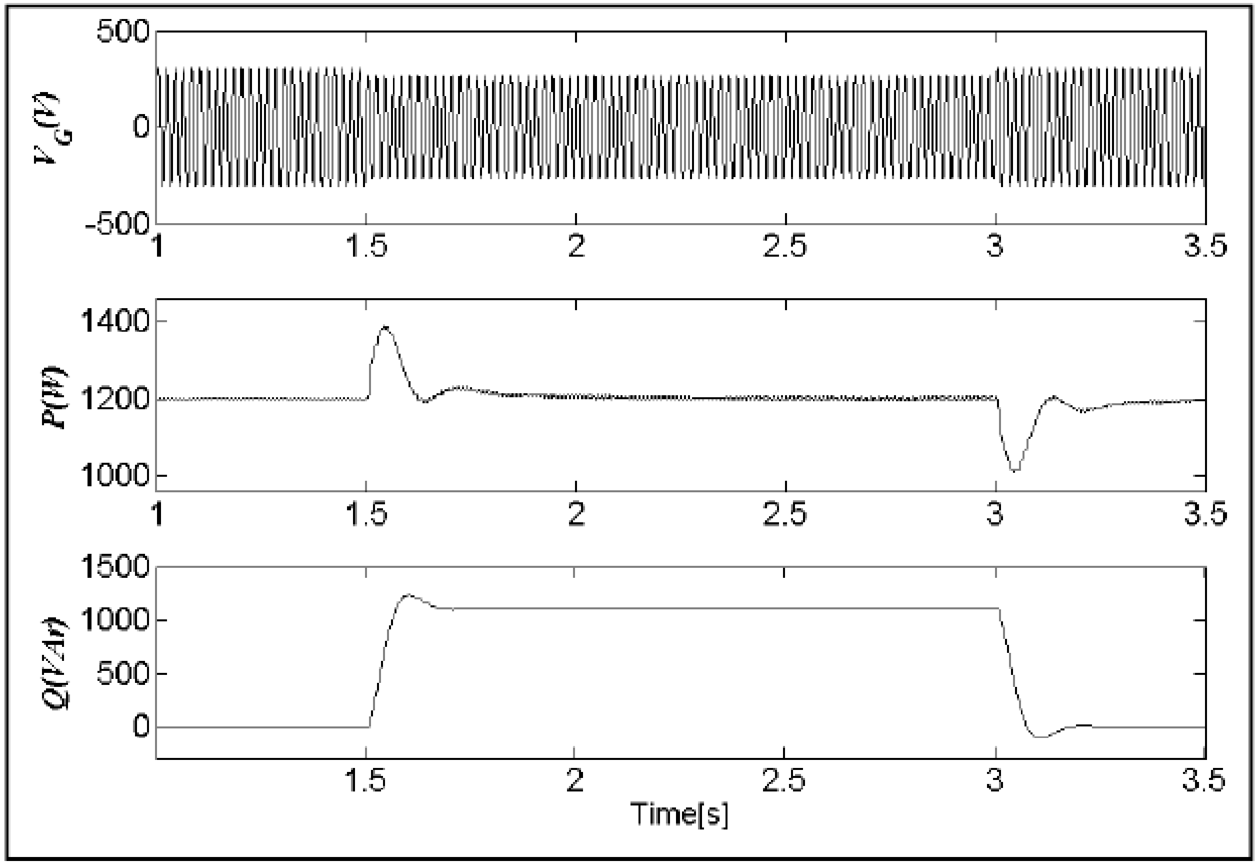


During the voltage grid, the converter injects reactive current (90º)

Low voltage ride-though

Low voltage ride-through

- Reactive power control of a grid-connected DG.



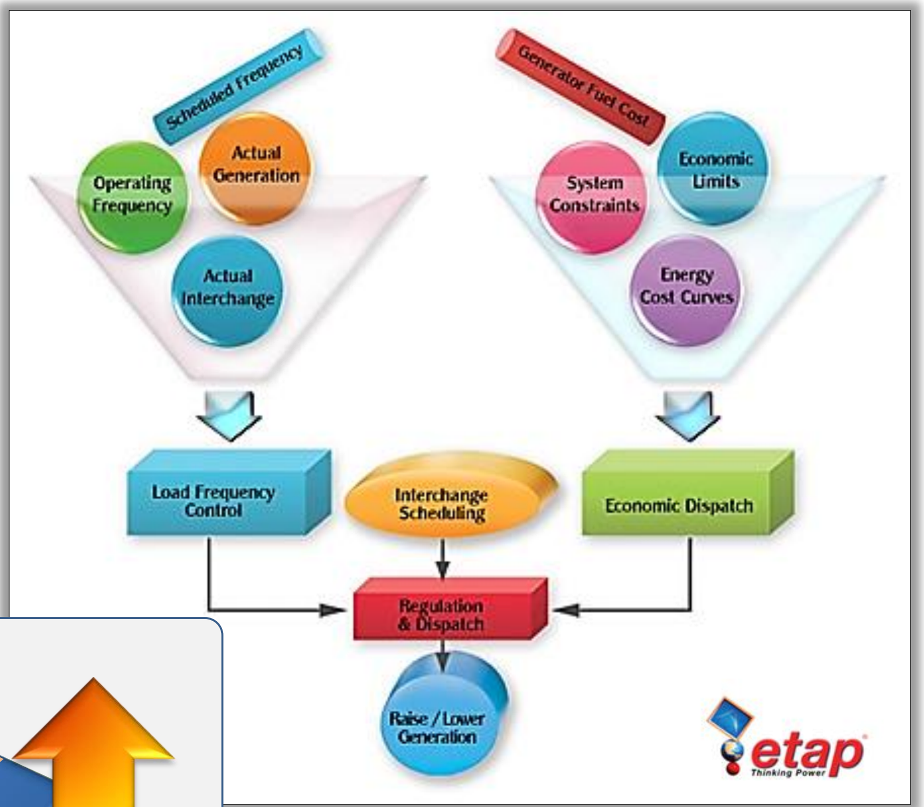
Active power remains constant (to the load). Reactive power is injected to mantain the voltage inside the droop characteristic.

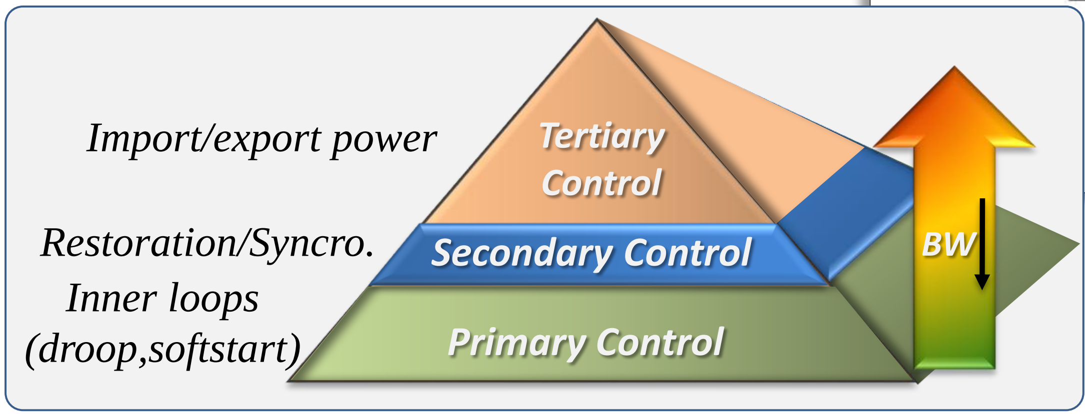
Hierarchical control

Hierarchical

Control

Principle

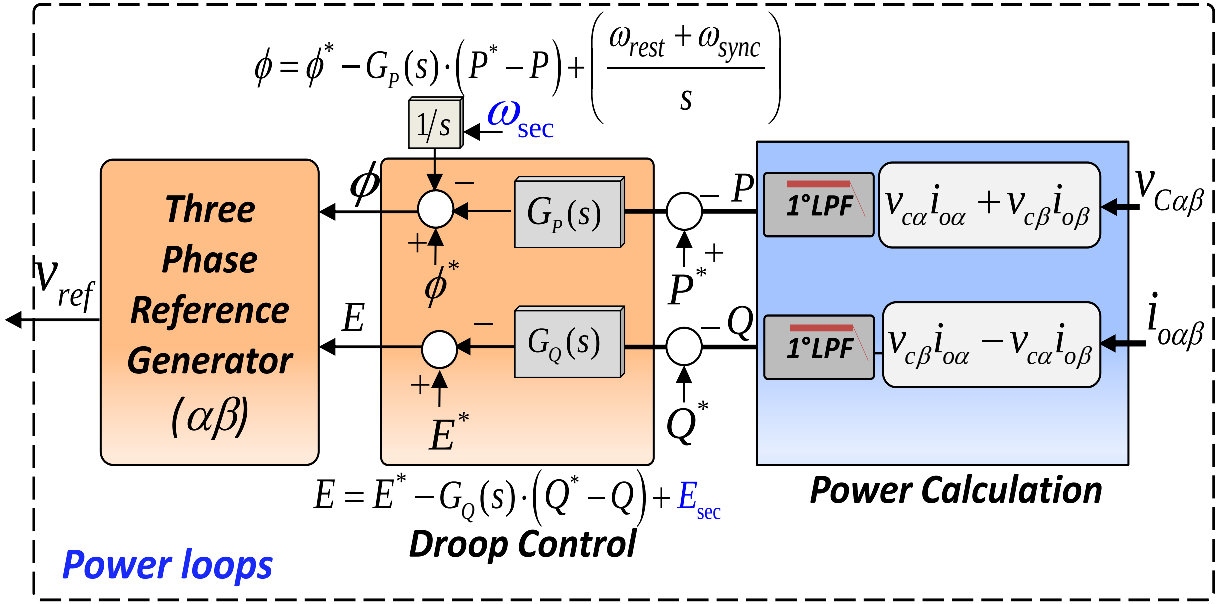




Enterprise Software Solution for Power Systems

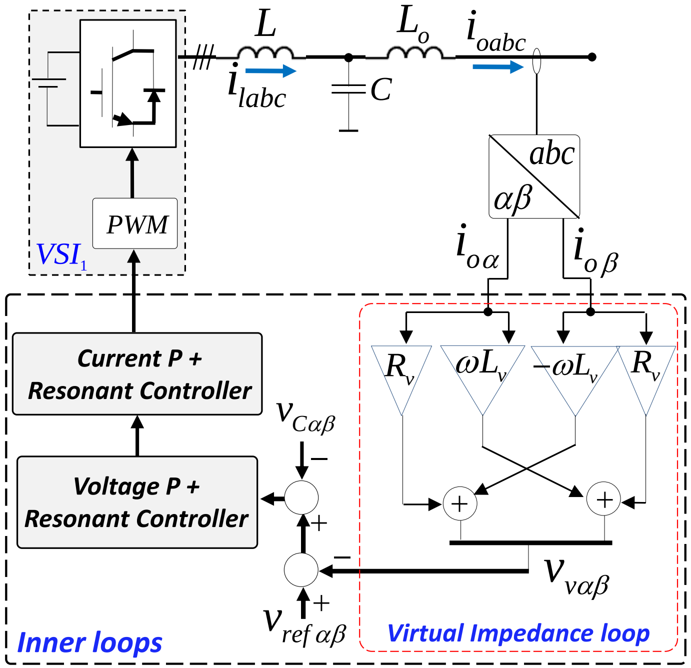
Hierarchical control

Droop control for three phase VSIs

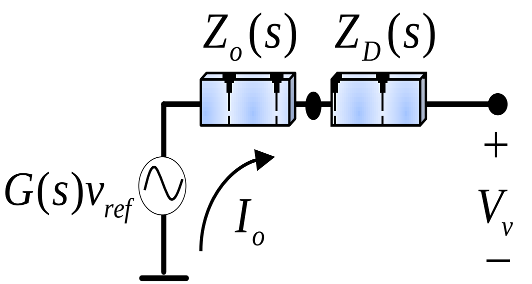


Hierarchical control

Virtual impedance control for three phase VSIs



$$\begin{cases} V_{V\alpha} = R_v \cdot i_{o\alpha} - \omega L_v \cdot i_{o\beta} \\ V_{V\beta} = R_v \cdot i_{o\beta} + \omega L_v \cdot i_{o\alpha} \end{cases}$$



$$v_{out}(s) = G(s)v_{ref} - Z_o(s)i_o$$

$$Z_o(s) = \frac{1/Cs + G_v(s)G_i(s)G_{PWM}(s)Z_D(s)}{LCs^2 + \left(Cs + G_v(s)\right)G_i(s)G_{PWM}(s) + 1} + L_o s$$

Secondary Control

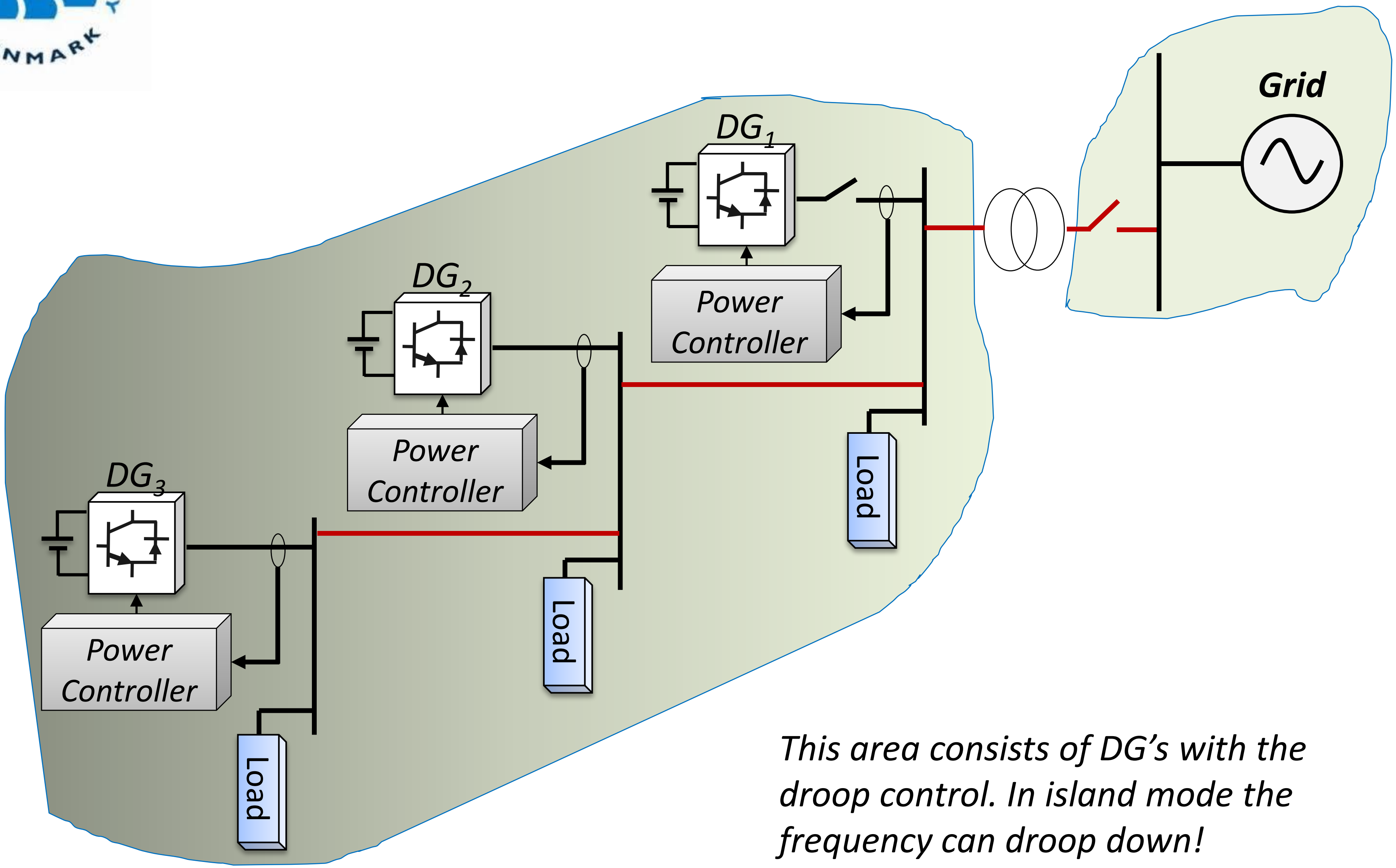
Islanding microgrids

- Grid-connected microgrids operate synchronized with the grid
- Islanded microgrids:
  - Frequency and amplitudes are load-dependent
- Secondary control can contribute to:
  - Frequency restoration
  - Amplitude regulation
  - Power quality (harmonics and unbalance compensation)

