IECON 2005 Tutorial

“Grid Converters and their Control in Distributed Power Generation Systems”

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Outline of the content of the Tutorial

I. Distributed Power Generation Systems (DPGS) (speaker: Zhe Chen – 30 min)
Energy situation is discussed in respect to past situation and future trends. The need of distributed power generation is justified by both the limitations of fossil fuels in terms of sustainability and pollution and by the stability an reliability problems related to large central power plants (ex. California blackout). Renewable energy technologies are introduced with attention paid to the Kyoto Protocol and to the European Directives. Then distributed power generation systems are introduced and difference sources are briefly addressed with reference to costs and benefits. The energy potential, actual technology, development and economics of PV and WT RES is described. DPGS based on WT and PV require maximum power point trackers (MPPT) in order to maximize the yield of energy at all times.

II. Photovoltaic generation systems (speaker: Marco Liserre – 30 min)
Different power configurations for PV systems are discussed (central inverters, string inverters, module inverters, with/without dc/dc converters, with/without isolation). Different topologies for dc-dc boost converters are reviewed in view of the “max efficiency” criterion. Finally single-phase dc-ac grid inverters are reviewed (standard buck solution and innovative boost solutions). The choice of the position of current and voltage sensors is discussed in case an LCL-filter is adopted for the grid connection. The LCL-filter design is discussed.

III. Control of single-phase PV systems (speaker: Marco Liserre – 45 min)
Different control structures for single-phase PV systems are described and the blocks involved are described in detail. The issue of synchronizing is firstly addressed and different techniques like PLL and filtering are addressed. Then the quality of the current controller is emphasized as a key issue in order to ensure stability and compliance with the new stringent power quality standards like IEE 929. Both classical PI control and new P+Resonant control yielding better performacies and harmonic compensation is discussed. Next, different structures of MPPT are described and practical implementation and obtained performances are shown. Finally, the need of anti-islanding feature is explained as a safety measure for grid-connected PV inverters. The classical solution involves extra hardware. The new trend is to use software anti-island methods which need only some extra functions implemented in the existing DSP and no extra hardware. Practical implementation of an original method using non-characteristic harmonic injection is presented.

IV. Wind power generation systems (speaker: Zhe Chen – 30 min)
The most competitive renewable energy source, wind power, is detailed. The state of the art technologies of various types of wind power systems are presented. The basic power conversion topologies are introduced (fixed speed system and variable speed system). Different power converters, adopted in WT, are reviewed (two-levels and three-levels back-to-back, matrix converter, two-level inverter with boost-rectifier). The operation and control of these systems are discussed, their features are highlighted while the challenges are indicated as well. Furthermore, the requirements of interconnection of wind power systems are introduced, the power and voltage quality issues are addressed. The possible roles that the modern power electronic technology could play in meeting the challenges are discussed.

V. Control of three-phase inverters for wind systems (speaker: Marco Liserre – 45 min)
The use of different current control techniques, especially PI in synchronous frame and P-resonant in stationary frame, will be discussed with attention paid to the possible implementation of harmonic compensation and to the damping of the resonance in case of LCL-filter. The stability of these controllers for a large set of grid impedance values (for PV and WT systems) is discussed. The operation under unbalance condition or during voltage dips is discussed. Finally many synchronization and grid-monitoring algorithms will be reviewed.

All the topics will be discussed with the aid of several experimental results obtained on single-phase and three-phase prototypes present in the laboratories of the Aalborg University and of the Polytechnic of Bari.

Distributed Power Generation Systems (DPGS) and Renewable Energy Sources (RES)

Zhe Chen

Institute of Energy Technology
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Outline

- **Energy situation**
- **Renewable Energy Technologies**
- **Distributed Power Generation Systems**
- **Power Electronic Applications in DG Systems**

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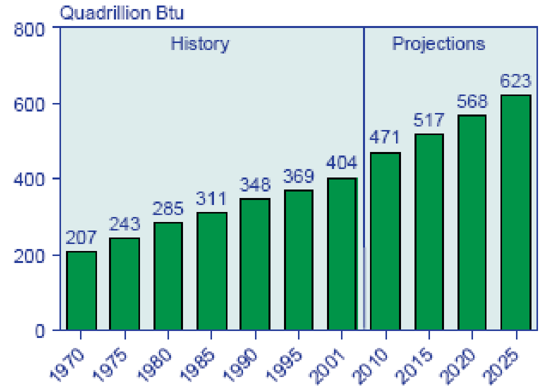
Energy situation:

World Primary Energy Consumption, 1970-2025



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2001*, DOE/EIA-0219(2001) (Washington, DC, February 2003), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2004).

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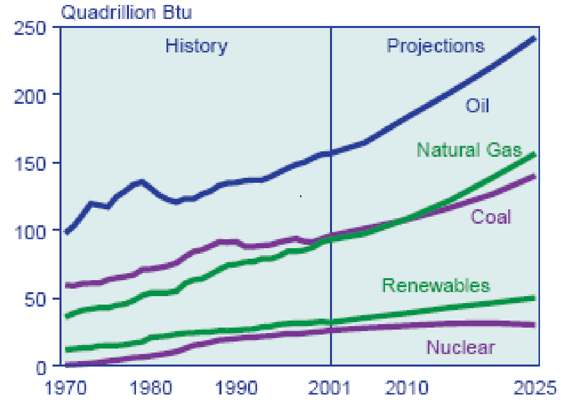
Energy situation:

World Primary Energy Consumption by Energy Source, 1970-2025



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2001*, DOE/EIA-0219(2001) (Washington, DC, February 2003), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2004).

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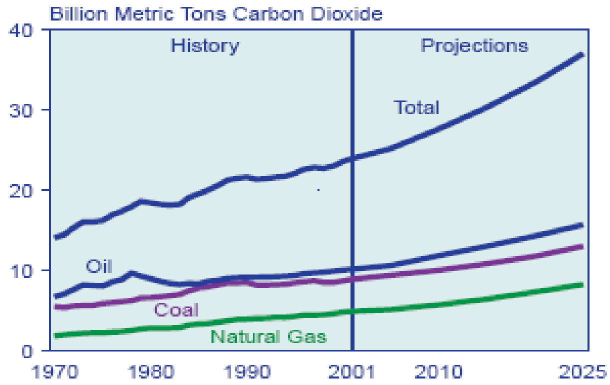
Energy situation:

World Energy-Related Carbon Dioxide Emissions by Fuel Type, 1970-2025



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2001*, DOE/EIA-0219(2001) (Washington, DC, February 2003), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2004).

Future energy systems:

Clean, sustainable, highly efficient and reliable

Solutions:

- **Energy efficiency**
- **Renewable energy**

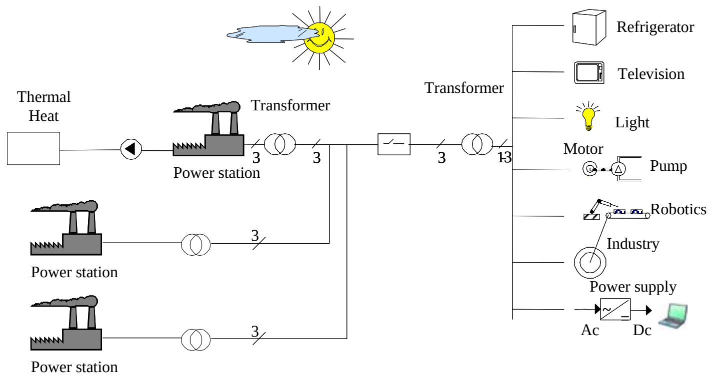
Background for DG Development

- Energy market deregulation
- Increase of Distributed Resources: Renewable Energy Source (RES) and other DG sources
- International agreements
  - Kyoto Protocol to reduce the Greenhouse effect gazes
  - European Directives to insert RES : 22% for 2010
- Obstacles to build new electric lines
- Last blackouts in the world
  - USA: August 2003 / Italy: September 2003 / Denmark &Sweden: September 2003
  - Need to maintain power quality, robustness

Conventional Central Utility

Classic System

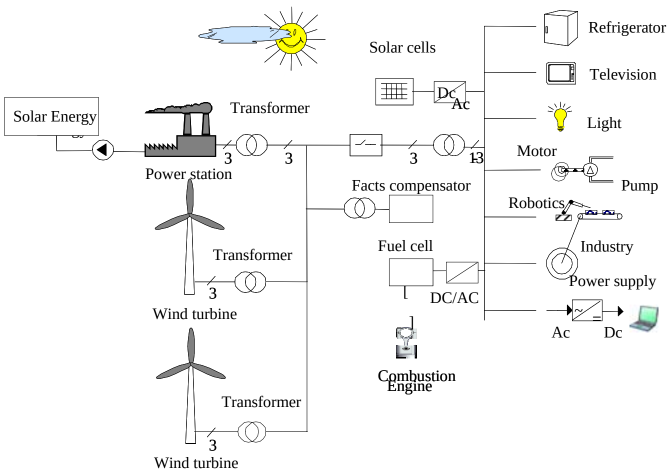
Customers



Distributed Generation (DG) Description

- Relatively small generating units and storage technologies
- Provide electric capacity and/or energy at or near consumer sites to meet specific customer needs
- Either be interconnected with the electric grid or isolated from the grid in "stand- alone"
- The location value is important to the economics and operation.