Energy management system can be used to:

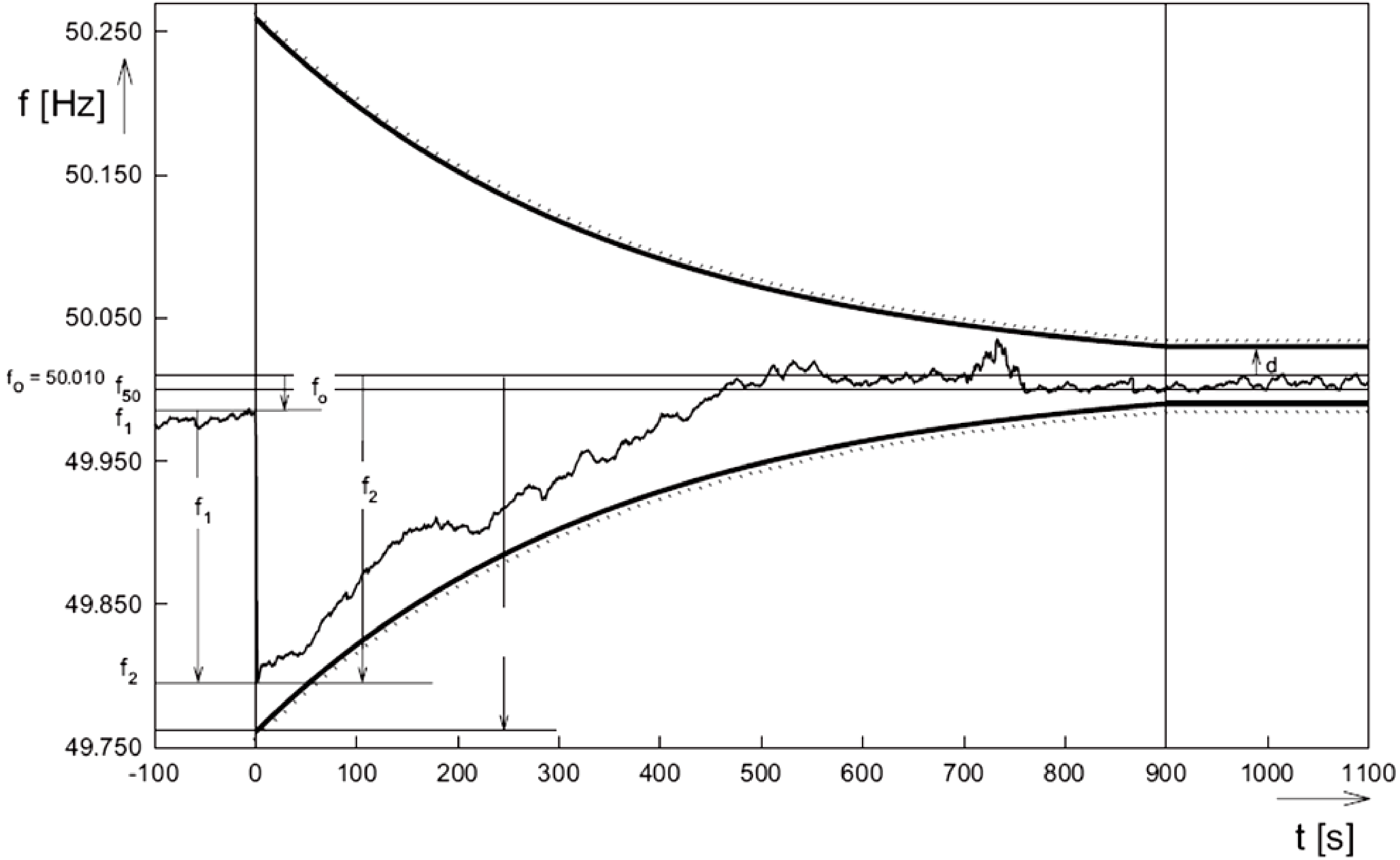
- Load shedding
- Regulation of the generator’s consumption

Secondary Control in Electric Power Systems



This area consists of DG's with the droop control. In island mode the frequency can droop down!

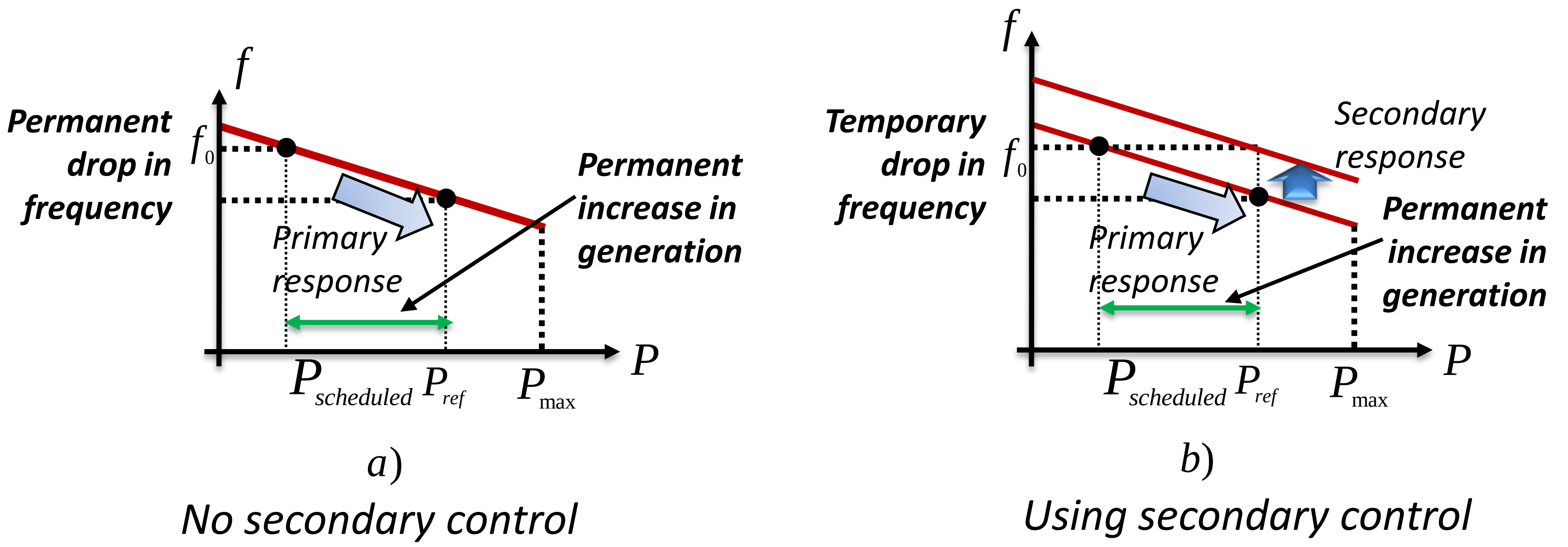
Secondary Control in Electric Power Systems



Source: UCTE. A1 – Appendix 1: Load-Frequency Control and Performance

Secondary Control for Microgrids

Secondary control action

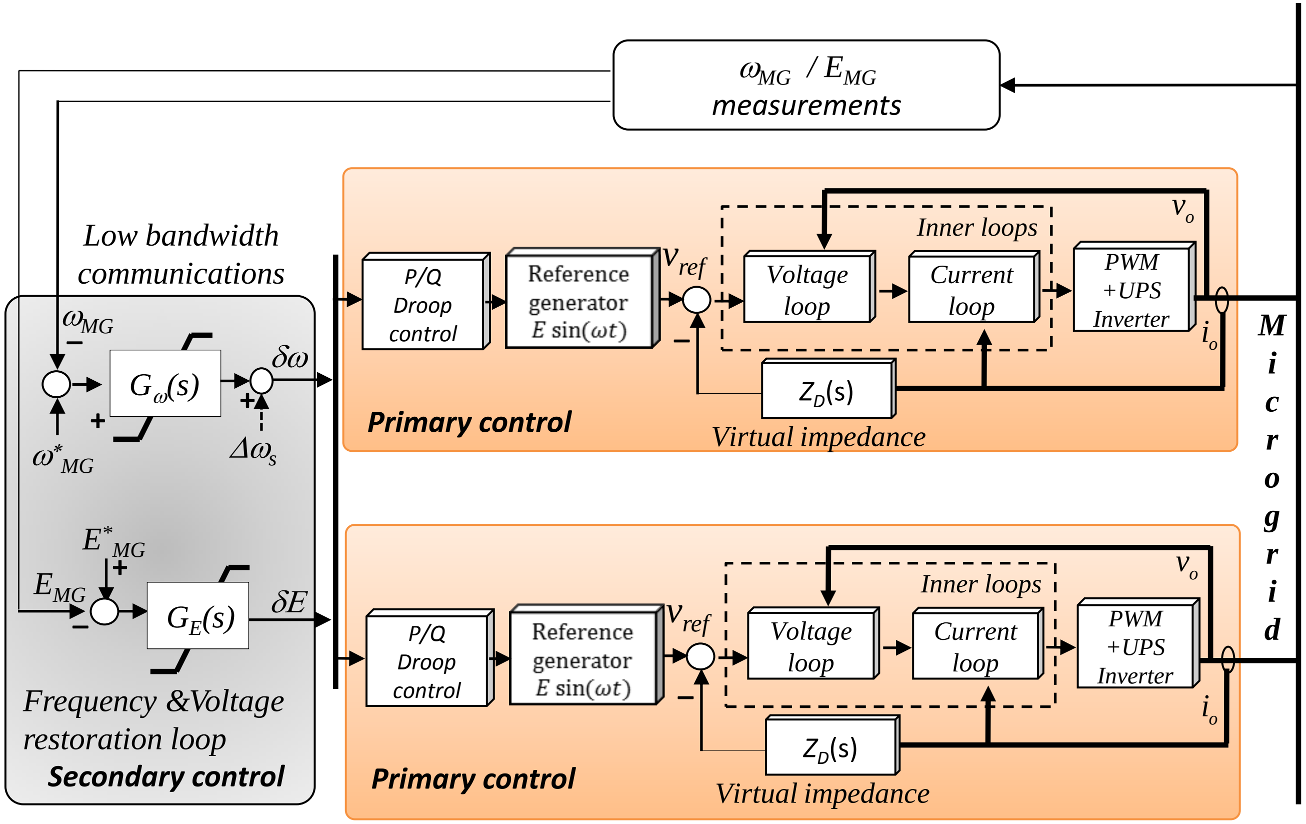


Primary control ensures P sharing by drooping the frequency

Secondary control:

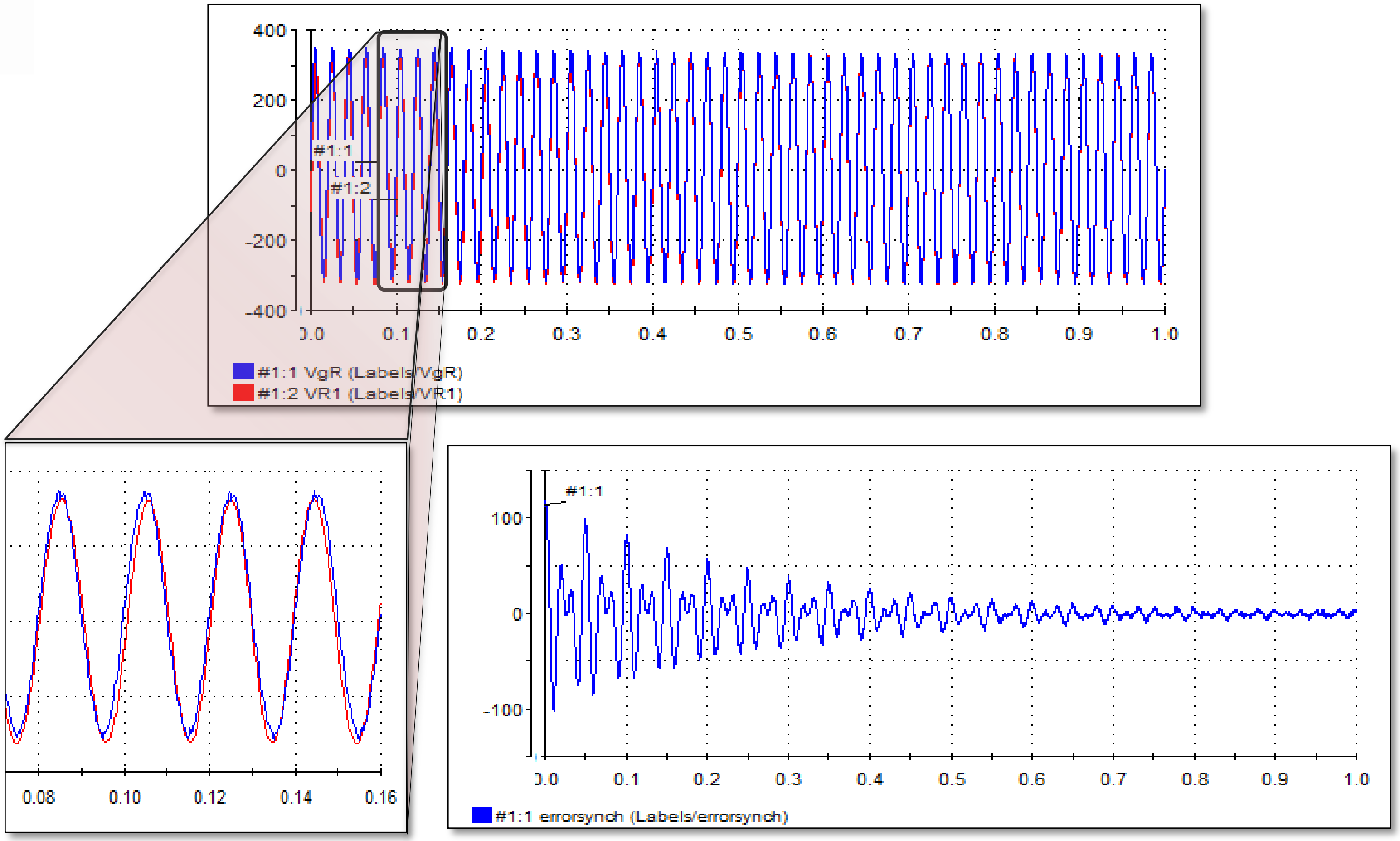
- Restore the nominal frequency
- Cannot work localy, it needs to be centralized.

Secondary control Implementation



Secondary control is located in the Microgrid Central Controller measure frequency and voltage. The output of the control is send through communications to adjust the reference of the local primary controllers (*droops*).

Microgrid synchronization with the grid

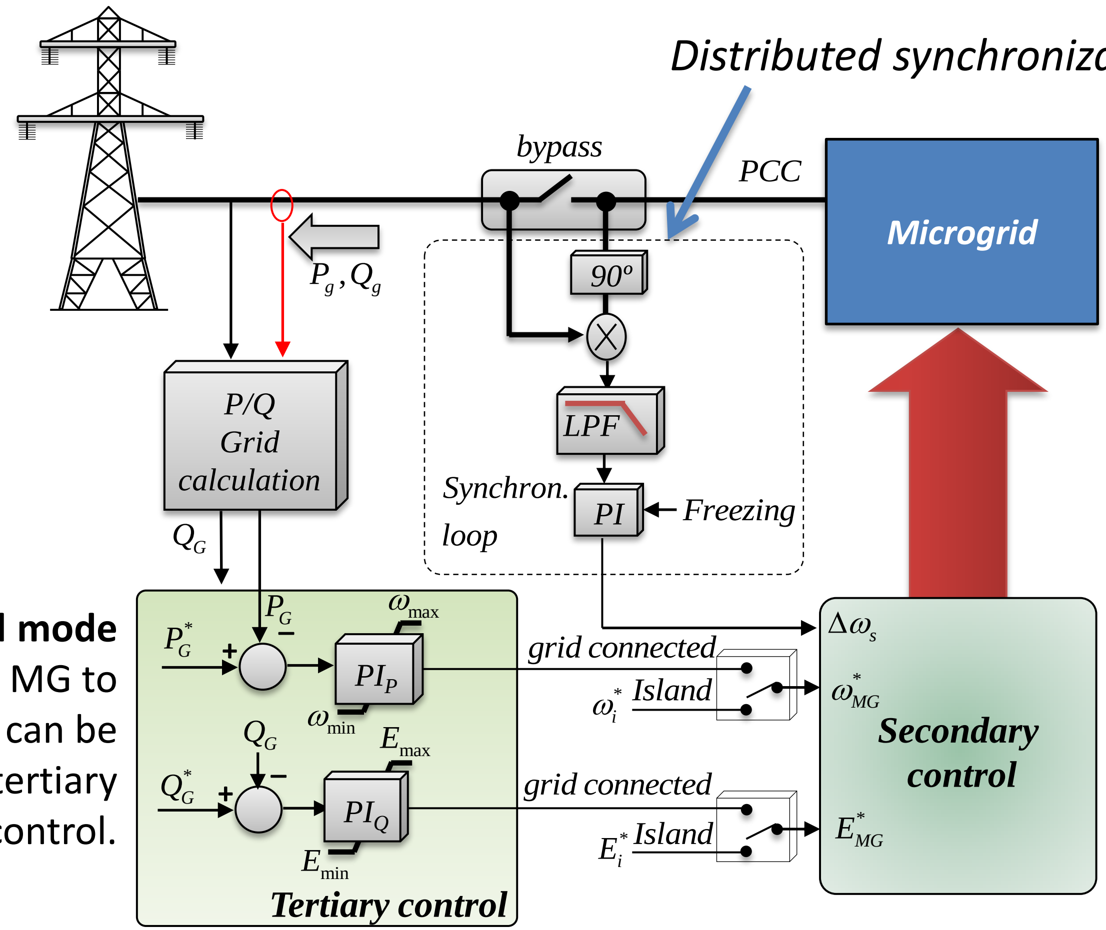


Synchronization is not necessary to be fast. ***Slow*** *(to avoid unstability problems) but well* ***accurate*** *(allowing seamless transition to grid-connected mode).*

Tertiary Control

Tertiary control for AC microgrids

- Terciary control and synchronization control loops implementation



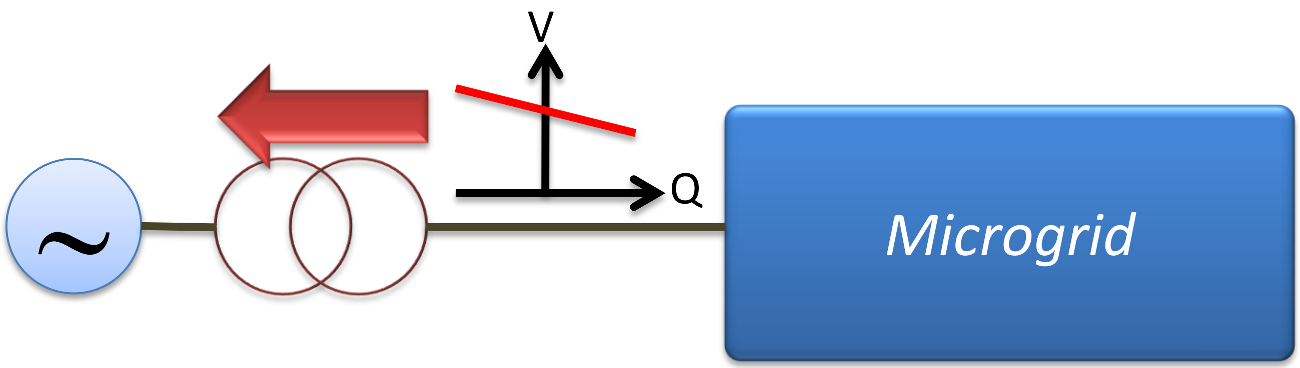
In **grid connected mode** P and Q from the MG to the grid can be controlled by tertiary control.

In **islanded mode** secondary control fixes frequency and amplitude of the MG.

Tertiary Control

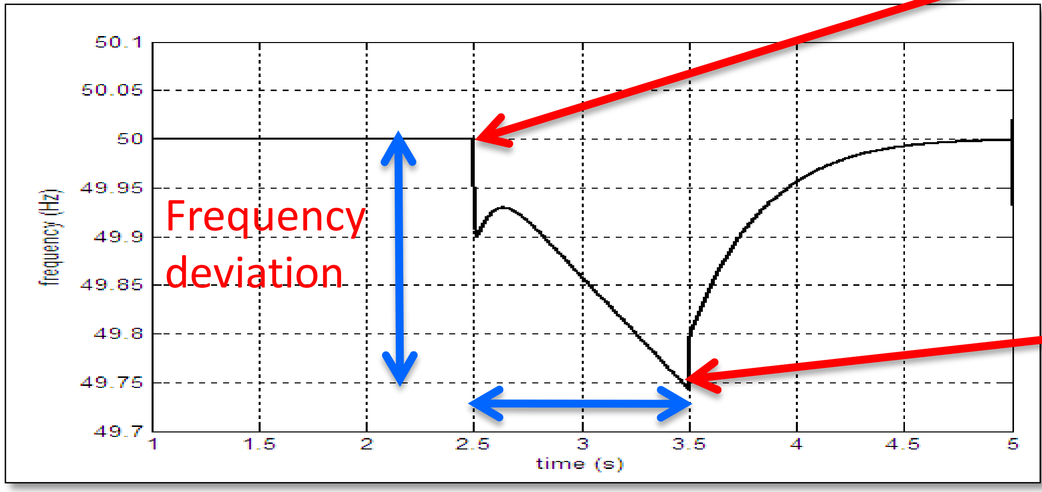
Tertiary control for AC microgrids

- Low voltage ride-trough of the Microgrid
  - *Freezing or disconnecting the integral term of the E – Q tertiary control.*
  - *The Microgrid will work like a STATCOM*



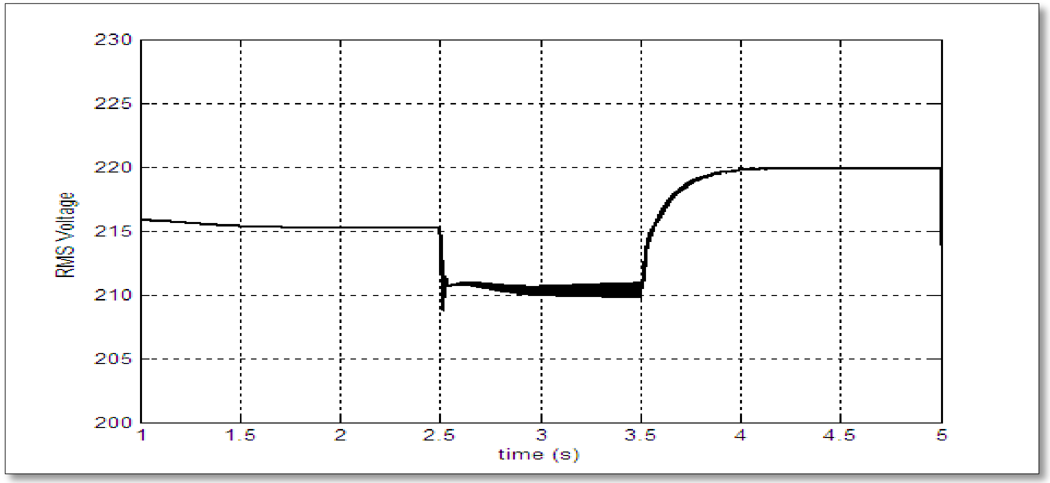
Microgrid example

Islanding detection



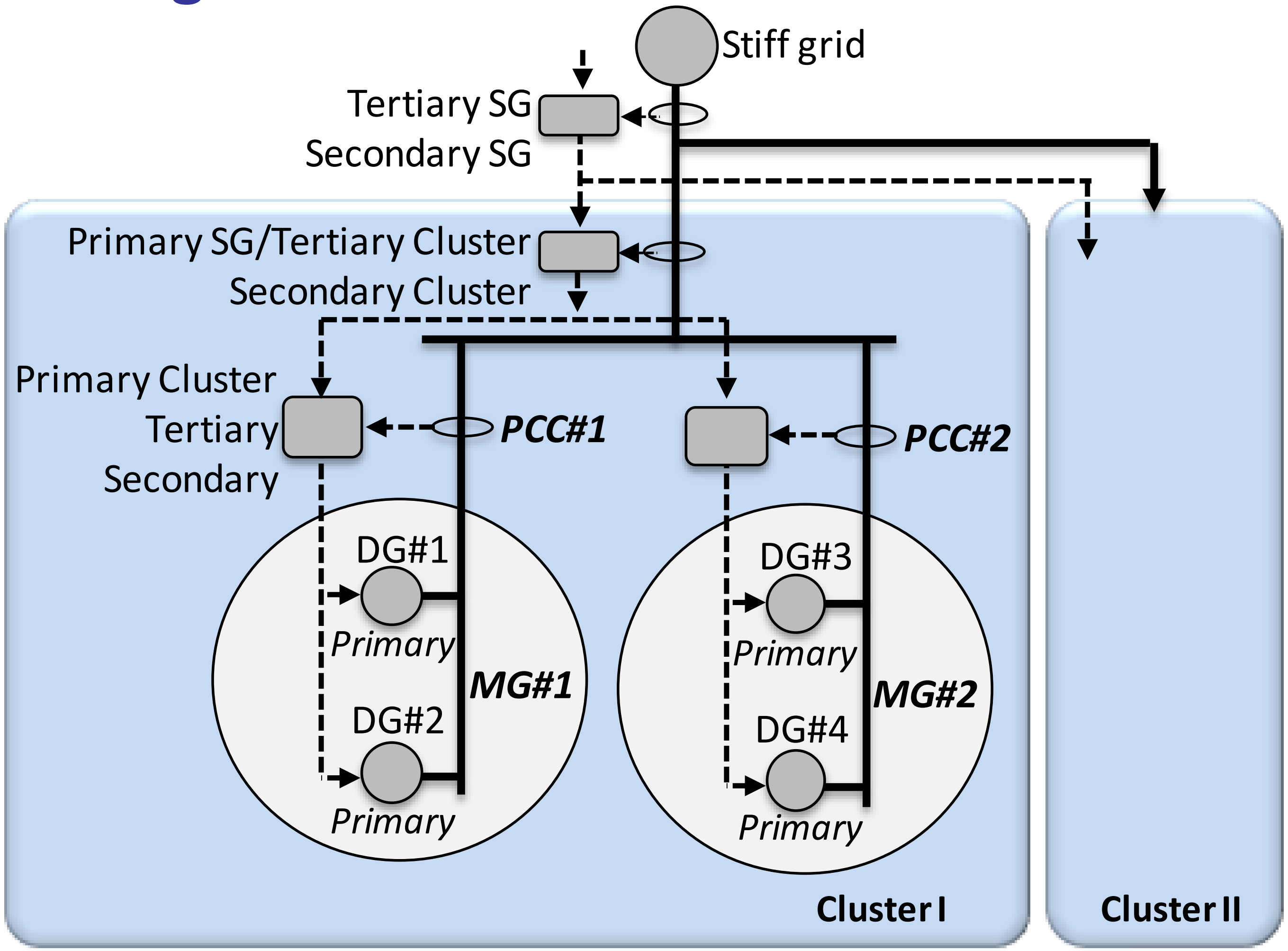
Non-planning Islanding

Islanding detection



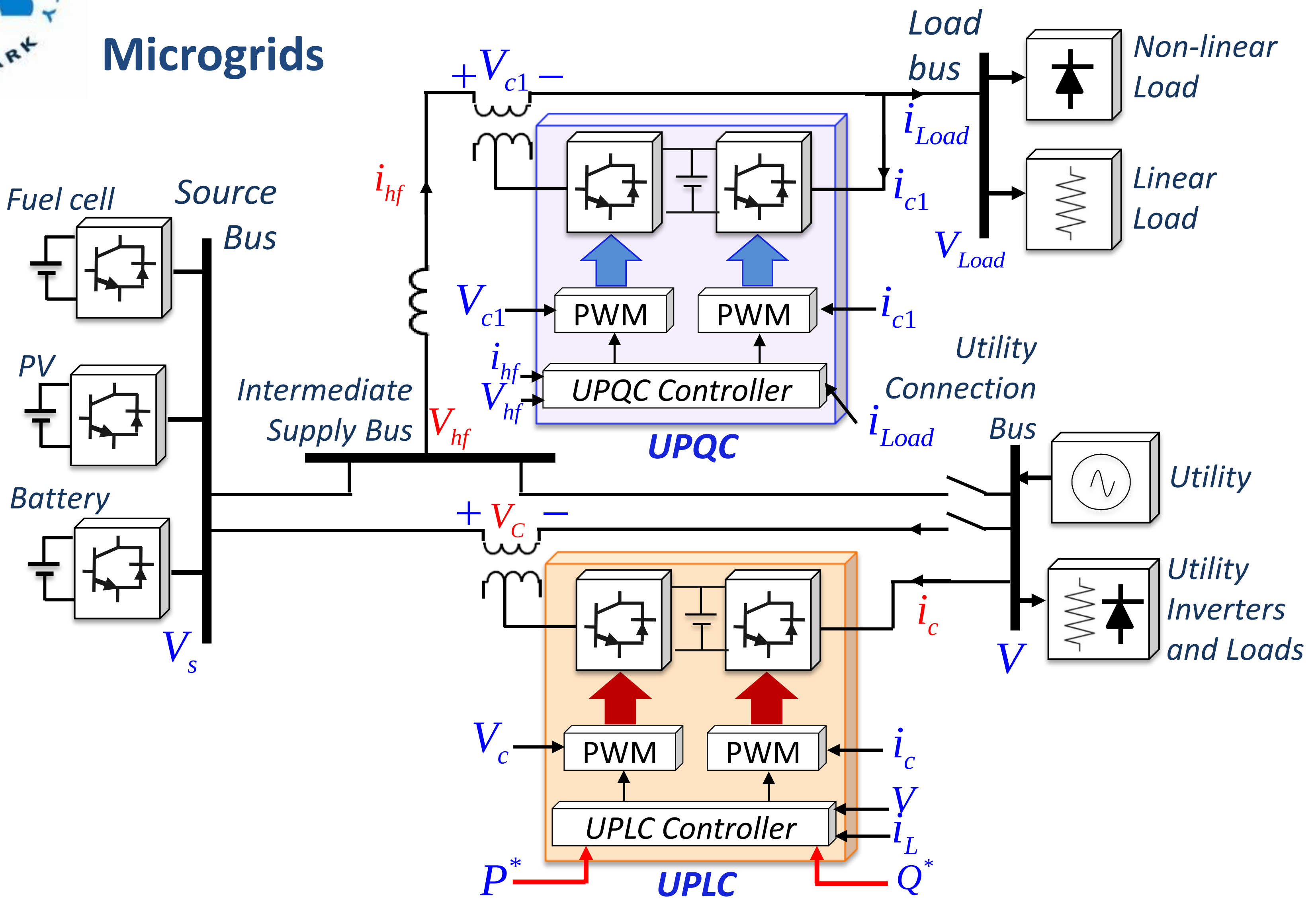
STS open (protection)
Q integrators disconnected

Microgrids interconnection



Power Quality in Microgrids

Microgrids

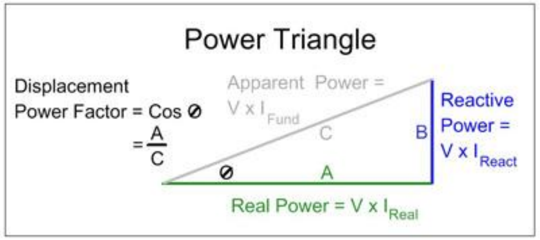


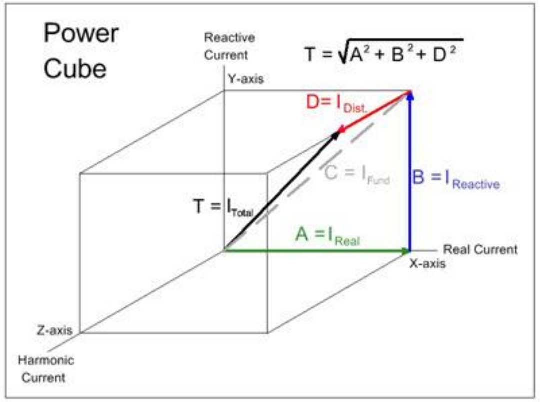
Advanced Active Filtering in a Single Phase High Frequency AC Microgrid - **Sudipta Chakraborty**