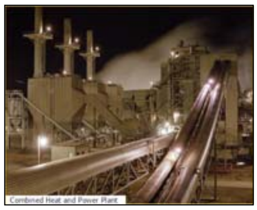
Distributed Generation System

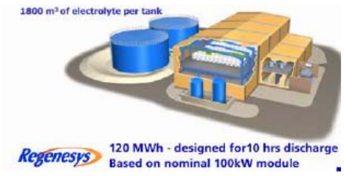


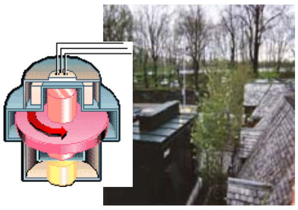
Distributed Generation (DG)

Various existing DG:

Windmills, CHP (Combined Heat and Power), PV panels, Fuel cells, energy storage systems,…

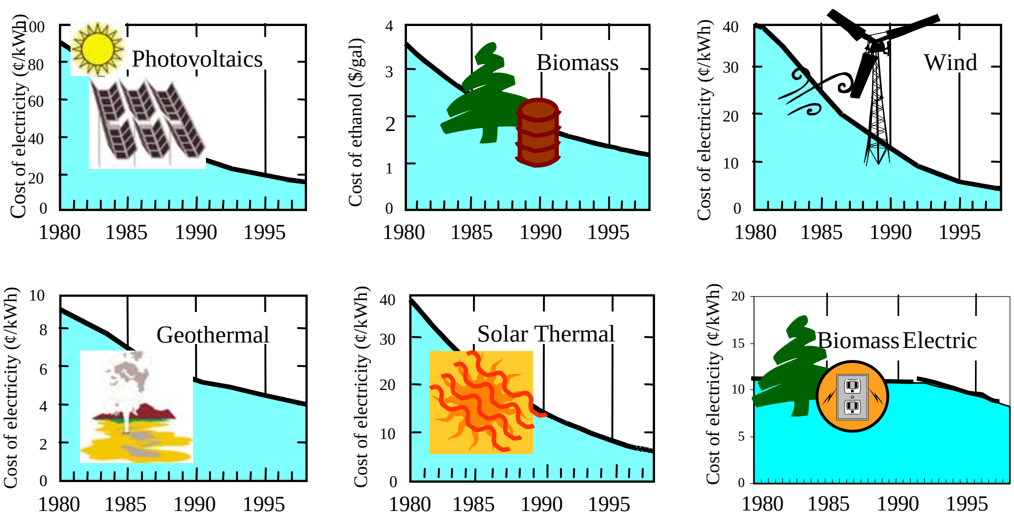






The cost of renewable generation

Historic Cost Curves



Source: Billman, Advances in Solar Energy submission, 1/8/99

DG Applications

- ***Emergency generation*** **-** historical application. Concern over changing profile.
- ***Combined Heat and Power*** **-** common practice by large industrials; large untapped potential in small industrial and commercial establishments
- ***Peaking*** **-** potential growth market for customer peak shaving (500 to 2000 hours/year) by light industrial and commercial
- ***Premium Power*** **-** emerging market to provide quality power to sensitive customers

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Benefits of Distributed Generation

- Load management
- Power quality
- Fuel flexibility
- Cogeneration
- Enhanced voltage stability and reduced line losses
- Deferred or reduced T&D investment or charge
- Potential of improving distribution grid reliability/stability

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Renewable Energy Sources

Wind

Small Hydro

Biomass

Tidal

Wave

Solar energy
photovoltaic

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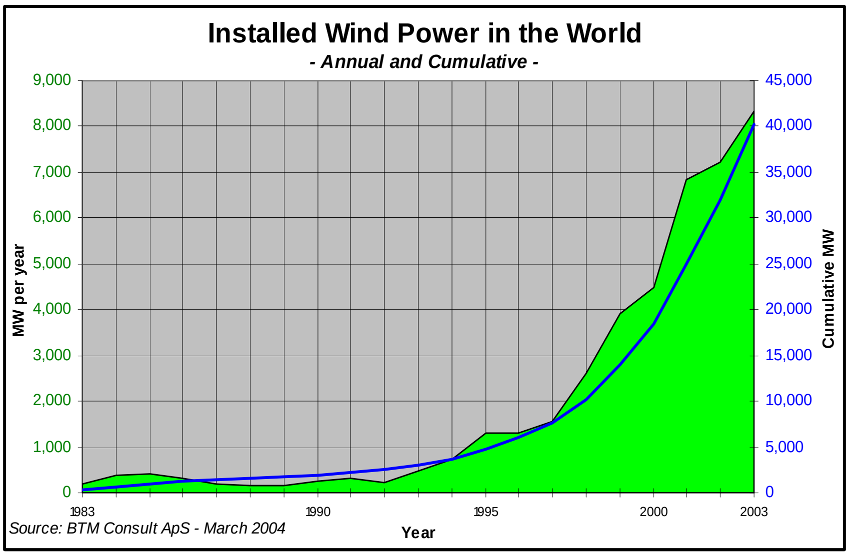
Wind Energy Development

Wind Energy Development



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Wind Energy Development

Plans for Wind Power in Some European Countries

Country	Wind power in 2001 (MW)	Goal in 2010 (MW)
Germany	8.700	22.000
Netherlands	520	2.500
Italy	400	2.500
Spain	3.500	9.000
Norway	17	1.000
UK	520	6.000
France	110	5.000
Denmark	2.500	3.500 (estimate)

(Source: Risø National Laboratory, Denmark)

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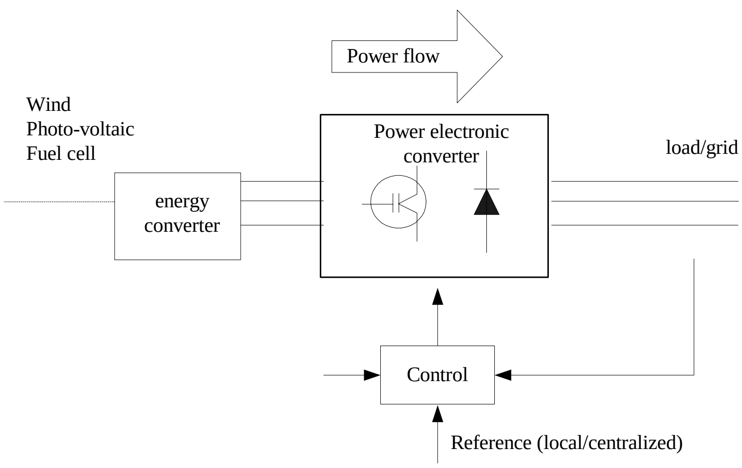
Power electronics: enabling technology



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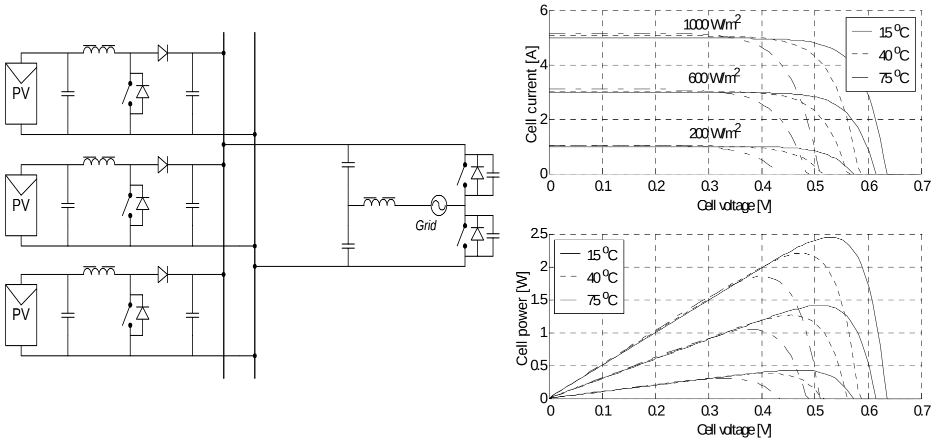
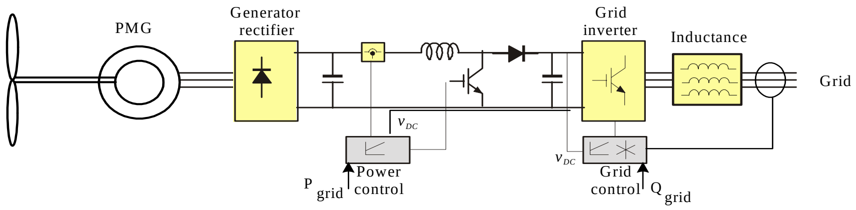
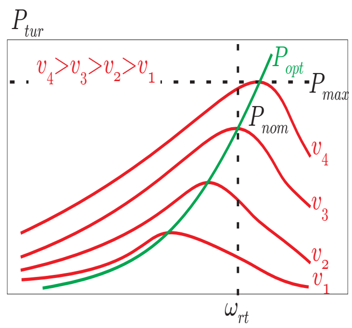
An Example of a Power Electronic Interfacing PV system



Topology of a multi-string inverter power electronics for PV system (Maximum power per string 2200 W at 150 V ~ 750 V)

An example of a power electronic interfacing wind turbine system

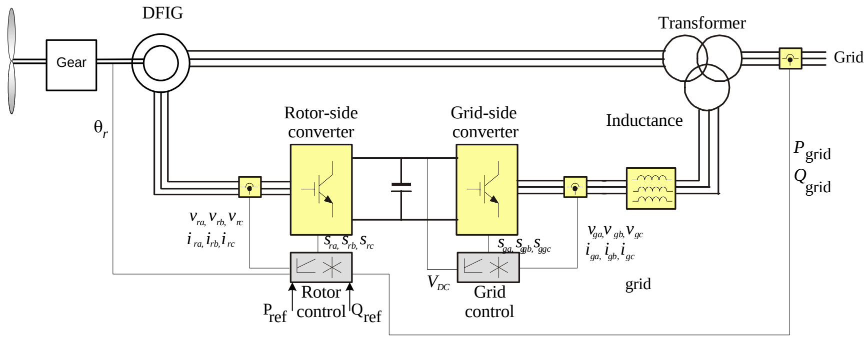




- **Full speed range**
- **Possible to avoid gear (multi-pole generator)**
- **Complete control of active and reactive power**
- **Full scale power converter**
- **Multi-pole generator big and heavy**

Power electronic control of a wind turbine

Doubly-fed induction generator system



- ➢Limited speed range (-50% to +30% around synchronous speed)
- ➢Small-scale power converter (Less power losses, lower price)
- ➢Complete control of active P_{ref} and reactive power Q_{ref}
- ➢Need for slip-rings and gear

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Lab-facilities at AAU

- 2.75 MW DFIG
- Access to system
- Equipped with sensing equipment
- 6 km from Campus

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Photovoltaic generation systems

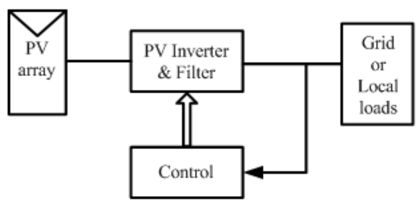
By Remus Teodorescu, Aalborg University and Marco Liserre, Polytechnic of Bari

Agenda

- **Power configuration for PV systems**
- Topologies for dc-dc boost converters
- Single-phase dc-ac grid inverters

PV array

- Can be configured in several strings in parallel (multi-string) or single-string
- In multi-string configuration, the orientation of the strings can be different. It is like several generators in parallel!
- In single-string configuration higher dc-voltage is obtained making the boost converter not necessary. It yelds lower power capture due to partial shading.



PV Inverter and Filter

- The PV inverter can include a dc-dc boost converter, a dc-ac converter and a smoothing filter L or LCL type for connection to the grid.

Control

- Can include: control of dc-dc converter, control of dc-ac converter, grid monitoring (PLL), anti-islanding protection, etc

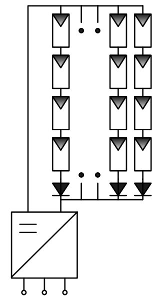
Grid

- The power generated by the PV array is transferred to the utillity grid.
- In stand-alone systems, the power is transferred directly to local loads

PV array configurations

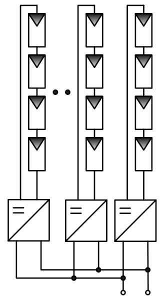
Central inverters

- >10 kW, three-phase, several strings in parallel
- high efficiency, low cost, low reliability, not optimal MPPT



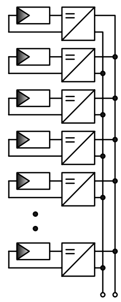
String inverters

- 1.5 . 5 kW, typical residential application
- each string has its own inverter enabling better MPPT
- the strings can have different orientations (practical!)

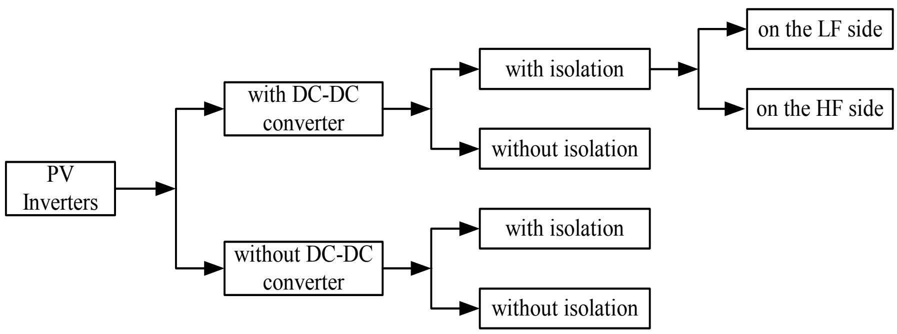


Module inverters

- 50-400W, each panel has its own inverter enabling optimal MPPT
- lower efficiency, difficult maintenance



The issues of dc-dc boost converter and isolation!



- The question of having a dc-dc converter or not is first of all related to the PV string configuration. It is possible to avoid the boost function of the dc-dc converter by using more panels in series or by having a lower grid voltage, like in US or Japan.Thus a single stage PV inverter can be used leading to higher efficiency in those cases.
- The issue of isolation from the mains is mainly related to safety standards and is for the moment only required in US. The drawback of having more panels in series is that MPPT is harder to achieve especially during partial shading

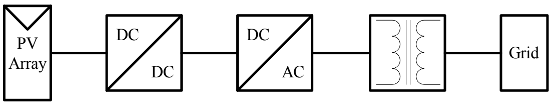
Agenda

- Power configuration for PV systems
- **Topologies for dc-dc boost converters**
- Single-phase dc-ac grid inverters

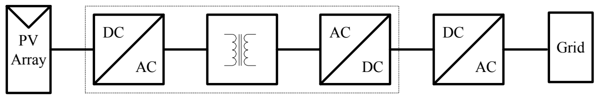
Need of boost converter

- In DPGS with PV or Fuel Cells, the dc voltage is typically much lower than the grid voltage and thus a boost is required
- Depending on boost factor and optimization criteria, different topologies can achieve the best results
- In the following, we consider "max efficiency" as optimization criteria and we consider three isolated topologies:
  - Full-bridge isolated boost dc-dc converter (FB) [1]
  - Single-inductor boost push-pull converter (SIC) [2]
  - Dual-inductor boost push-pull converter (DIC) [2]

PV inverters with dc-dc converter and isolation

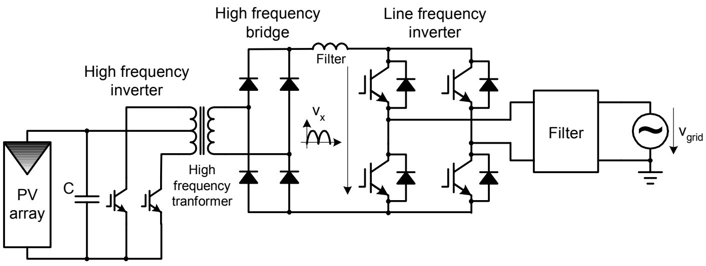


on low frequency (LF) side



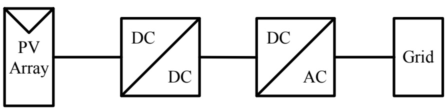
on high frequency (HF) side

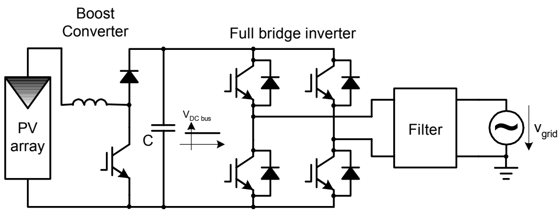
• The HF transformer leads to more compact solution but complex design



• Typical solution with push-pull dc-dc converter with HF transformer and PWM full-bridge inverter with filter

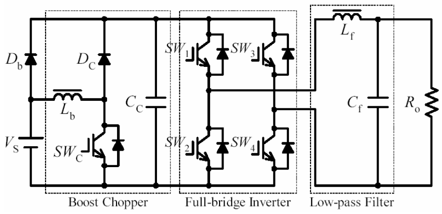
PV inverters with dc-dc converter without isolation

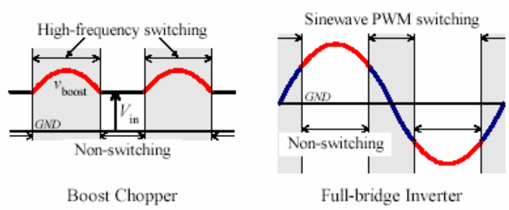




Typical example with boost dc-dc converter and PWM full-bridge inverter

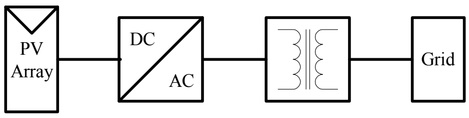
Care should be taken for the leakage (earth) current that can pose safety problems when touchint the panels on the roof

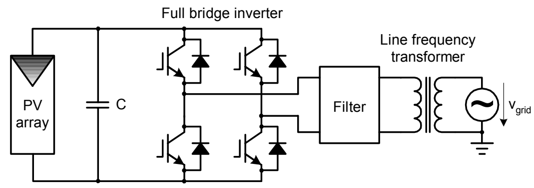




Time-sharing solution using sine-wave boost chopper with a new functional diode Db and sine-wave PWM inverter working on shifts. The boost is boosting only when the required output voltage is higher than the input voltage and the inverter is running only when the required output voltage is lower than the input voltage. High efficiency >96%

PV inverters without dc-dc converter with isolation

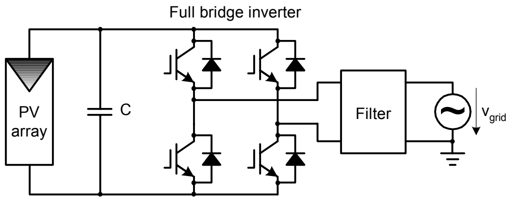


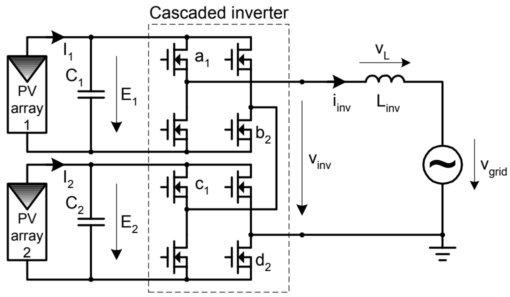


Typical example with PWM full-bridge inverter and LF trafo

Are used for high power systems where the number of panel is high enough to produce the required input dc voltage (min grid voltage peak!) at any time

• PV inverters without dc-dc converter without isolation





Typical solution with full-bridge inverter

Multi-level solution for lower dc voltage input

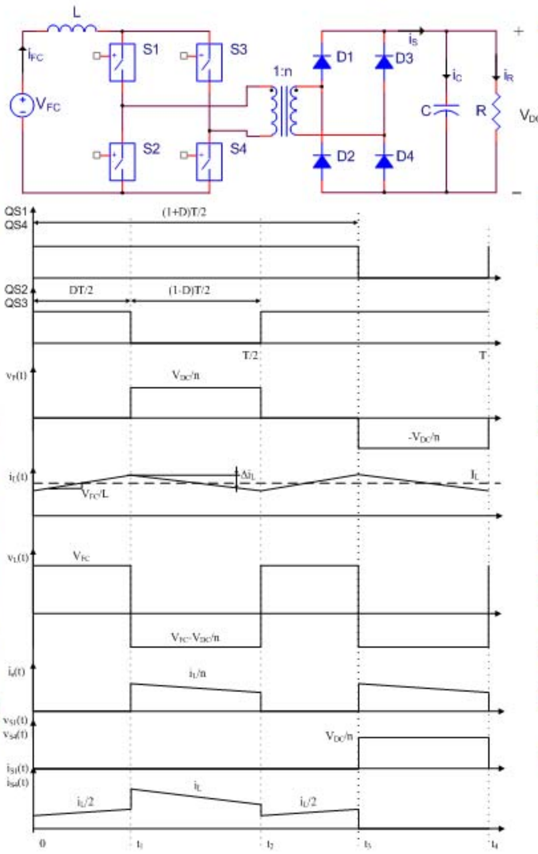
Conclusions

- There is a large variety of power configurations for single-phase PV systems mainly dependent on power level and isolation requirements
- Dual stage ropologies are currently employed on the market for residential applications (up to 4.5kW)
- Transformerless (single-stage) topologies are becoming more and more intresting as they have a potential for improving the efficiency especially in the countries where isolation is not required (Japan, Germany, etc)
- More research is needed to be done in order to minimize the leakeage current and ensure safety and panels reliability with transformerless topologies

References

[1] Ciobotaru,M., Teodorescu,R., Blaabjerg,B., "Overview and Improved Control Strategy of the Grid-Connected Single-Phase PV Inverter Systems" – IEEE Transactions on IE, 2005 [publishing in progress]

Full bridge isolated dc-dc boost converter



The steady-state transfer ratio:

$$\frac{V_{DC}}{V_{FC}} = \frac{n}{1-D}; \quad \frac{I_R}{I_{FC}} = \frac{1-D}{n}; \quad I_{FC} = I_L$$

D is controlling the output voltage. The input current ripple: $\Delta I_L = D \cdot \frac{V_{FC}}{2Lf_L}, \Delta I_L = \Delta I_{FC}$