Power Quality in Microgrids

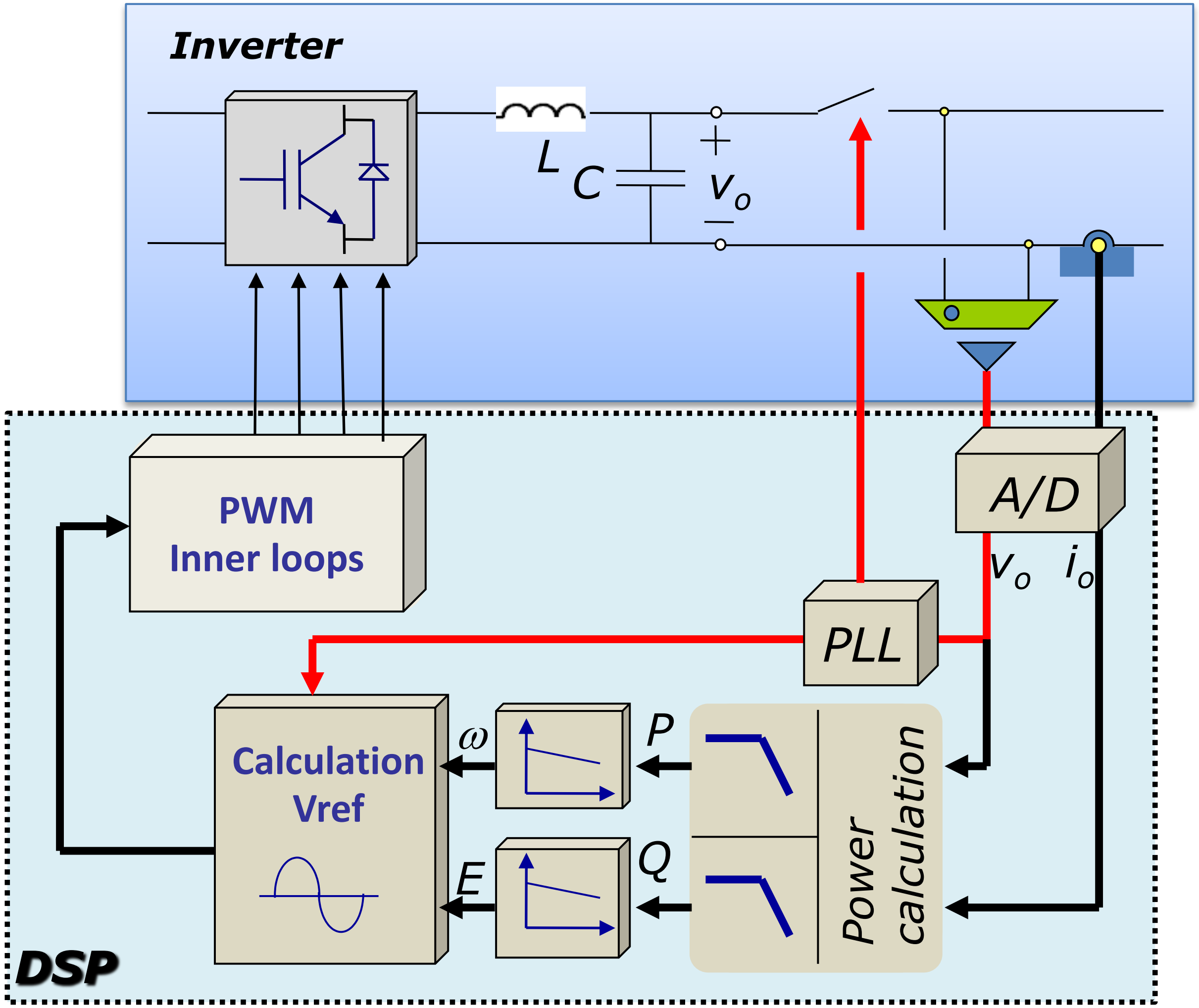
Harmonic current sharing

- Droop control allows P and Q sharing, averaged over the fundamental frequency.
- It is not able to guarantee harmonic current sharing!





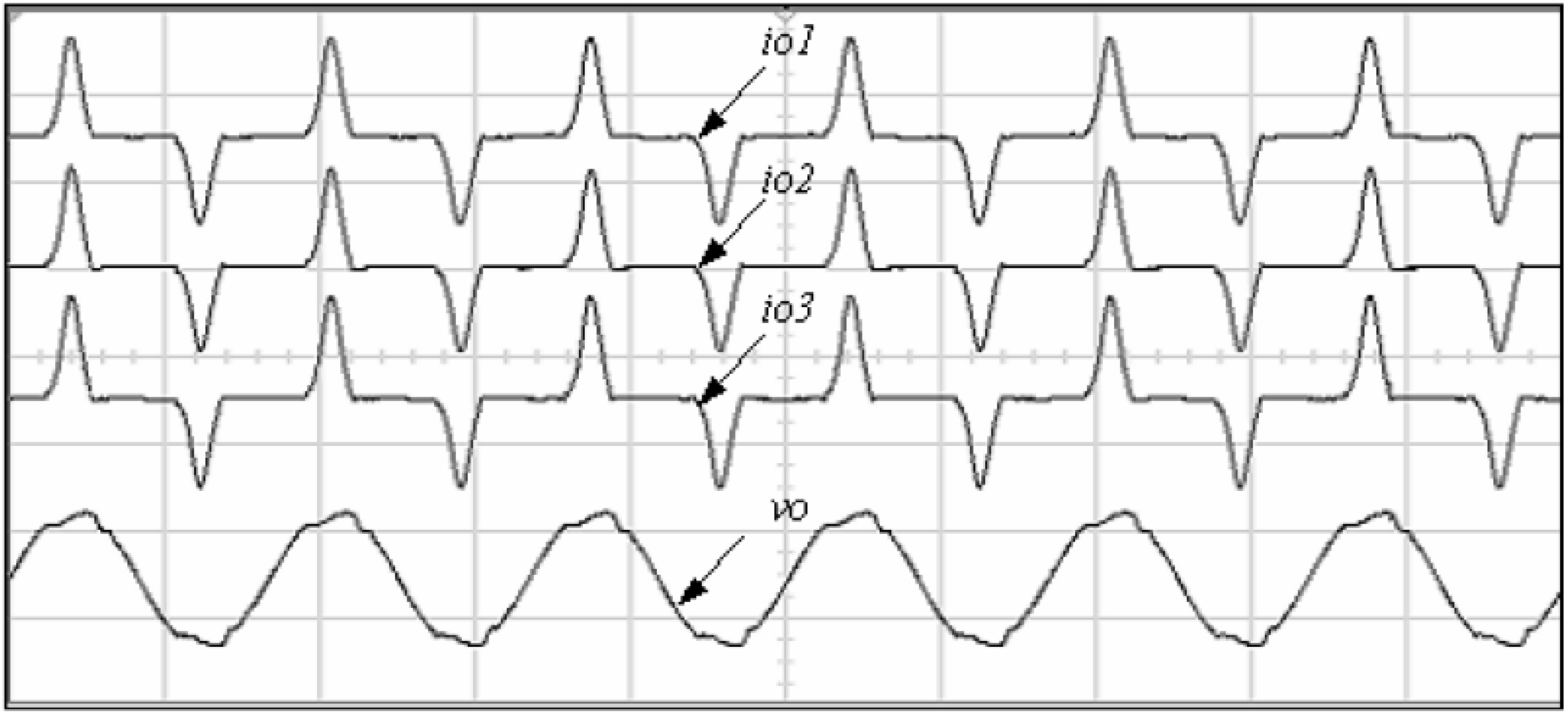
$$D = \sqrt{S^2 - P^2 - Q^2}$$



Power Quality in Microgrids

Harmonics current sharing

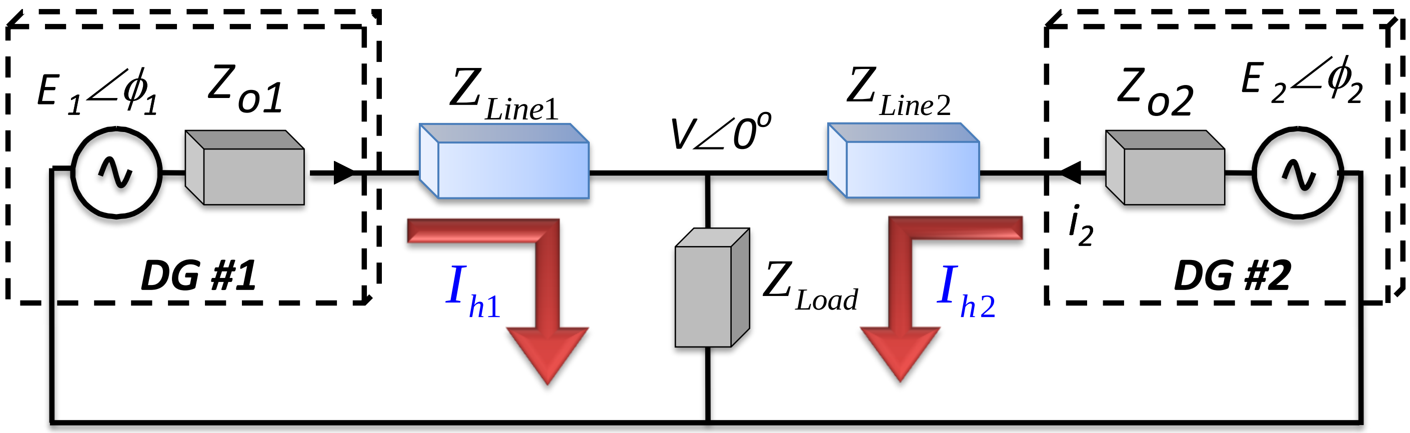
- Control objective: Harmonic current sharing proportional to the nominal DG power.
- Trade off: harmonic current sharing/voltage THD



Source: Y. E. Wu

Power Quality in Microgrids

Harmonics current sharing



- For Z_{line1} # Z_{line2}, harmonic current sharing is not possible
- Harmonic virtual impedance can enhance sharing

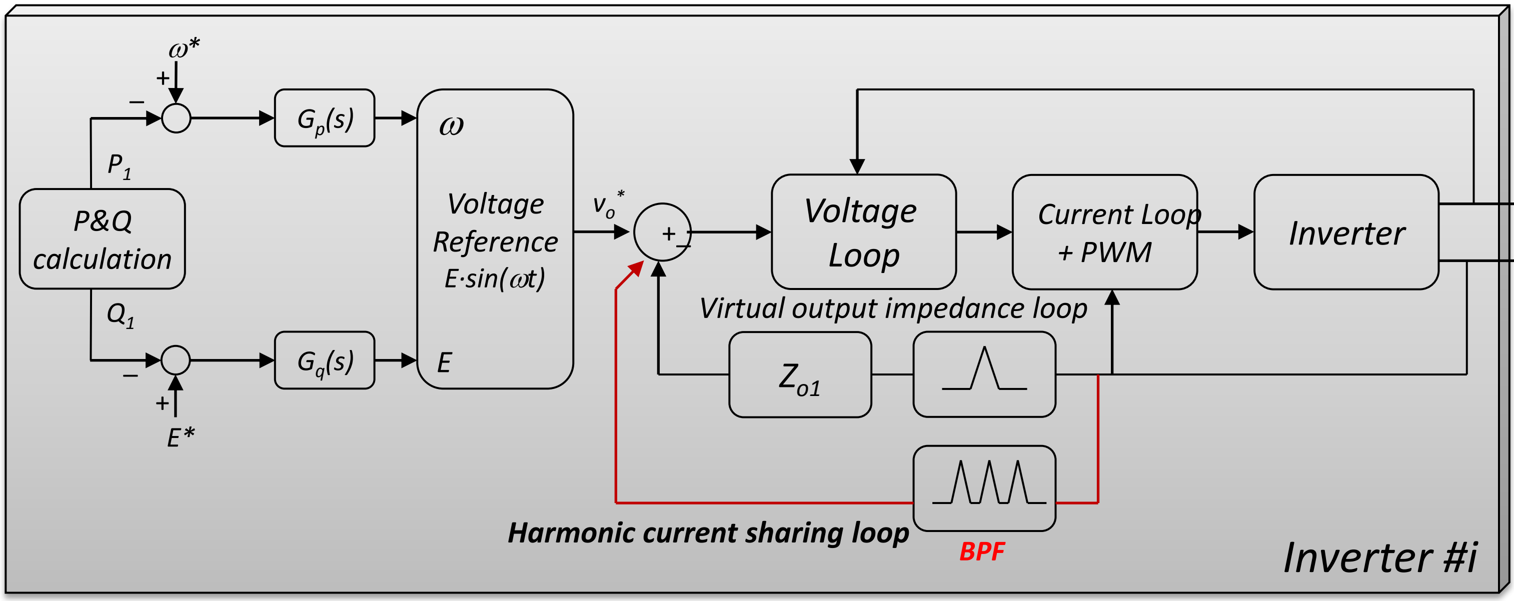
Zh = Vh/Ih

- Trade off V_{THD} and harmonic current sharing.

Power Quality in Microgrids

Droop control

Virtual Output Impedance with harmonic current sharing loop



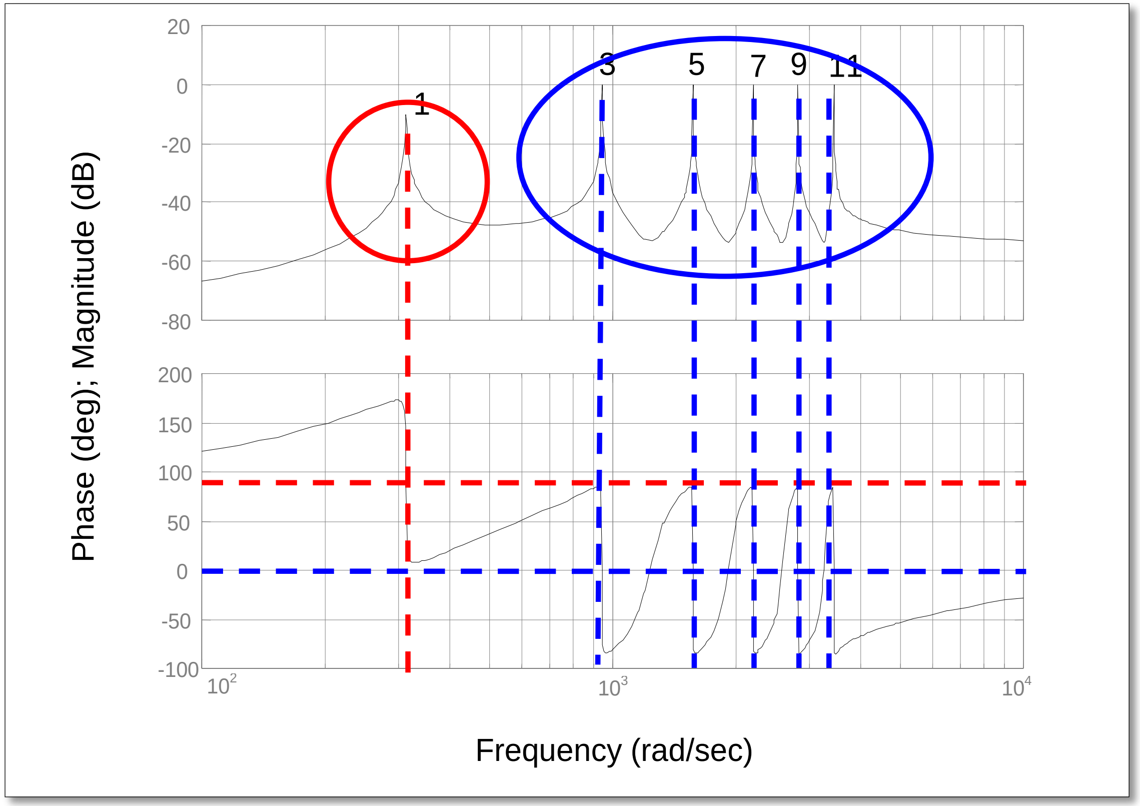
Selective harmonic selection: fundamental and each of the harmonics can have different output impedance.

Power Quality in Microgrids

Harmonic current sharing

$$H_i(s) = \frac{2k_i s}{s^2 + 2k_i s + \omega_i^2}$$

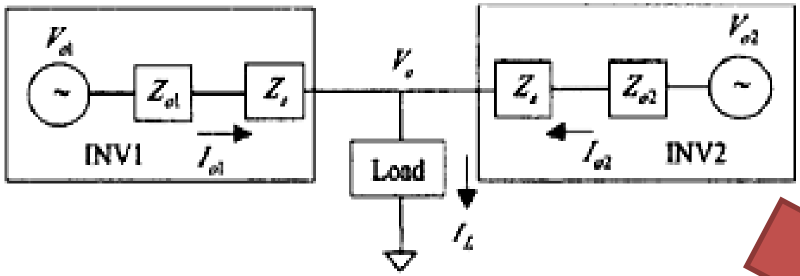
$$Z_V(s) = L_D \frac{2k_1 s^2}{s^2 + 2k_1 s + \omega_1^2} + \sum_{\substack{i=3 \\ odd}}^{n} R_i \frac{2k_i s}{s^2 + 2k_i s + \omega_i^2}$$



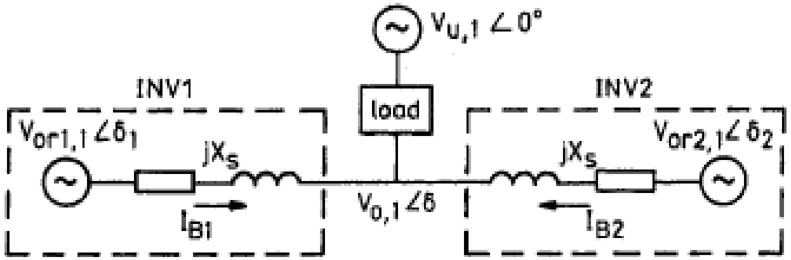
Power Quality in Microgrids

Harmonic current sharing

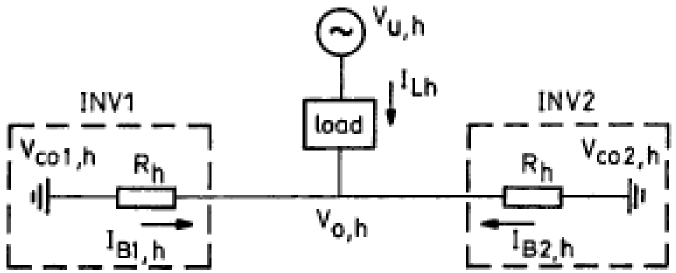
Whole frequency range



Fundamental



Harmonics

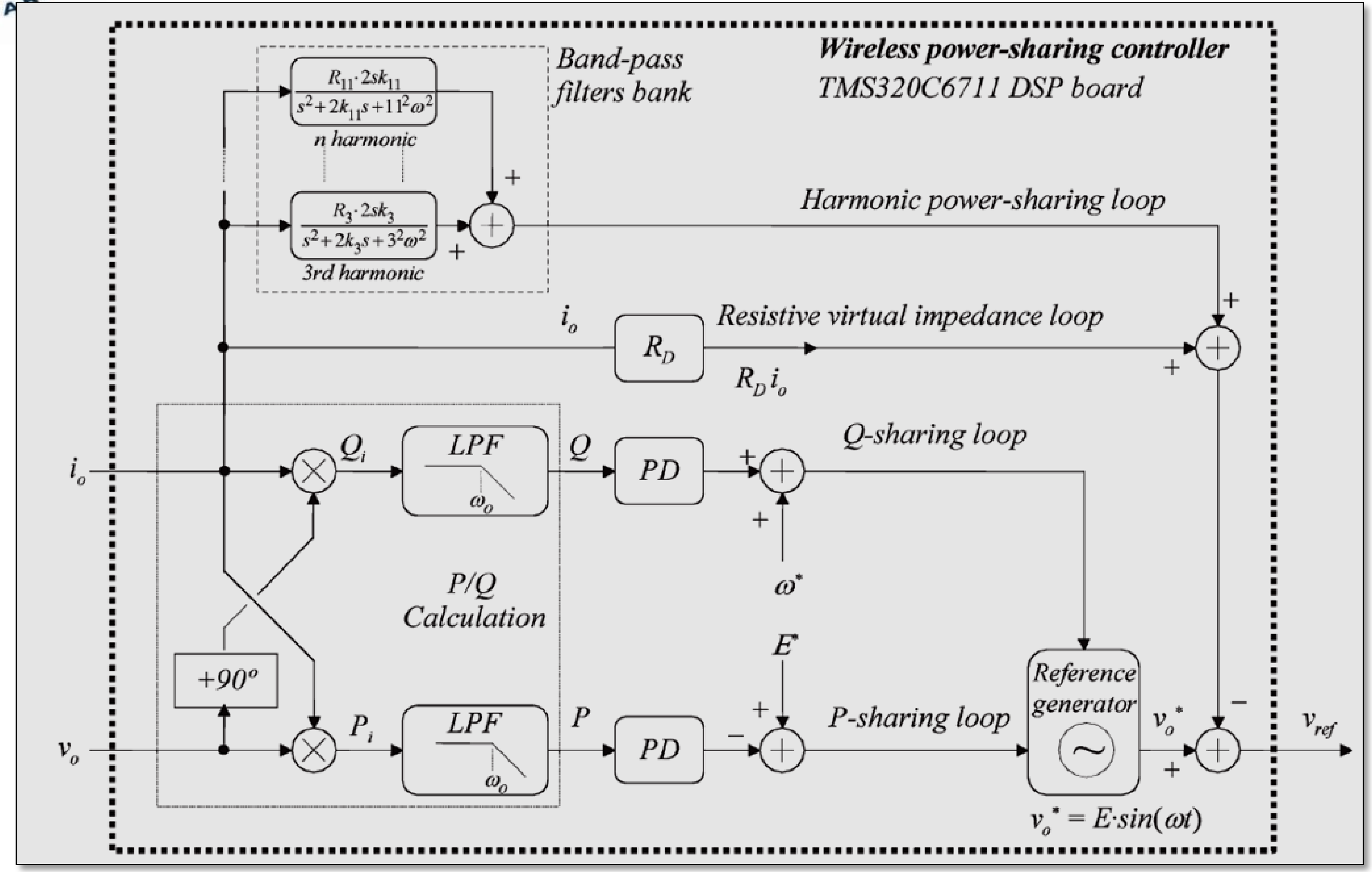


Parallel Control of the UPS Inverters With Frequency-dependent Droop Scheme

S . J. Chiang and J. M. Chang

Power Quality in Microgrids

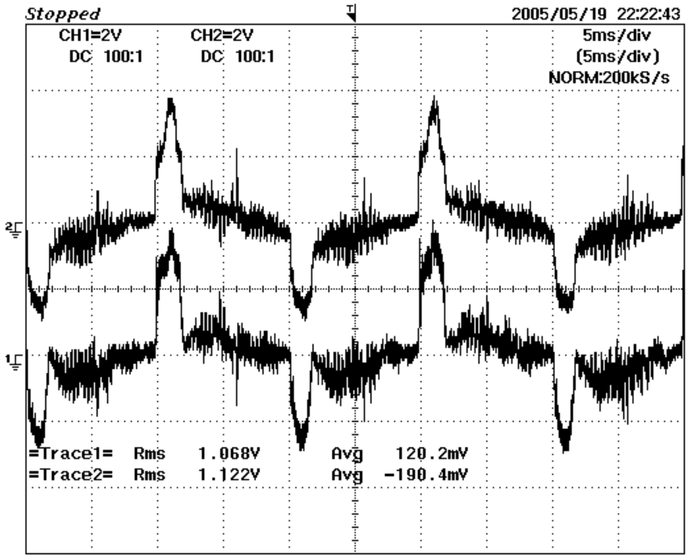
Droop method with virtual output impedance and selective harmonic



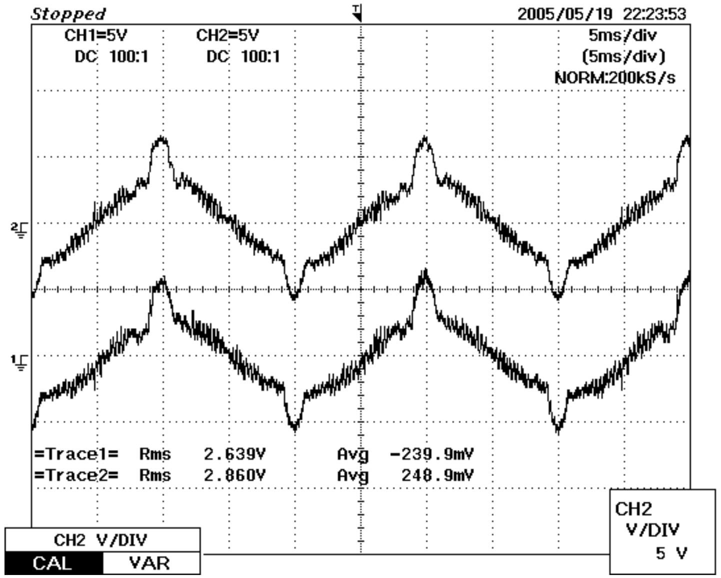
DSP implementation is appropriate for the multi-loop droop framework

Power Quality in Microgrids

Droop method for resistive output impedance



(a)

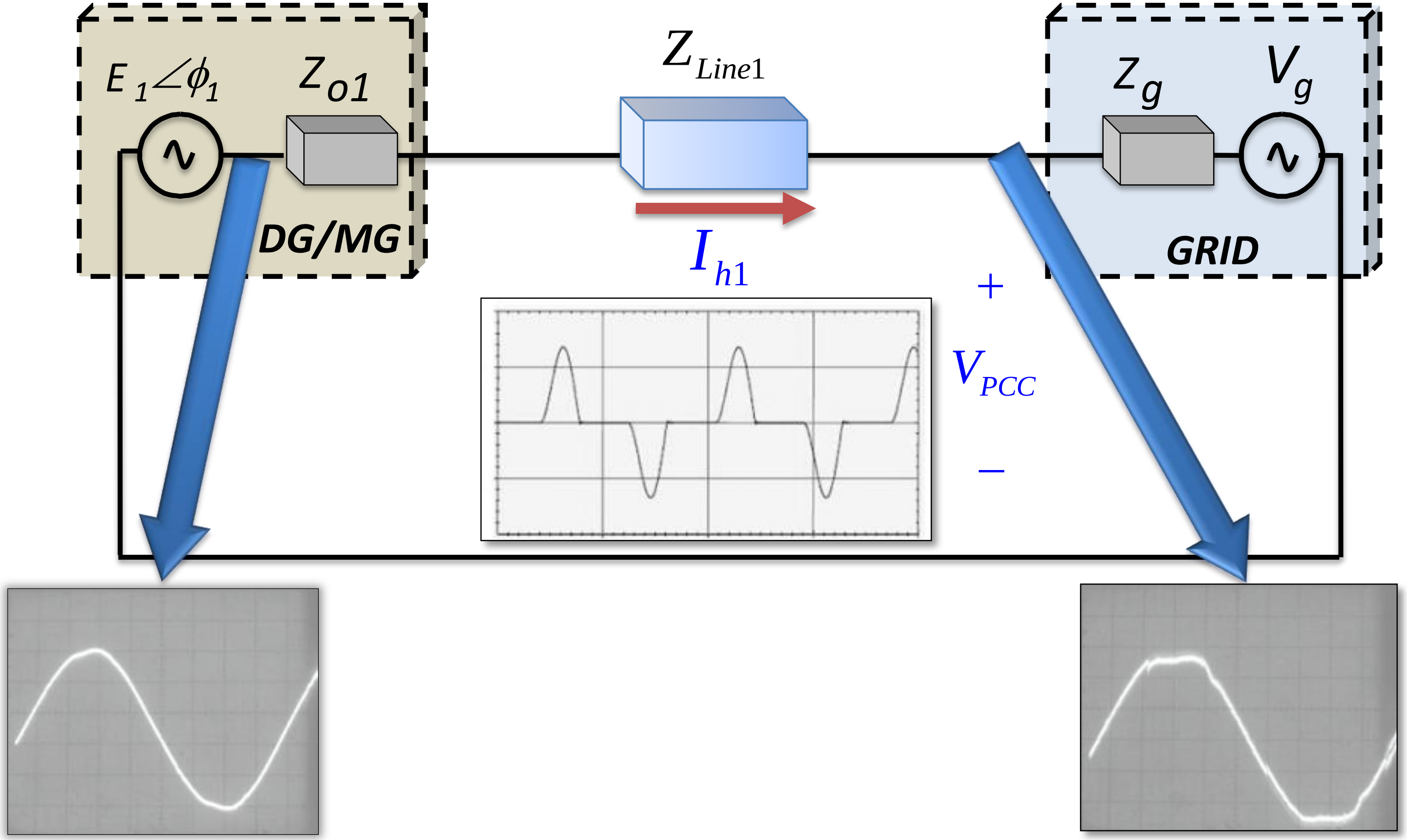


(b)

(a) Nonlinear load, Y: 2 A/div, X: 5 ms/div;
(b) Resistive // nonlineal load, Y: 10 A/div, X: 5 ms/div.

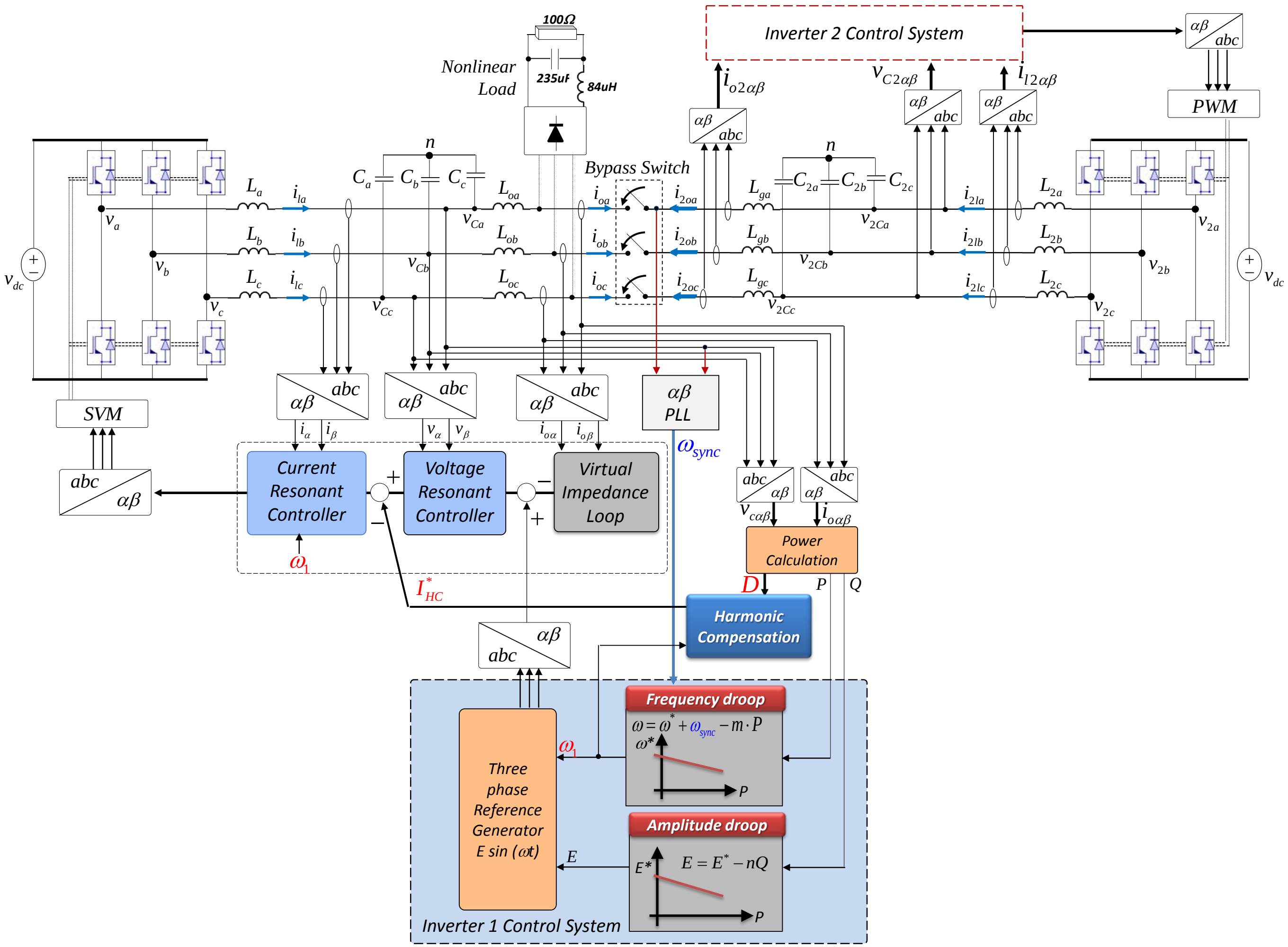
Power Quality in Microgrids

Voltage harmonic reduction by using current harmonics injection



Power Quality in Microgrids

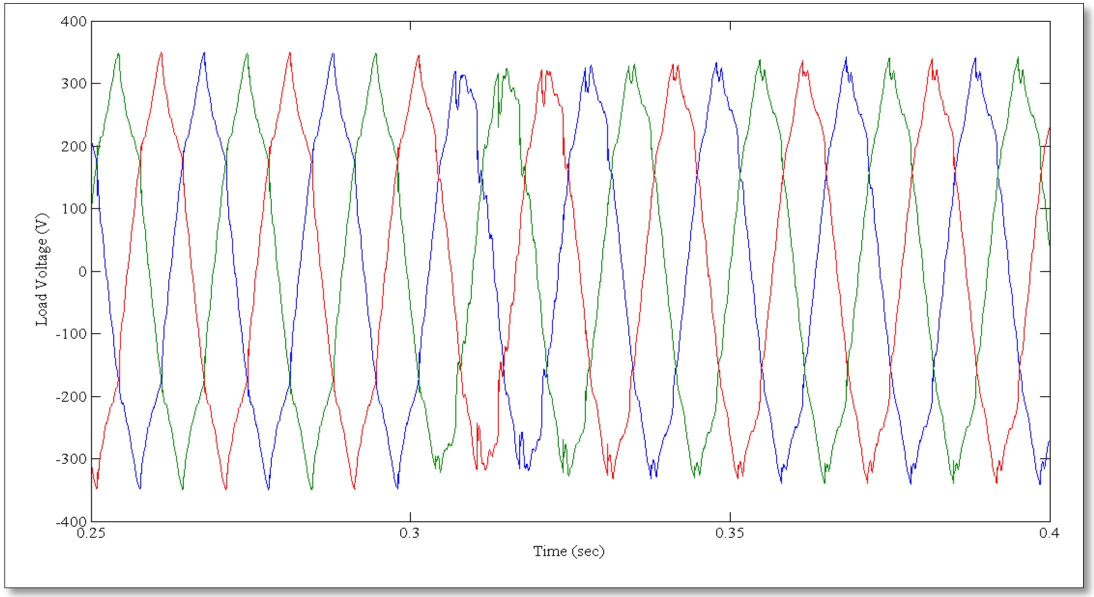
Decentralized voltage harmonic reduction in an islanded microgrid