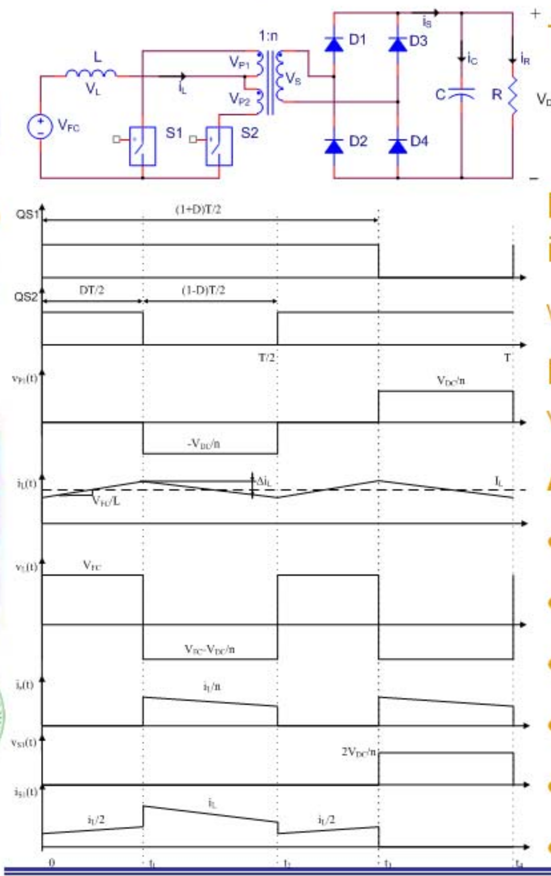
where $f_L = 2f_s, f_s = \frac{1}{T}$

Is usually utilized at above 750W with high input dc-voltages e.g. PV inverters

Advantages:

- good transformer utilization – bipolar magnetization of the core
- good performance with current programmed control
- **Disadvantages**: high part count

Single inductor boost push-pull converter (SIC)



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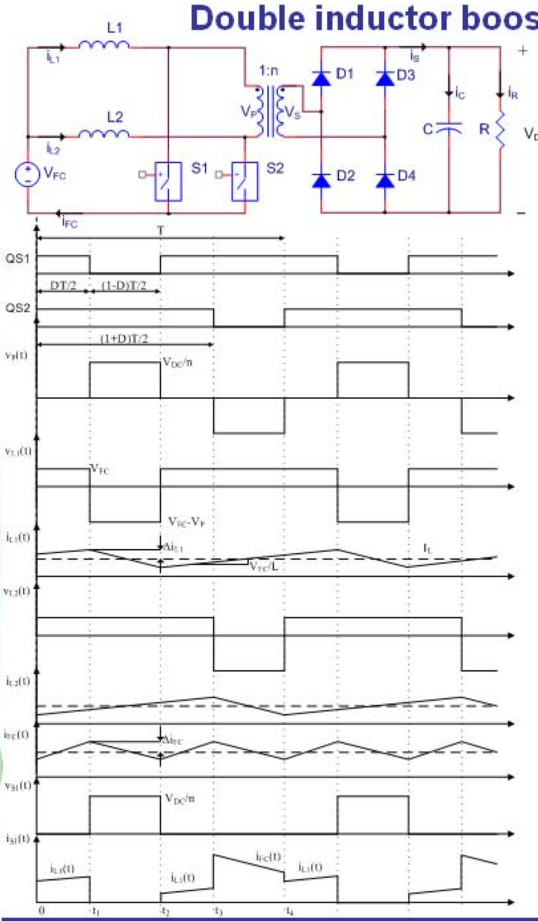
where $f_L = 2f_s, f_s = \frac{1}{T}$

Is usually utilized with low input dc-voltages e.g. Fuel-Cells converter

Advantages:

- high efficiency capability
- good transformer utilization
- smooth input current
- **Disadvantages**:
- high blocking voltage for the switches
- difficult transformer construction (tap)

Double inductor boost push-pull converter (DIC)



The steady-state transfer ratio:

$$\frac{V_{DC}}{V_{FC}} = \frac{2n}{1-D}; \quad \frac{I_R}{I_{FC}} = \frac{1-D}{2n}$$

D is controlling the output voltage. The input current ripple: $\Delta I_{FC} = D \cdot \frac{V_{FC}}{2 L f_L}$

where $f_L = f_s, f_s = \frac{1}{T}$

Is usually utilized at above 750W with low input dc-voltages e.g. Fuel-Cells converters.

Aditional advantages vs. SIC:

- simpler transformer
- lower ripple in input current
- lower voltage across the switches [6]
- lower inductor switching frequency
- **Disadvantages**: Two input inductors

Comparison of dc-dc converters

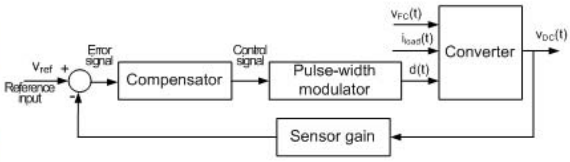
Parameter	Full-Bridge	SIC	DIC
Number of switches	4	2	2
Number of Boost Inductor	1	1	2
Transformer	1 primary coil	2 primary coils	1 primary coil
Switch peak voltage	V_{DC}/n	$2*V_{DC}/n$	V_{DC}/n
Switch rms current			
Boost inductor current	I_{FC}	I_{FC}	$I_{FC}/2$
Inductor current ripple frequency	$2f_S$	$2f_S$	f_S
Trafo peak volt- ampere	$(V_{DC}/n)*I_{FC}$	$(V_{DC}/n)*I_{FC}$	$(V_{DC}/n)*I_{FC}/2$
Duty-cycle	0.69	0.69	0.38

Loss types	Full-Bridge	SIC	DIC
P_{SW}, switch	1	~1	~0.5
P_C, switch	1	~0.5	~0.61
P_{COPPER}, transf	1	~1	~0.5
P_{CORE}, transf	1	~1	~1
P_{COPPER}, inductor	1	~1	~0.64
P_{CORE}, inductor	1	~1	~2.65

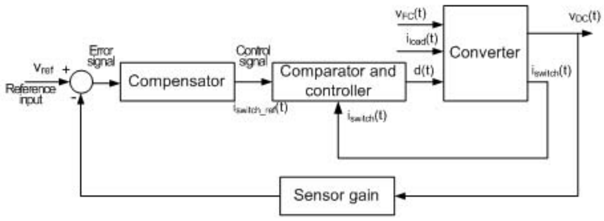
DIC - lowest losses, suitable for low voltage input voltages (MOSFET)

FB – uses standard H modules, suitable for higher input voltages (IGBT)

Control strategies for dc-dc converters



Duty-cycle control



Current control (peak current)

Advantages of Current control vs. Duty-cycle control

- Better dynamics
- Better protection to overcurrent
- Reduction of transformer saturation
- Allows modular design (current sharing)

Disdvantages of Current control vs. Duty-cycle control

- Susceptibility to noise
- Unstable for duty-cycle larger than 50%

Conclusions

- Three isolated dc-dc boost converter topologies have been analyzed and compared considering "max efficiency" as optimization criteria
- The Full-Bridge isolated dc-dc converter (FB) is advantageous as it uses the same power stage as the grid inverter (proven technology) and it is more suitable for applications with higher input voltages (PV)
- Push-pull dc-dc converters are more suitable for applications with low input voltage (FC) and the topology with dual-inductor (DIC) yelds in slightly higher efficiency as single-inductor topology (SIC)

References

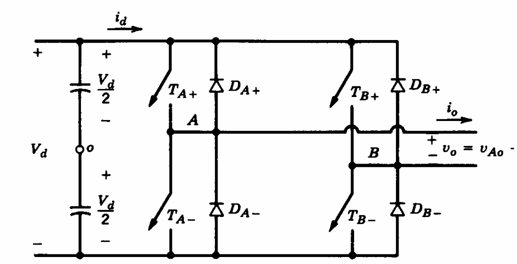
[1] Mohan, N., Undeland, T., Robbins, P.W., *Power Electronics. Converters , Applications and Design.*, John Wiley & Sons, 2003, ISBN:0471226939

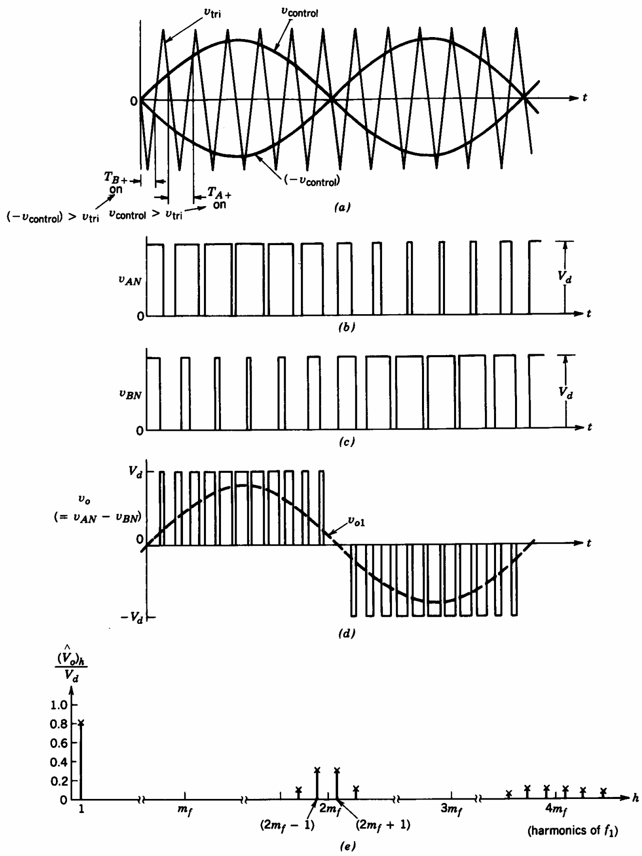
[2] De Aragao Filho, W.C.P.; Barbi, I. "A comparison between two current-fed push-pull DC-DC converters-analysis, design and experimentation" Telecommunications Energy Conference, 1996. INTELEC '96., 18th International 6-10 Oct. 1996 Page(s):313 - 320

Agenda

- Power configuration for PV systems
- Topologies for dc-dc boost converters
- **<u>Single-phase dc-ac grid inverters</u>**

Single-phase full-bridge dc-ac inverter with unipolar PWM [1]

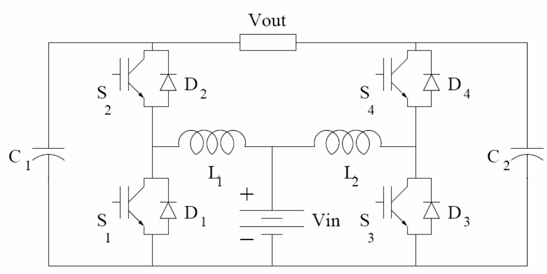




Consists of two inverter legs

Harmonic components around the switching frequency are absent

New step-up inverter



$$\frac{V_1}{V_{in}} = \frac{1}{1-D}$$

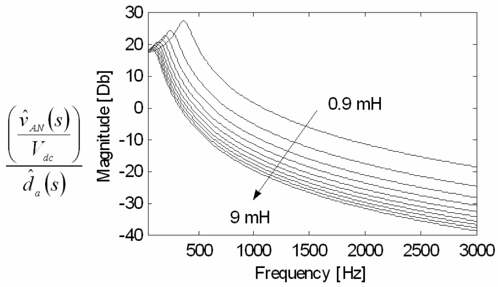
$$V_{out} = V_1 - V_2 = \frac{V_{in}}{1-D} - \frac{V_{in}}{D} \Longrightarrow \frac{V_{out}}{V_{in}} = \frac{2D-1}{D(1-D)}$$

$$v_1(t) = V_{DC} + V_M \sin(\omega t)$$

$$v_2(t) = V_{DC} - V_M \sin(\omega t)$$

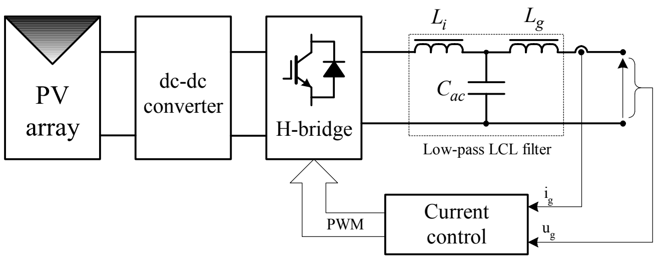
$$v_{out}(t) = v_1(t) - v_2(t) = 2V_M \sin(\omega t)$$

$$\frac{\hat{v}_{AN}(s)}{\hat{d}_a(s)} = -\frac{V_{dc}}{LC} \cdot \frac{1}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad *$$



** obtained for the three-phase case*

Full-bridge PWM inverter with current control and LCL filter

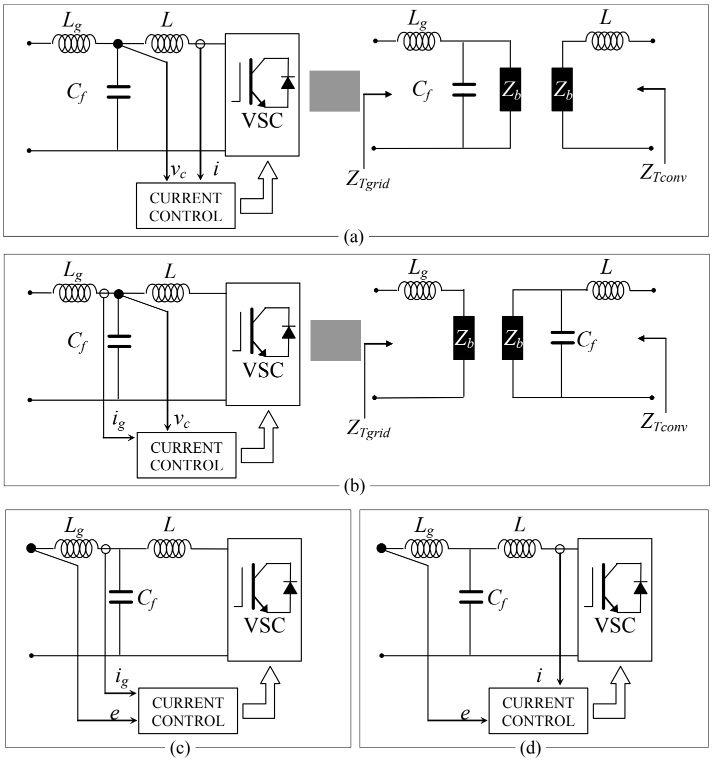


The most common topology for residential applications (1-5kW). Typically L filters are used but the new trend is to use LCL filters that have a higher order filter (3^{rd}) which leads to a more compact design. The drawback is that due to its own resonance frequency it can produce stability problems and a special control design is required

Typically PI controllers are used for the current control but Presonant controllers provides better harmonic rejection

Unipolar PWM strategy is used in order to provide double sw. frequency spectrum

Choice of the position of current and voltage sensors



$$z_{Tgrid} = 1 + j\left(x_g - x_C\right)$$
$$z_{Tconv} = 1 + jx$$

$$z_{Tgrid} = 1 + jx_g$$
$$z_{Tconv} = 1 + j\left(x - x_C\right)$$

(c)
$$z_{Tgrid} = 1$$
$$z_{Tconv} = 1 + j\left(x - x_g - x_c\right)$$

(d)
$$z_{Tgrid} = 1 + j\left(-x_C\right)$$
$$z_{Tconv} = 1 + j\left(-x\right)$$

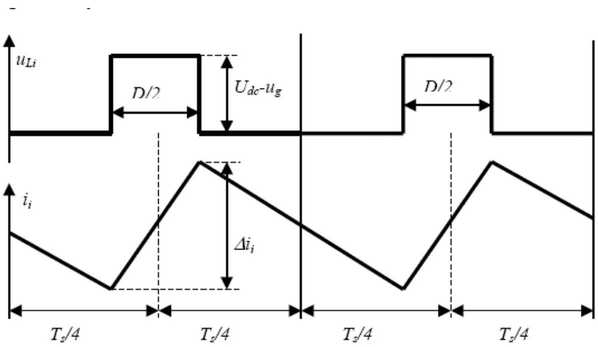
Design of LCL filter

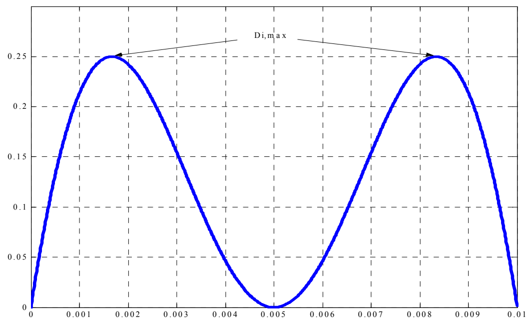
Current ripple in the inverter-side inductor L_i

$$\Delta i_i = \frac{\left(U_{dc} - u_g\right)}{L_i}\frac{D}{2}T_s \qquad D = m \cdot \sin(\omega t)\ ,\ (0 < \omega t < \pi)$$

$$\Delta i_i'(\omega t) = \frac{\Delta i_i(\omega t)}{\frac{U_{dc} \cdot T_s}{2L_i}} = \left(1 - m \cdot \sin(\omega t)\right) \cdot \sin(\omega t)$$

$$\Delta i_{i,\max}' = \Delta i_{i,\max}'\left(\arcsin\left(\frac{1}{2m}\right)\right) = \frac{1}{4 \cdot m}$$



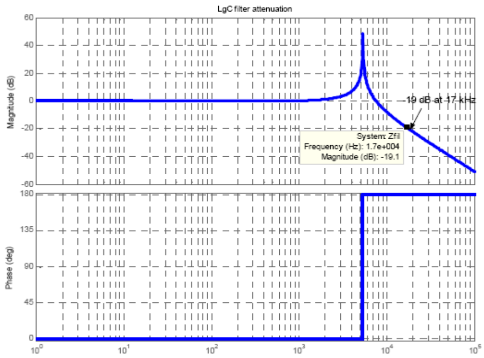


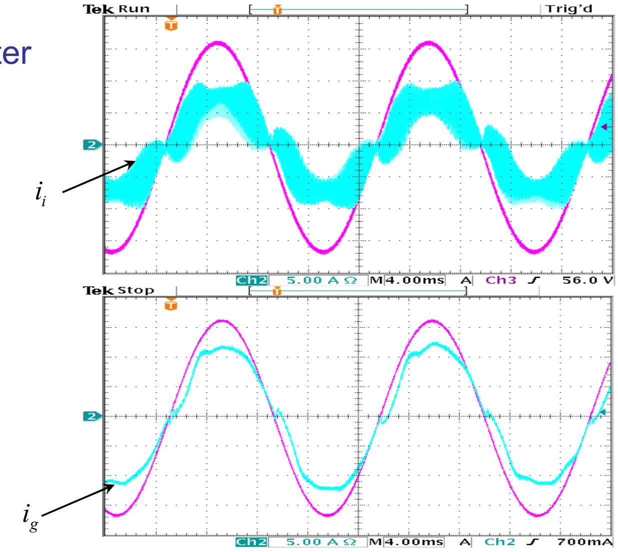
- The inductor side inductor L_i is first determined by limiting the max. current ripple at a certain value for a given dc voltage and switching frequency.
- Knowing the maximum ripple, the peak current can be calculated and used for the choice of the IGBTs, design of the current protection and design of L_i magnetics

Design of LCL filter

Ripple attenuation in the L_g-C_f filter

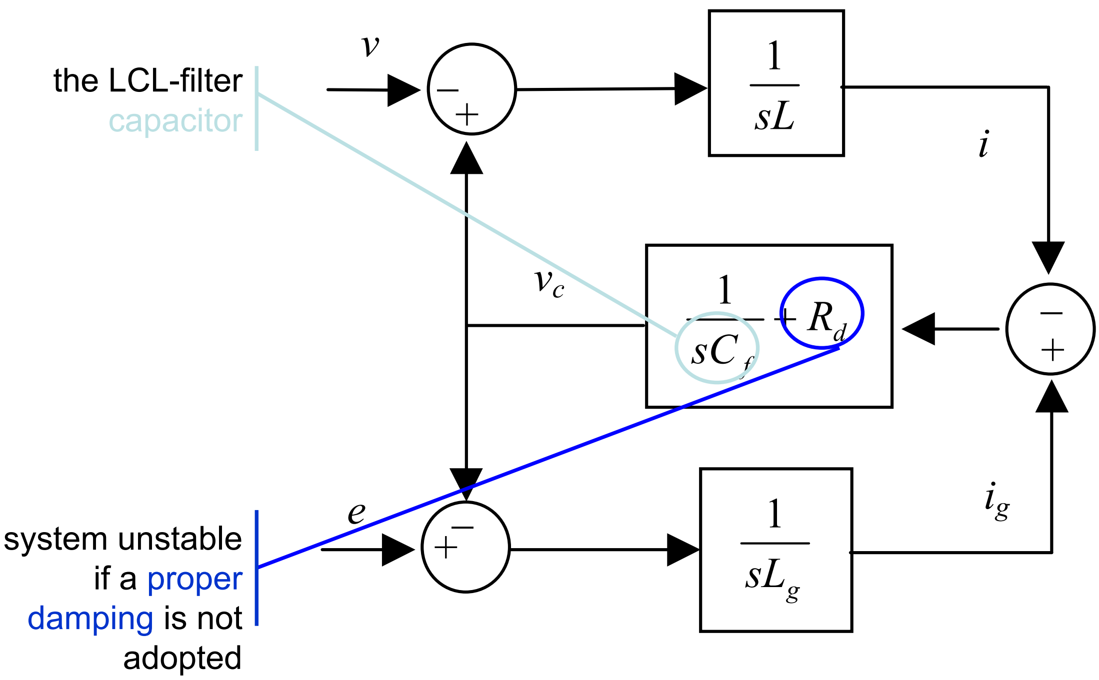
$$\frac{i_g(s)}{i_i(s)} = \frac{1}{1 + C_f \cdot L_g \cdot s^2}$$





- C_f is then sized such as the reactive power produced not to exceed 5% of the rated [kVA]
- Then, the product L_gC_f is determined by designing the L_g-C_f LP filter to exhibit a significant attenuation at the switching frequency (ex 20 dB).
- Finally, the L_g is determined.