Power Quality in Microgrids

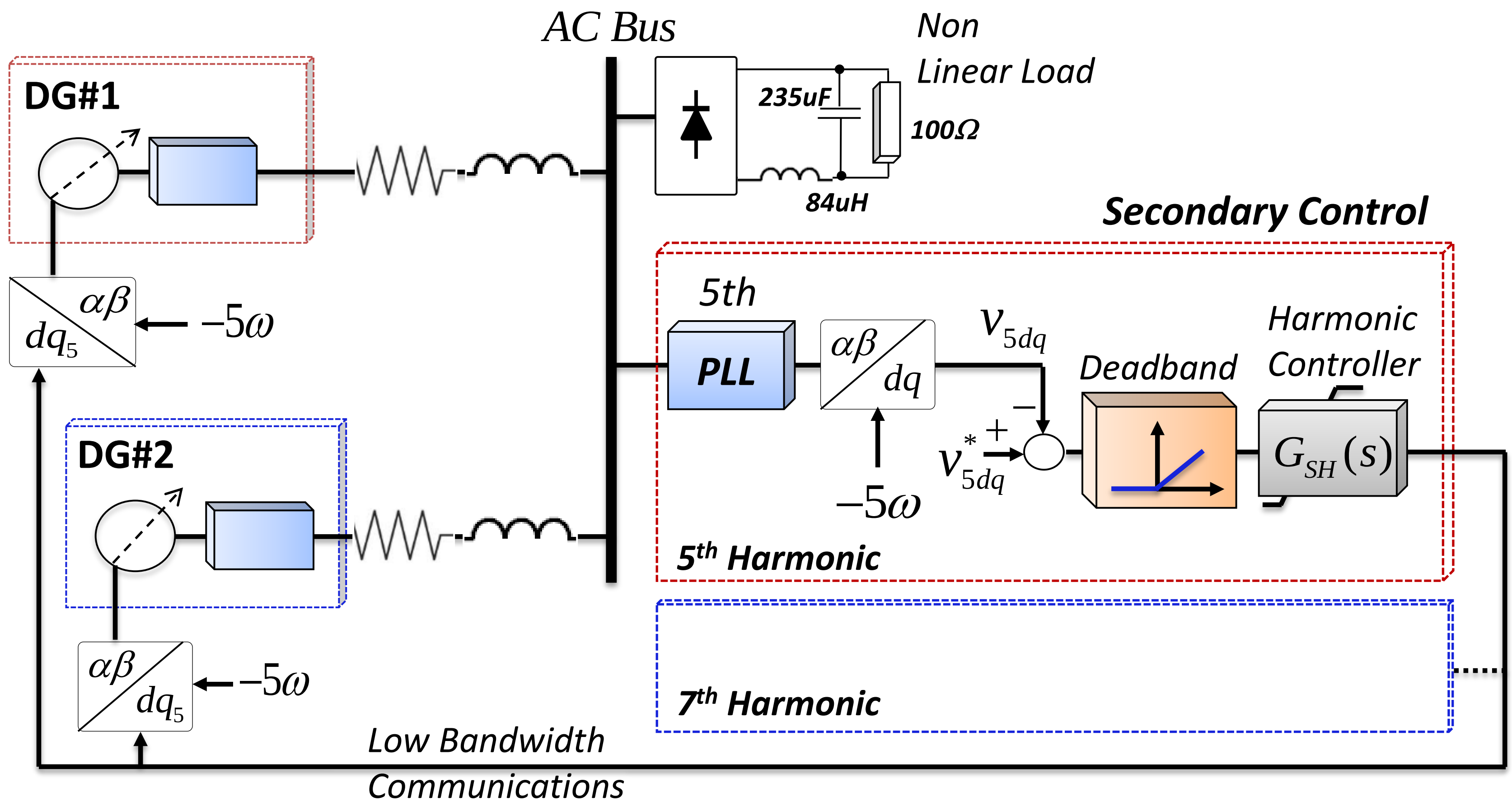
Decentralized voltage harmonic reduction in an islanded microgrid

		Before Compensation			After Compensation		
		THD%	5^{th} %	7^{th} %	THD%	5^{th} %	7^{th} %
Voltage	DG1	3.8	2.9	2.0	1.2	0.6	0.5
	DG2	2.9	2.1	1.5	1.1	0.5	0.4
	Load	5.3	4.2	2.8	3.2	2.3	2.0
Current	DG1	58.6	53.7	22.9	87.6	75.2	44.1
	DG2	45.8	41.5	18.8	44.5	38.1	22.5
	Load	52.2	45.6	20.9	66.1	56.7	33.3



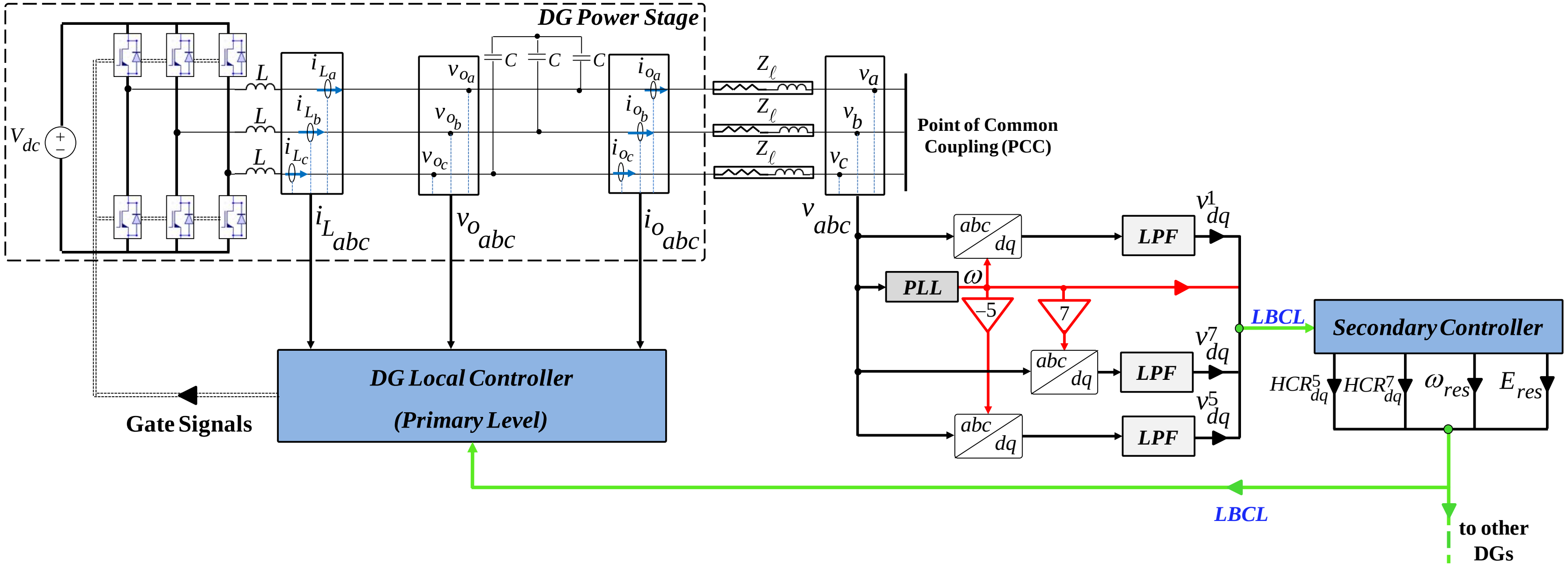
Power Quality in Microgrids

Secondary control for voltage harmonic distribution in islanded microgrids



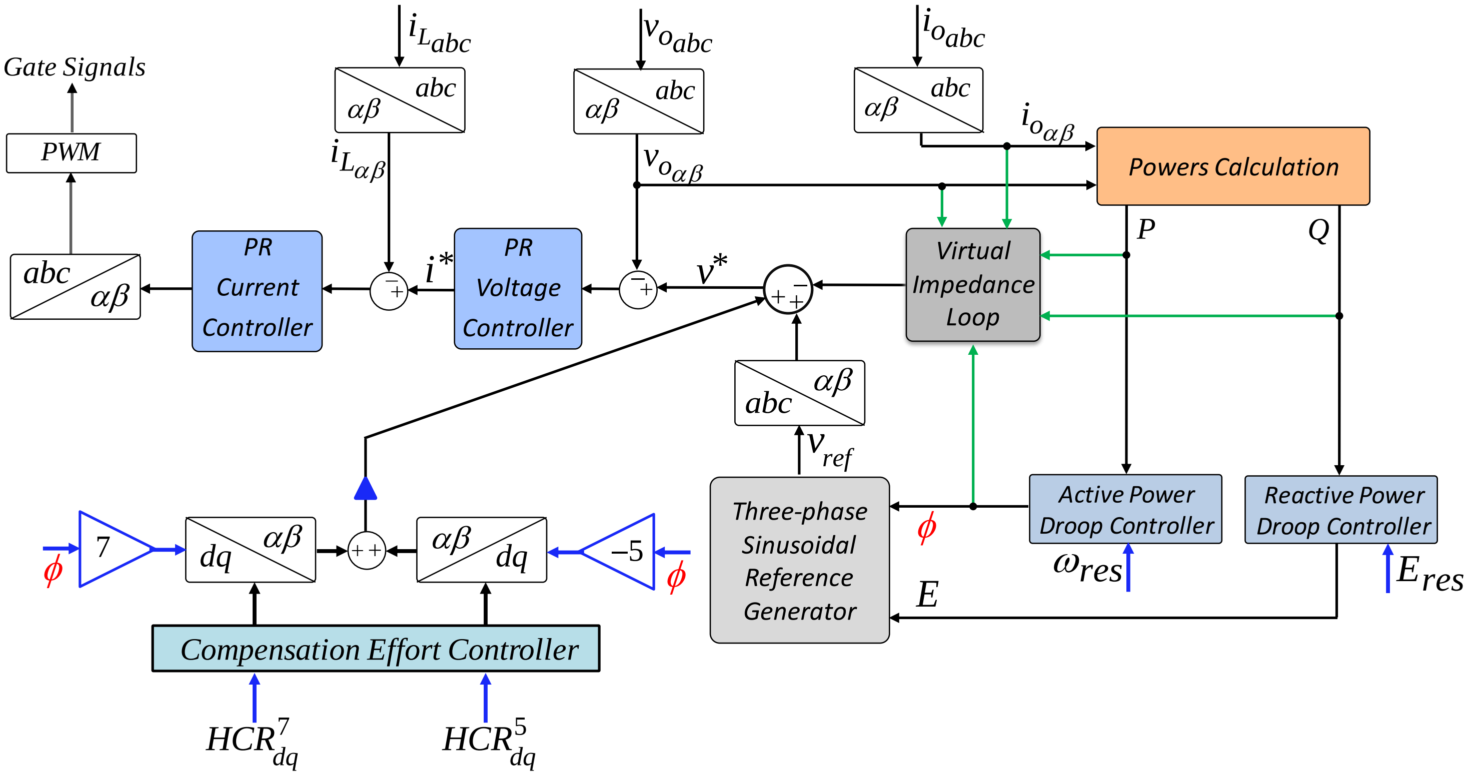
Harmonics in Microgrids

Secondary control for voltage harmonic compensation in islanded Microgrids



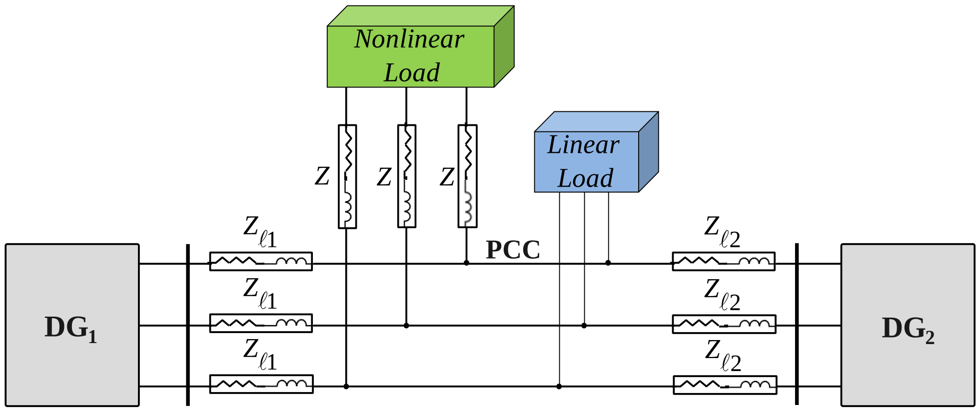
Harmonics in Microgrids

DG local controller (primary level)



Harmonics in Microgrids

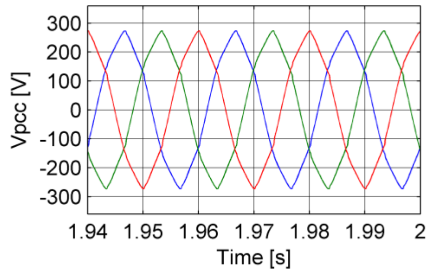
Test system for secondary harmonic compensation



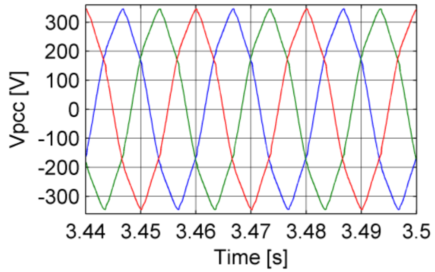
Harmonics in Microgrids

Secondary control for voltage harmonic compensation

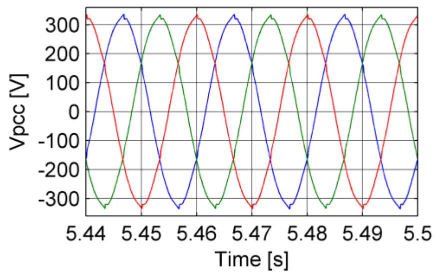
(a) Before amplitude restoration and harmonic compensation



(b) After amplitude restoration (no harmonic compensation)