Calculation of the minimum passive damping



Calculation of the minimum passive damping

if the current is sensed on the grid side . . .

$$G(s)=\frac{i_g(s)}{v(s)}=\frac{1}{LL_gC_fs}\frac{1}{\left(s^2+\omega_{res}^2\right)}$$ undamped plant

$$G(s)=\frac{i_g(s)}{v(s)}=\frac{1}{LL_gC_fs}\frac{\left(C_fR_ds+1\right)}{\left(s^2+\omega_{res}^2C_fR_ds+\omega_{res}^2\right)}$$ passively damped plant

---

$$G_1(s)=\frac{i_g(s)}{i(s)}=\frac{\left(C_fR_ds+1\right)}{\left(L_gC_fs^2+C_fR_ds+1\right)}$$ used to caclulate LCL-filter ripple attenuation

$$G_2(s)=\frac{i_c(s)}{v(s)}=-\frac{s}{L}\frac{1}{\left(s^2+\omega_{res}^2C_fR_ds+\omega_{res}^2\right)}$$ to calculate the damping losses

Optimization procedure

Parameters

- the current controller proportional gain kp;
- the sampling frequency fsampling ;
- the damping resistor value Rd.

Goals

a) for the stability ρ_{MAX} - maximum radius of poles of the current closed loop - ρ_{MAX} should be at least < 1 in order to have a stable current loop;

b) for the bandwidth: *bw* – the lowest between the frequencies at which the gain of the closed loop is reduced to 3 dB and at which the phase delay becomes larger than 45°;

c) for the LCL-filter switching ripple attenuation: r_a – it can be calculated on the basis of $G_2(s)$;

d) for the damping losses: P_d – they can be calculated using $G_1(s)$ since they depend on the square of the LCL-filter capacitor C_f rms current.

Conclusions

- The full-bridge PWM inverter is the most typical topology for the single-phase grid inverters for DPGS (proven technology)
- Unipolar PWM is used to ensure lower switching ripple and thus lower filtering requirements on the output
- LCL filters are more and more used as they lead to higher compactness when compared with equivalent L filters
- Current-controlled VSI is the typical control method used
- The choice of the sensors position and of the values of the LCL-filter parameters is a key point
- Single-phase new step-up converters based on boost dc/dc converters are an in interesting alternative with some advantages:
  - it does not need reverse voltage blocking diodes

  and disadvantages:
  - low frequency resonance
  - big ripple in the input inductor and dc component in the output capacitors

References

[1] Mohan, N., Undeland, T., Robbins, P.W., Power Electronics. Converters , Applications and Design., John Wiley & Sons, 2003, ISBN:0471226939

[2] B.K. Bose, Modern Power Electronics and A.C. Drives, 1st ed., Prentice Hall, 2001, ISBN 0- 13-016743.

[3] M. Liserre, F. Blaabjerg, A. Dell'Aquila, "Step-by-step design procedure for a grid-connected three-phase PWM Voltage Source Converter" International Journals of Electronics, Vol. 91, Agosto 2004, pp. 445-460.

[4] M. Liserre, A. Dell'Aquila, F. Blaabjerg, R. Teodorescu"A stable three-phase LCL-filter based active rectifier without damping", IAS 2003, Salt Lake City, Utah, USA, October 2003.

[5] R.O. Caceres and I. Barbi, "A boost DC-AC converter: analysis, design, and experimentation" IEEE Transactions on Pow. Electron.s, vol. 14, no. 1, January, 1999, pp. 134-141.

Institute of ENERGY TECHNOLOGY

Control of single-phase PV systems

Control of Single-Phase PV Systems

By Remus Teodorescu, Aalborg University

Agenda

- **Control structures for single-phase PV systems**
- Grid synchronization and monitoring
- Current control design
- MPPT strategies
- Anti-islanding strategies

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Control structures for single-phase PV systems

Objectives

- Control structures for PV inverters with dc-dc converter
- Control structures for PV inverters without dc-dc converter
- Practical implementation
- dq control
- Conclusions
- Reference papers

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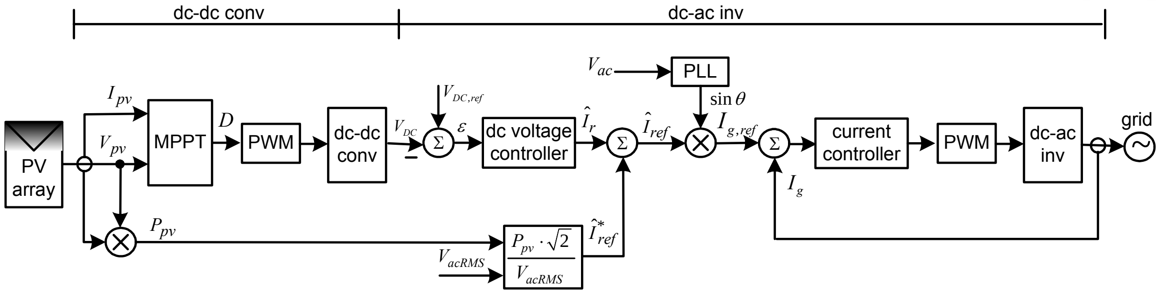
Control structures for single-phase PV systems

Topologies with dc-dc converter (dual-stage)



- In these topologies, which are the classical solution used by the industry at the moment, the MPPT is implemented in the dc-dc boost converter.
- The output of the MPPT is the duty-cycle function. As the dc-link voltage V_{DC} is controlled in the dc-ac inverter the change of the duty-cycle will change voltage at the output of the PV panels, V_{PV} as:

$$V_{DC} = K\frac{V_{PV}}{1-D}$$

- The dc-ac inverter is a typical current regulated voltage source inverter (VSI) with unipolar PWM and dc-voltage controller.
- The power feedforward requires communication between the two stages and improves the dynamics of MPPT

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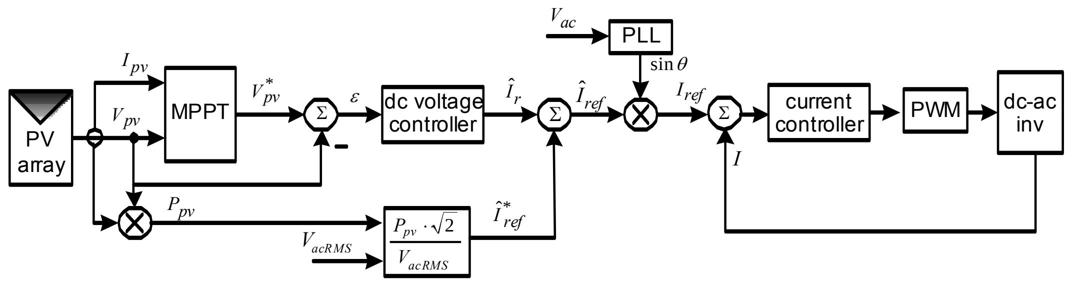
Control structures for single-phase PV systems

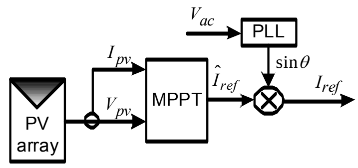
Topologies without dc-dc converter (single-stage)



- In these topologies -which are becoming more and more popular in countries with low grid voltage (120V) like Japan and thus the voltage from the PV array is high enough- the MPPT is implemented in the dc-ac inverter
- The output of the MPPT is the dc-voltage reference. The output of the dc-voltage controller is the grid current reference amplitude. The power feedforward improves the dynamic response as MPPT runs at a slow sampling frequencies (typ. 1 Hz).
- A PLL is used to synchronize the current reference with the grid voltage

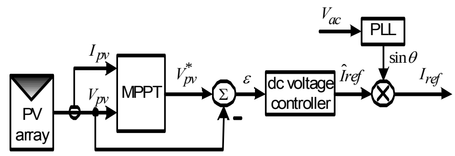
MPPT implementation in PV converters without dc-dc converter

The output of the MPPT is the ac current reference amplitude which is multiplied by $\sin\theta$ captured from a phase-looked-loop (PLL) circuit to produce the output current reference command I_{ref} of the inverter in synchronism with the grid voltage.



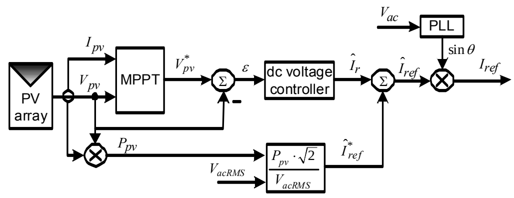
A – Controlling directly the ac current amplitude reference

The output variable of the algorithm is the dc voltage reference (V^{*}_{pv}). A PI controller is used to control the dc voltage loop. The output of dc voltage controller is the ac current amplitude reference.



B – Controlling the DC voltage.

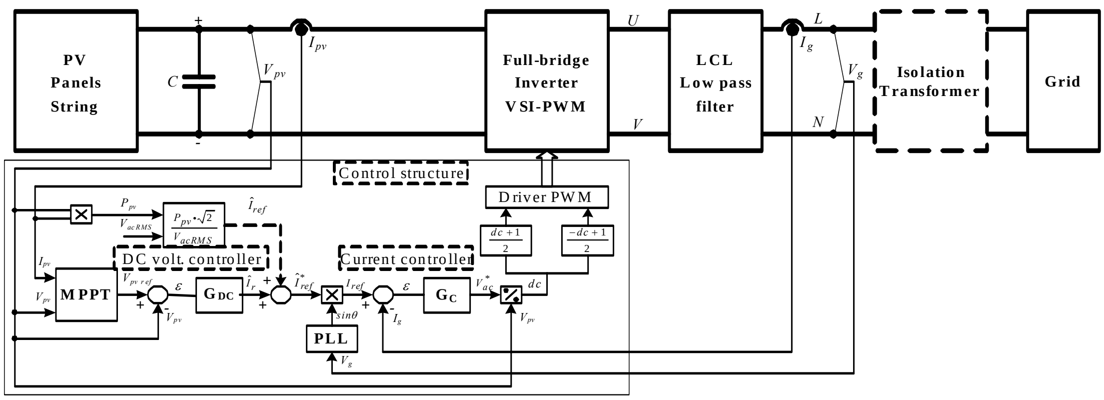
Using the input power feed-forward the dynamic of the PV system is improved being known the fact that the MPPT is rather slow



C – Controlling the DC voltage with power feedforward

Practical PV inverter control implementation

Single-stage full-bridge PWM inverter with LCL filter and grid trafo



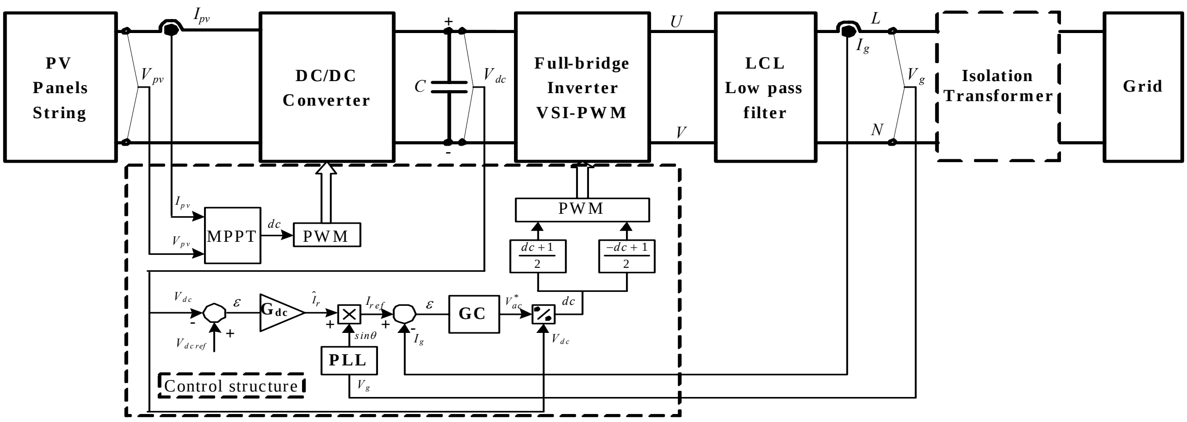
•The current controller Gc can be of PI or PR (Proportional Resonant) type

•Other non-linear controllers like hysteresis or predictive control can be used for current control

•The dc voltage controller can be P type due to the integration effect of the typical large capacitor

Practical PV inverter control implementation

Dual-stage full-bridge PWM inverter with LCL filter and grid trafo

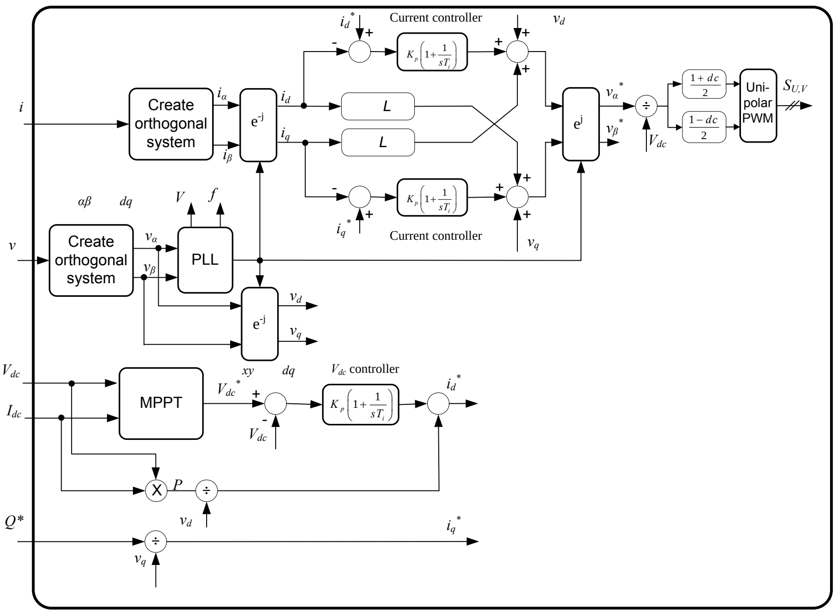


•The dc-dc controller can have isolation (high frequency trafo) and so there is no need for output trafo!

•This is the current typical industrial solution for residential PV inverters up to 4.5 kW

dq Control of Single-Phase PV inverter

Single-stage full-bridge PWM inverter with LCL filter and grid trafo



•Creating "virtual" orthogonal components of current and voltage, the well-known dq-control structure can be applied to single-phase PV inverters

•The advantage is that well-proven PI controllers can be used as dc variables are to be controlled and an independent Q control is achieved

Conclusions

- The most typical control structure for single-phase grid-connected PV inverters is the current controlled voltage source inverter with LCL filter
- For systems that require dc voltage boost an additional stage of boost dc-dc converter is used
- The MPPT is a necessary feature in order to extract the maximum power from a panel array at any conditions of irradiation and temperature. According to the topology (dual- or single-stage) the MPPT is implemented in the dc-dc converter or in the dc-ac inverter
- Different types of current control can be used like for example PI, PR, dq or hysteresis.
- Dq control si also possible by creating ”virtual” orthogonal components leading to independant Q control
- For grid synchronization PLL are typically used.

References

[1] Ciobotaru,M., Teodorescu,R., Blaabjerg,B., “Control of Single-Stage Single-Phase PV inverter” – Proceedings of EPE 2005, 11-13 sep 2005, Dresden

Agenda

- Control structures for single-phase PV systems
- **<u>Grid synchronization and monitoring</u>**
- Current control design
- MPPT strategies
- Anti-islanding strategies

Objectives

- Grid monitoring requirements for PV inverters
- PLL Basics
- Design of PLL
- Practical PLL for single-phase systems
- Methods to create the orthogonal component
- Comparison of different methods
- Conclusions
- Reference papers

Grid monitoring requirements for PV inverters

- In Europe the "draft" standard IEC61727 [1] is coming soon!
- In US there is already IEEE 929 [2] that have similar requirements!

The following conditions should be met, with voltages in RMS and measured at the point of utility connection.

Voltage (at point of utility connection)		*Maximum Trip Time**
V<0.5xVnominal		*0,1sec.*
50%≤V<85%		*2,0 sec.*
85%≤V≤110%		*Continuous Operation*
110%<V<135%		*2,0sec.*
135%≤V		*0,05sec.*

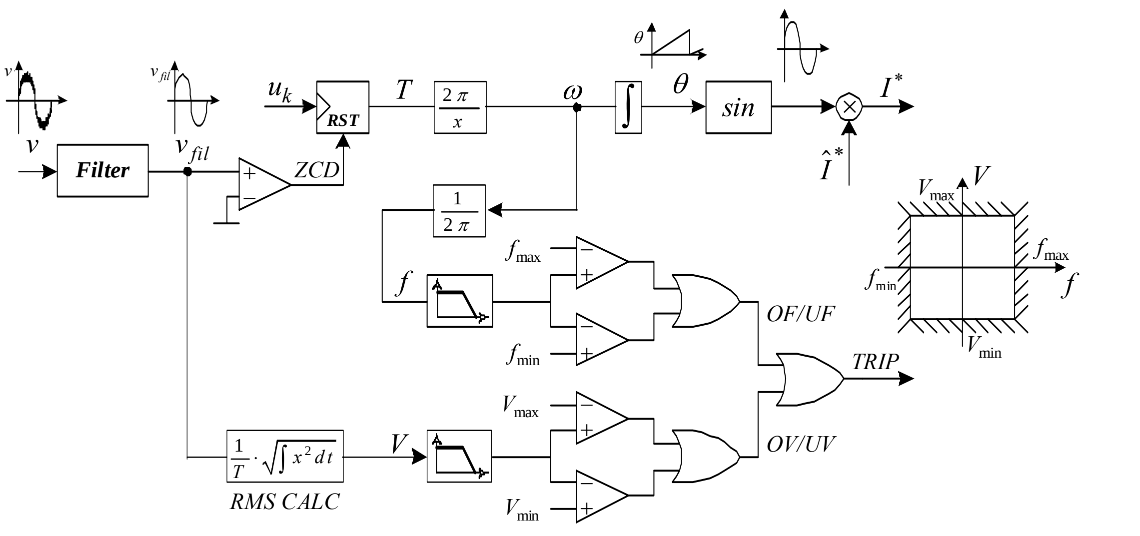
- When the utility frequency is outside the range of +/- 1 Hz the inverter should cease to energize the utility line within 0.2 seconds.
- The PV system shall have an average lagging power factor greater than 0,9 when the output is greater than 50% rated.

- **Thus the grid voltage and frequency should be estimated and monitored fast and accurate enough in order to cope with the standard**

Grid synchronization requirements

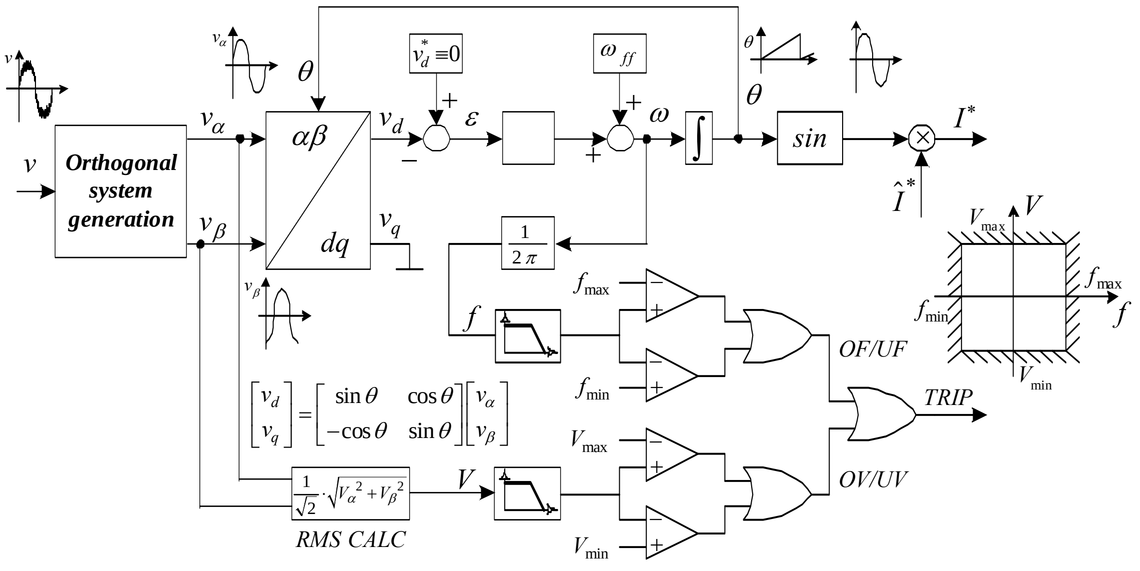
- A good synchronization of the current with the grid voltage is necessary as:
  - the standards require a high power factor (> 0.9)
  - a "clean" reference for the current is necesarry in order to cope with the harmonic requirements of IEC61727/IEEE929
  - grid connection transients needs to be minimized in order not to trip the PV inverter
- There are two basical synchronization methods::
  - Filtered Zero Cross Detection (ZCD)
  - PLL
- The classical solution for single-phase systems was Filtered ZCD as for the PLL two orthogonal voltages are required.
- PLL is used usually in three-phase systems!
- The trend now is to use the PLL technique also by creating "virtual" orthogonal components using different techniques!