(c) After amplitude restoration and harmonic compensation



Unbalance in Microgrids

Voltage unbalance definition

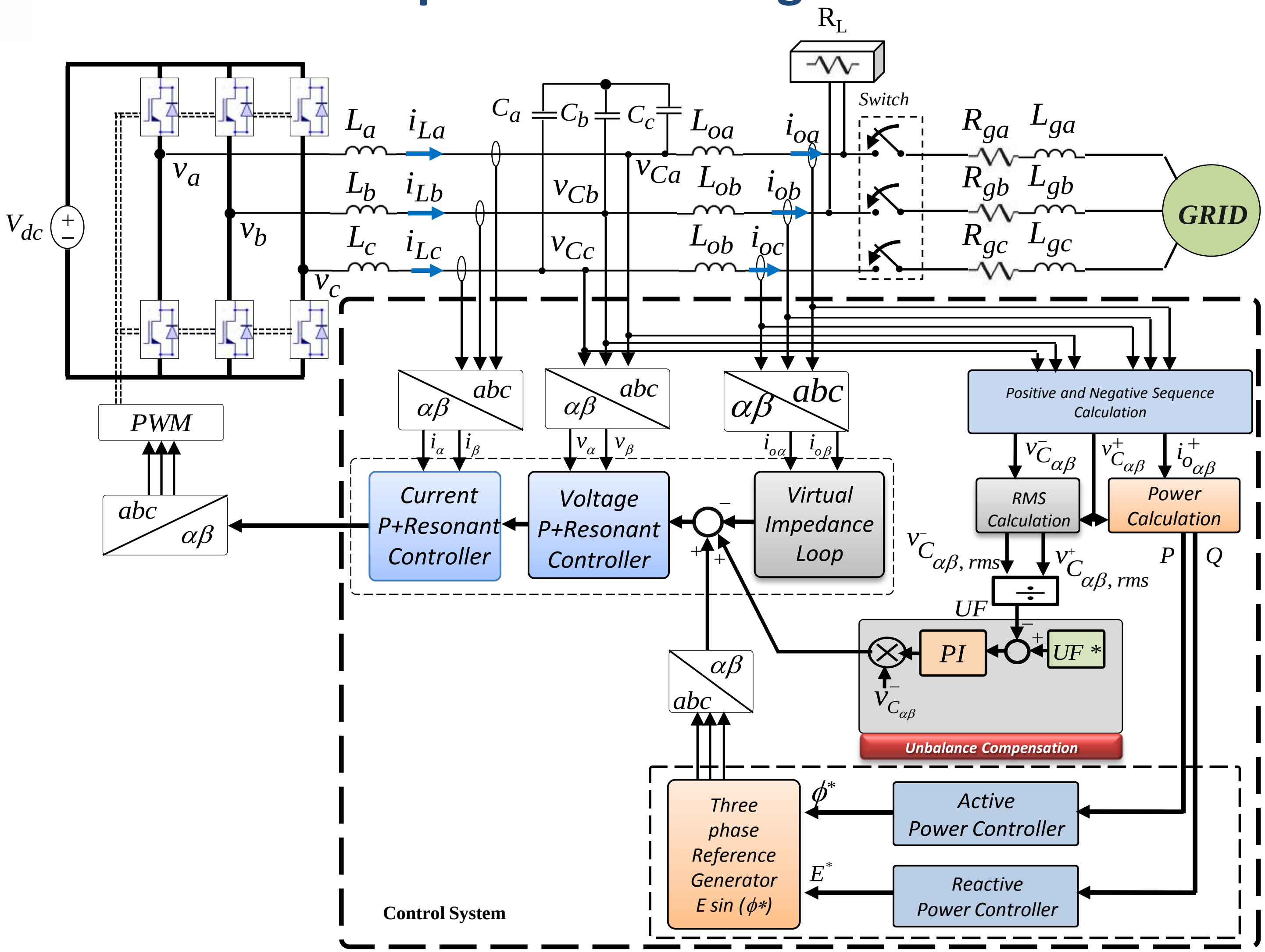
Voltage unbalance factor (*UF*) is considered as the index of unbalance. *UF* can be defined as follows:

$$UF = \frac{v^{-}_{C_{\alpha\beta,rms}}}{v^{+}_{C_{\alpha\beta,rms}}}$$

where $v^{-}_{C_{\alpha\beta,rms}}$ and $v^{+}_{C_{\alpha\beta,rms}}$ are *rms* values of negative and positive sequences of the DG output voltage.

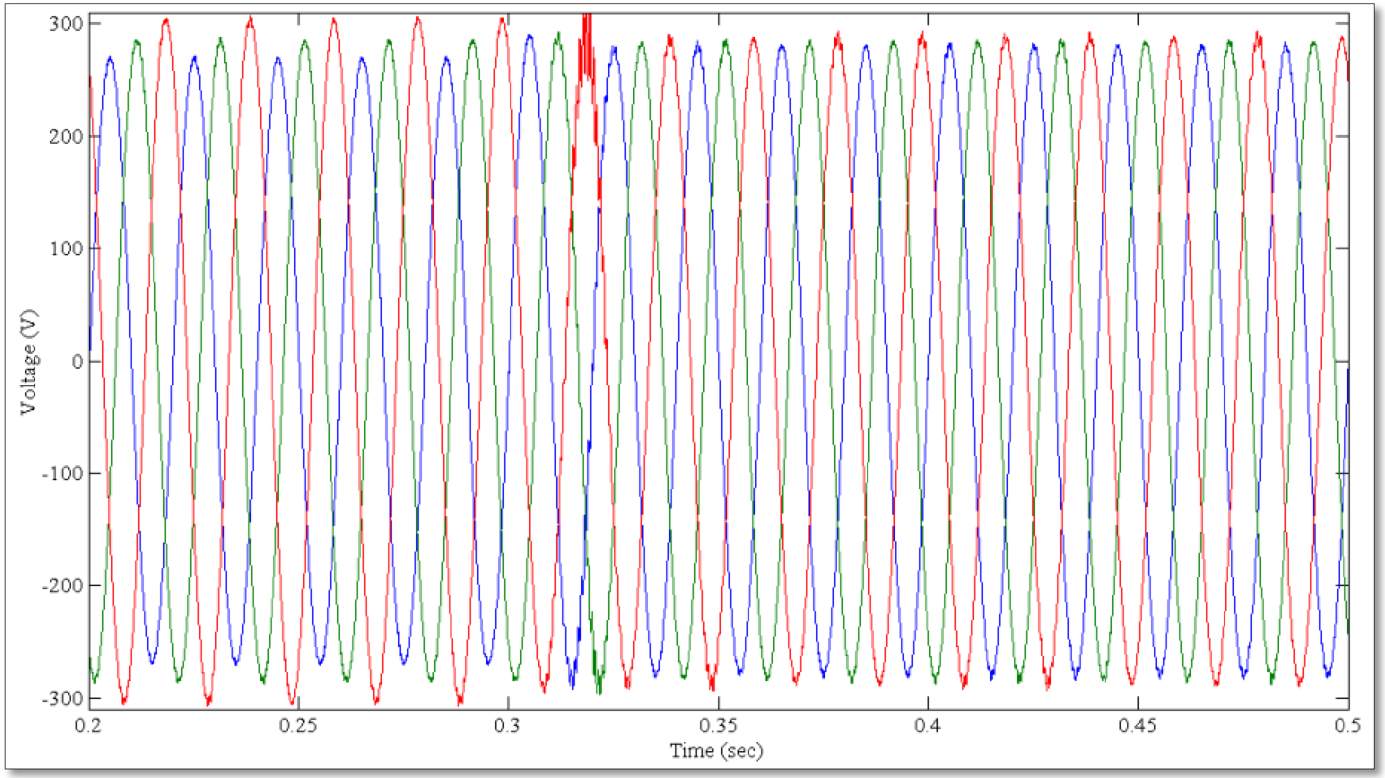
Unbalance in Microgrids

Unbalance compensation for a grid-connected DG



Unbalance in Microgrids

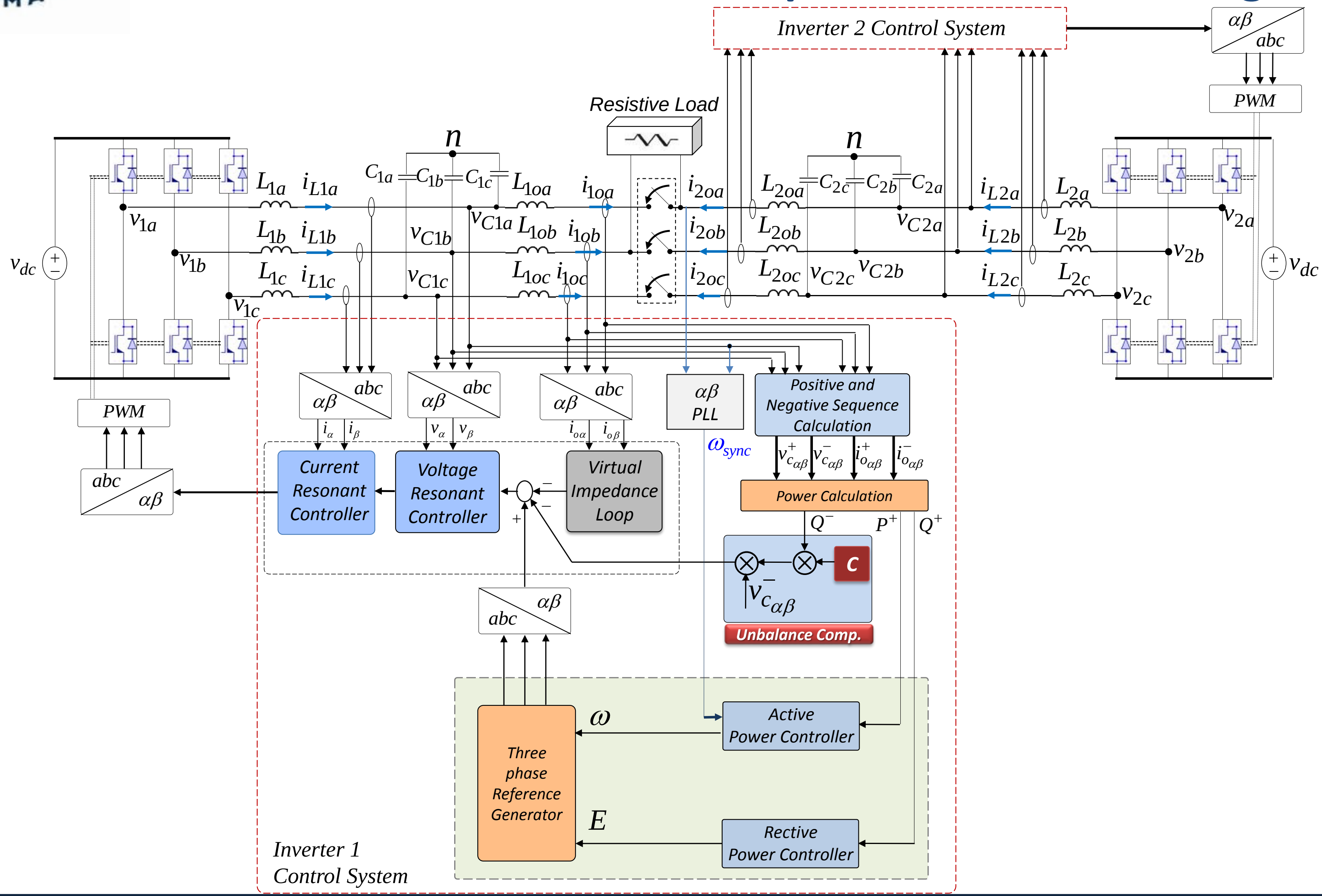
Unbalance compensation for a grid-connected DG



DG output Voltage

Unbalance in Microgrids

Decentralized unbalance compensation for a microgrid

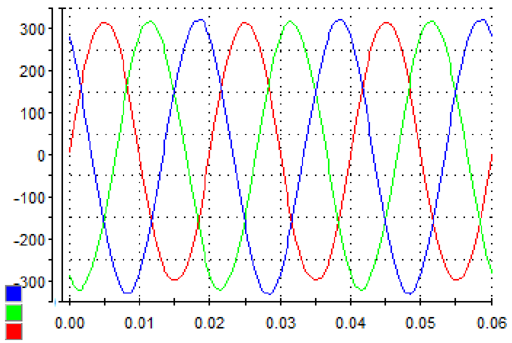


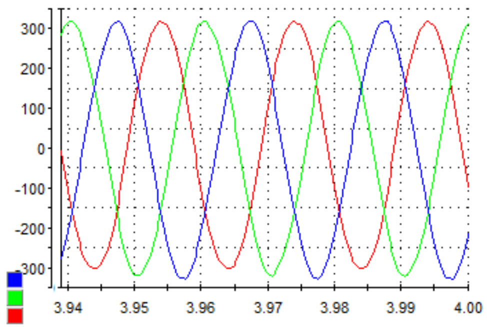
Unbalance in Microgrids

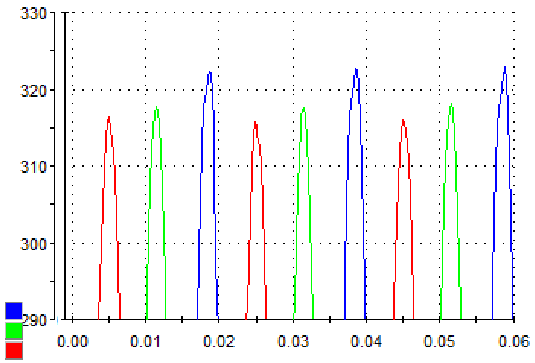
Decentralized unbalance compensation for a microgrid

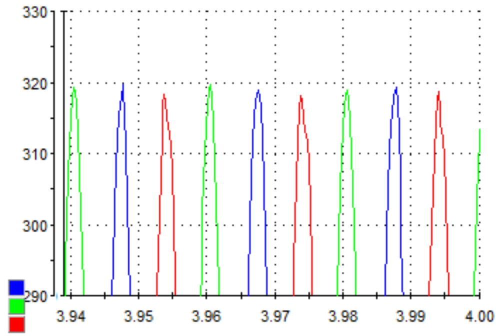
Unsymmetrical line

Voltage after and before compensation



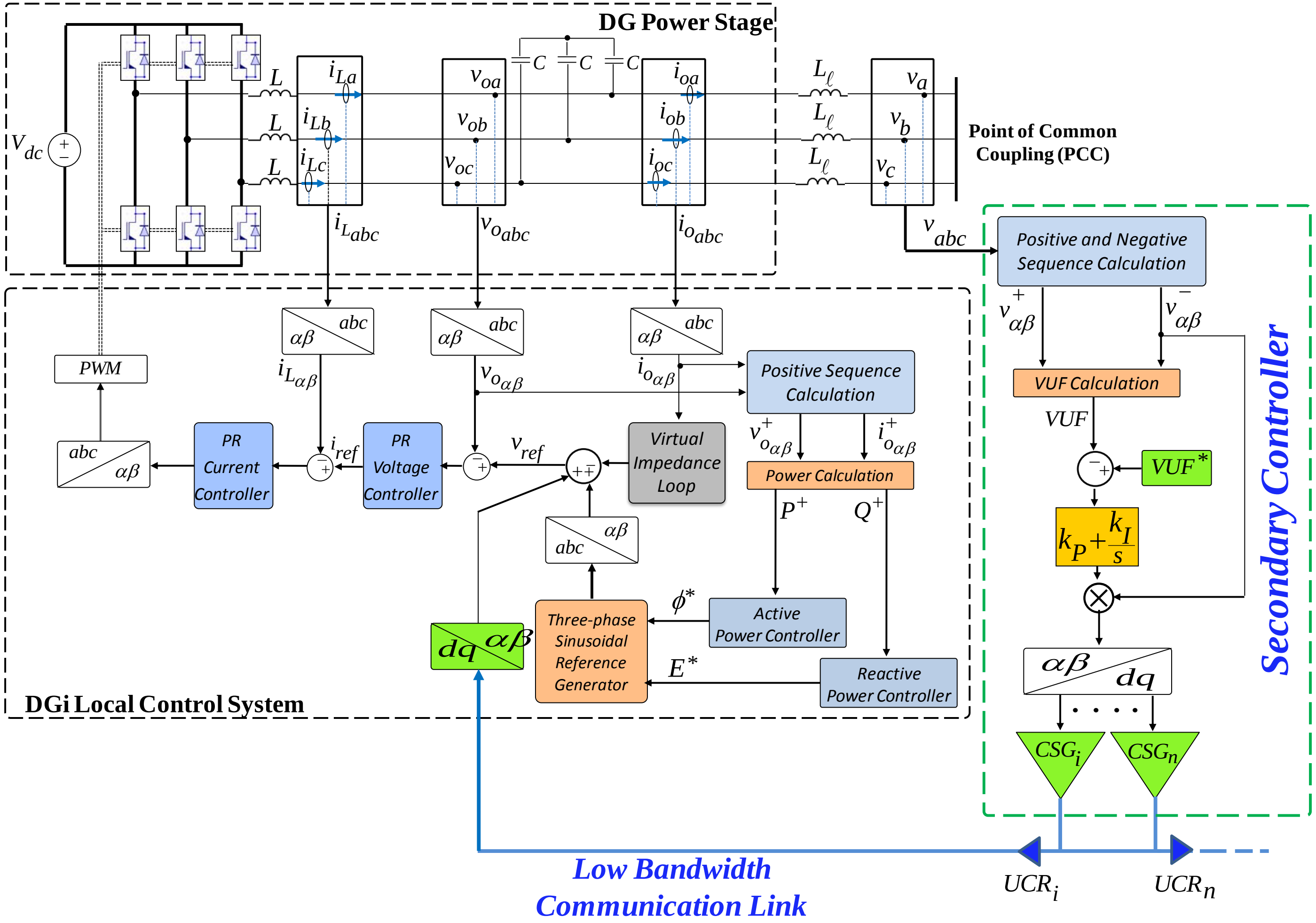




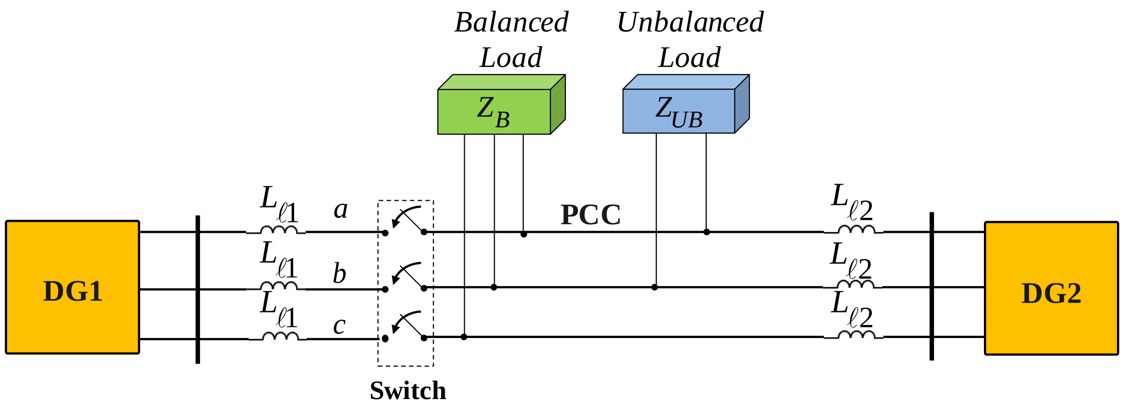


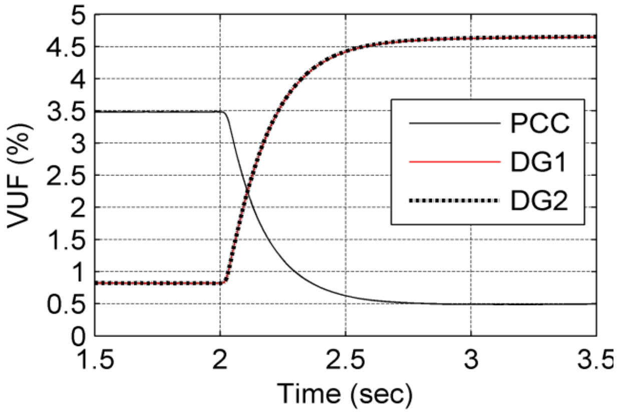
Unbalance in Microgrids

Secondary control for unbalance compensation in islanded Microgrids

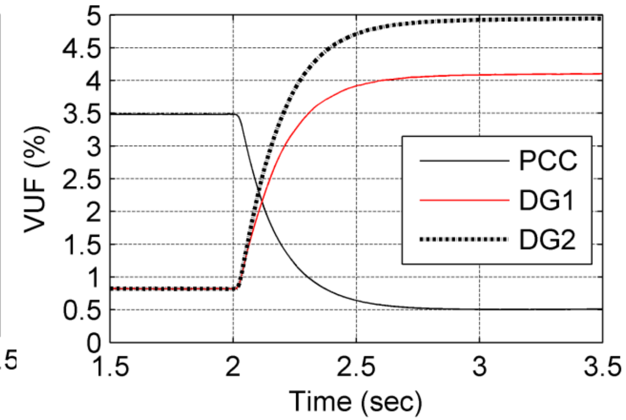


Unbalance in Microgrids

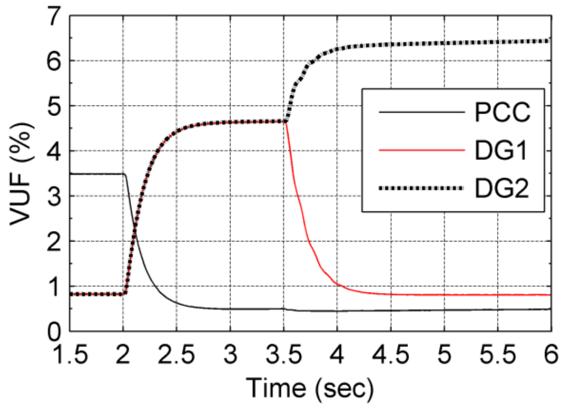




VUF at PCC and DGs terminal (CSG_1=CSG_2=1)



VUF at PCC and DGs terminal (CSG_1=1,CSG_2=1.25)



VUF at PCC and DGs terminal (DG1 communication link failure at t=3.5sec)

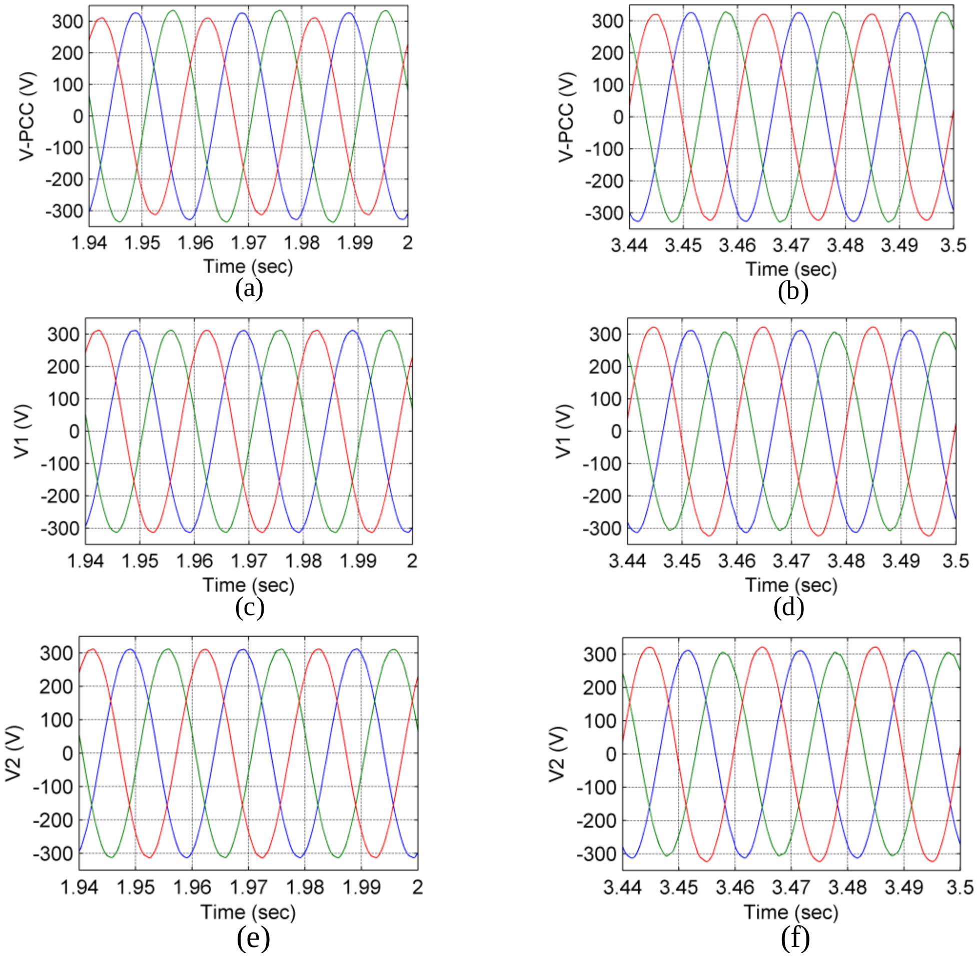
Unbalance in Microgrids

BEFORE COMPENSATION | AFTER COMPENSATION

PCC

DG1

DG2



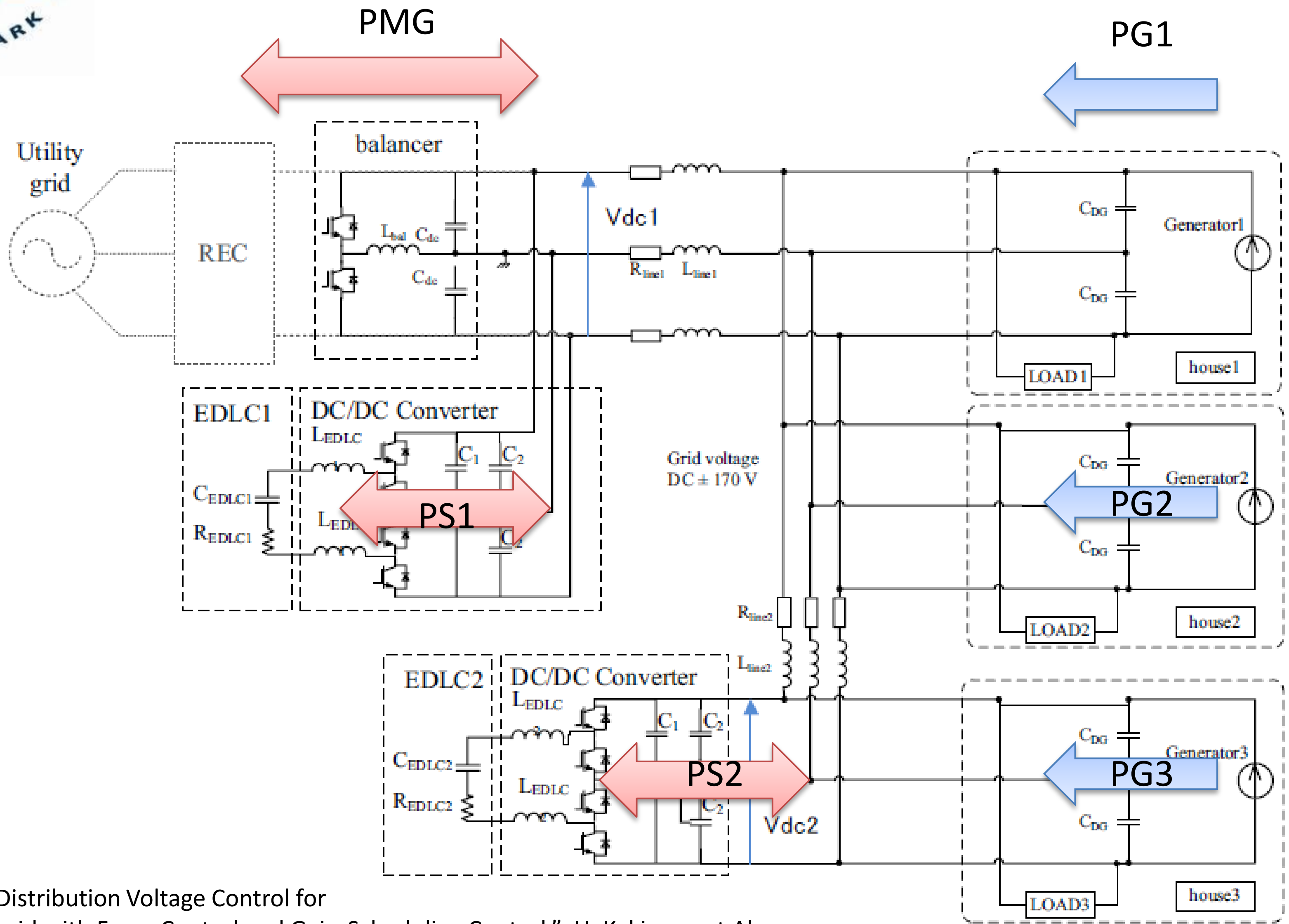
Three-phase voltage waveforms

Power Quality in Microgrids

Conclusions

- Voltage harmonics in microgrids can be reduced by injecting current harmonic or adjusting harmonic voltage in the DG terminals
- Secondary control can be used to close the loop of the harmonic voltage compensation in the microgrid
- Tertiary control can be used to reduce the current harmonics injected by the microgrid to the grid
- A ponderated trade off between the secondary and tertiary controls have to be designed
- Unbalances in microgrids can be reduced by injecting a voltage negative sequence in the DG proportional to Q negative sequence
- Secondary control and tertiary control for unbalance compensation can be used for islanding and grid-connected microgrids.
- Reactive power have to be limited and ponderated for harmonics and unbalance compensation.

Distributed Energy Storage in Microgrids



Source: "Distribution Voltage Control for DC Microgrid with Fuzzy Control and Gain-Scheduling Control," H. Kakigano et Al.

Distributed Energy Storage in Microgrids

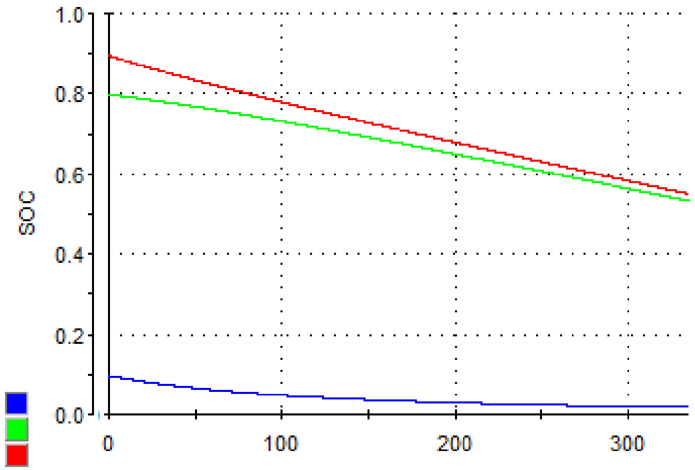
Adaptive droop control:

DC: $V=V^* - (k/SoC)Io$

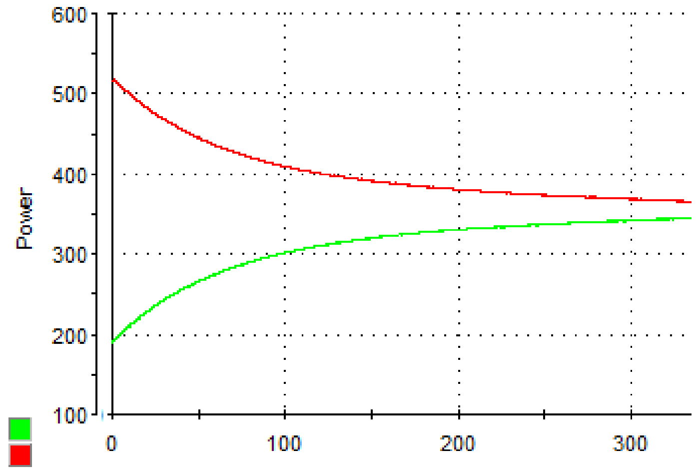
AC: $\omega=\omega^* - (k/SoC)P$

Extended Kalman Fiters are used to obtain the SoC of the batteries.

SOC1 – SOC2



PS1, PS2



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Educational Background	• 1993 ~ 1997. B.Sc Telecommunications Engineer (Technical University of Catalonia, Barcelona) • 1997 ~ 2000. M.Sc Electronic Engineer (Technical University of Catalonia, Barcelona) • 2000 ~ 2003. PhD Power Electronics (Technical University of Catalonia, Barcelona)	
Work Experience	• Feb 1999 ~Aug 2004 Assistant professor (Technical University of Catalonia, Barcelona) • Sept 2004 ~Aug 2008 Lecturer professor (Technical University of Catalonia, Barcelona) • Sept 2008~Present Associate Professor (now part time) (Technical University of Catalonia, Barcelona) • July 2011~Present Full Professor (Aalborg University, Spain)	

Autobiography

Josep M. Guerrero (S'01–M'04–SM'08) was born in Barcelona, Spain, in 1973. He received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, Spain, in 1997, 2000 and 2003, respectively.

He is part time Associate Professor with the Department of Automatic Control Systems and Computer Engineering, Technical University of Catalonia, where he currently teaches courses on FPGAs and control of renewable energy systems. From 2011 he is a Full Professor at the Institute of Energy Technology, Aalborg Universiy, Denmark, and responsible of the Microgrid research program. He has been a visiting Professor at Zhejiang University, China, and University of Cergy-Pontoise, France. His research interests include power electronics converters for distributed generation and distributed energy storage systems, control and management of microgrids and islanded minigrids, and photovoltaic and wind power plants control. He is an associate editor of the IEEE Transactions on Industrial Electronics and IEEE Transactions on Power Electronics. He currently chairs of Renewable Energy Systems Technical Committee of IEEE IES. He is an elected IEEE IES Adcom member.