Filtered Zero Cross Detection (ZCD) based monitoring and synchronization



- Filtering introduces delay. Ther are digital predictive FIR filters without delay bu with high complexity (very high order!)
- The RMS voltage and frequency are calculated once in a period → poor detection of changes (sags, dips, etc.)

PLL-based monitoring and synchronization



$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

$$\frac{1}{\sqrt{2}} \cdot \sqrt{V_\alpha^2 + V_\beta^2}$$

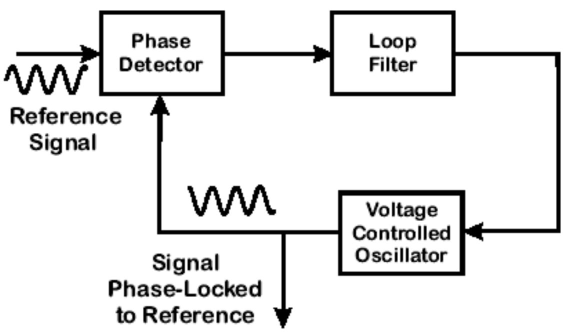
- PLL introduces no delay!
- The RMS voltage and frequency are calculated instantenously → better detection of changes (sags, dips, etc.)
- PLL is the most typical solution used in industry!

PLL Basics

- A PLL produces a signal to the output that synchronizes in phase and frequency with the input signal.
- It controls the phase of its internal signal such that the error- the difference between its phase and the one from the input signal- is kept to a minimum while the frequency is kept the same as the input signal

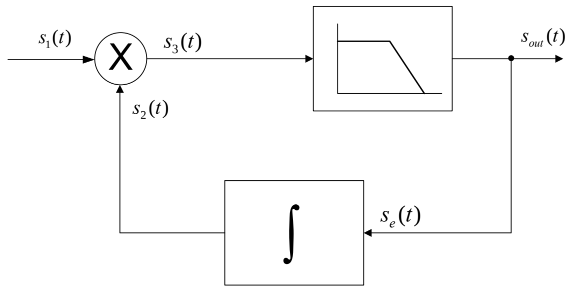
A PLL has three components:

- Phase Detector (PD) or the multiplier
- The Loop filter (LF)
- Voltage ControlledOscillator (VCO)



- PLLs are almost always low order, typically second order, i.e. using 1-st order LF or more typically a PI controller
- The design of the PLL is easier with 2-nd order PLL as for 2-nd order systems the bandwith and damping factor can be easiliy set using linear system theory

Design of PLL [3]



In order to analyse the PLL behaviour we linearize the loop using Laplace transform to get the transfer function.

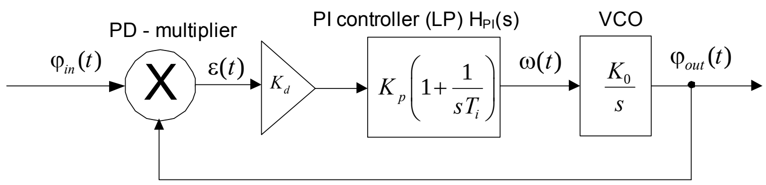
The transfer function VCO $\quad \omega_{out} = \omega_c + K_0 s_e(t) \rightarrow \varphi_i(t) = \int_0^t \omega_{out} dt = \omega_c t + K_0 s_e(t) t$

The VCO output signal in time domain and in Laplace will be:

$$V_{out} = A_0 \cos\left(\omega_c t + K_0 \int_0^t s_e(t) dt\right) \rightarrow \varphi_{out}(t) = K_0 \int_0^t s_e(t) dt \rightarrow \varphi_{out}(s) = \frac{K}{s} s_e(s)$$

The VCO transfer function will be: $\quad \dfrac{\varphi_{out}(s)}{s_e(s)} = \dfrac{K_0}{s}$

Design of PLL



Assuming Ko=Kd=1 (typically),the transfer function of PLL in open loop will be: $\quad \dfrac{\varphi_{out}(s)}{\varphi_{in}(s)} = \dfrac{H_{PI}(s)}{s}$

The transfer function of the closed loop for the output phase as function of input phase will be:

$$H_\varphi(s) = \frac{\varphi_{out}(s)}{\varphi_{in}(s)} = \frac{H_{PI}(s)}{s + H_{PI}(s)} = \frac{K_p s + \frac{K_p}{T_i}}{s^2 + K_p s + \frac{K_p}{T_i}}$$

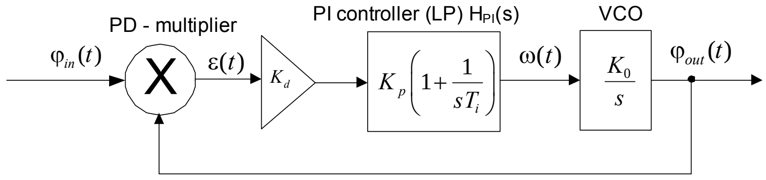
The transfer function of the closed loop for the phase error as function of the input phase will be:

$$H_\varepsilon(s) = \frac{\varepsilon(s)}{\varphi_{in}(s)} = \frac{s}{s + H_{PI}(s)} = \frac{s^2}{s^2 + K_p s + \frac{K_p}{T_i}}$$

Considering the general form of second order systems we can get the following equivalent expressions:

$$H_\varphi(s) = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad H_\varepsilon(s) = \frac{s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad \omega_n = \sqrt{\frac{K_p}{T_i}}; \quad \xi = \frac{\sqrt{K_p T_i}}{2}$$

Design of PLL

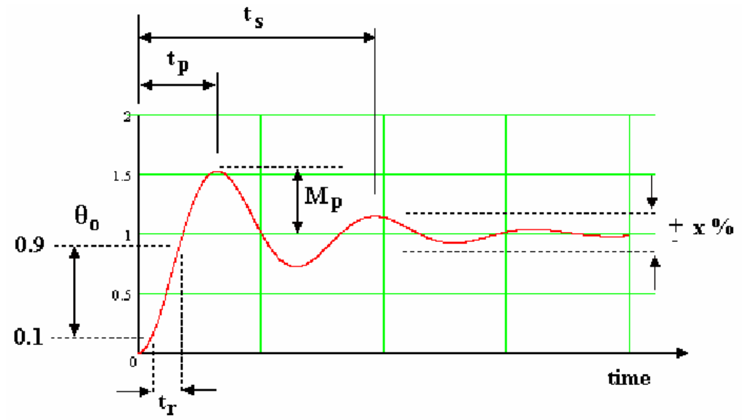


We can use the standard specifications for second order systems without zeros as a rough approximation that should give a 5% overshoot (Mp) at step response [8]

$$\xi = 0.707;\quad t_s = \frac{4.6}{\xi\omega_n};\quad t_r = \frac{1.8}{\omega_n}$$

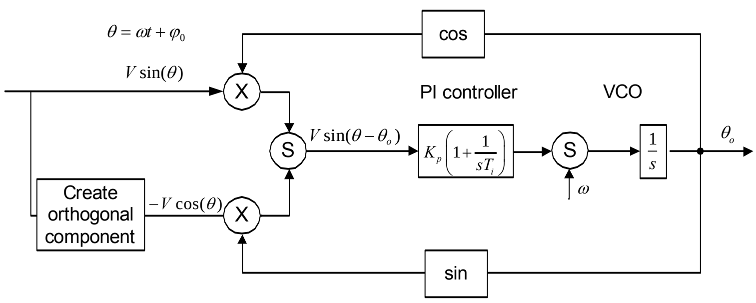
So the PI controller can be tunned for a specified settling time t_s and damping factor î as followings:

$$K_p = \frac{9.2}{t_s};\quad T_i = \frac{t_s\xi^2}{2.3}$$



PLL for single-phase systems [4]

- PLL is used in single-phase systems for obtaining an angle synchronous with the grid used for creating the current reference and also for the estimation of grid frequency and voltage for monitoring purposes
- In single-phase systems there is only one signal (voltage) so the orthogonal component must be created artificially. Also a center frequency equal with the grid frequency must be feedforwarded at the input of the VCO integrator



$$V\sin(\theta-\theta_o) = V\sin(\theta)\cos(\theta_o) - V\cos(\theta)\sin(\theta_o)$$

- In order to create the the input signal as phase error, multiplication with sin and cos of the pll output is used.
- Due to the fact that the phase error signal has an amplitude of V, the PI controller gain should be reduced accordingly:

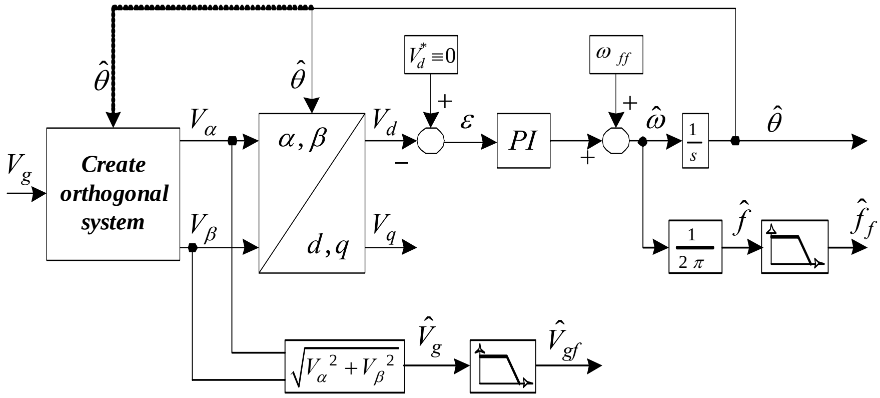
$$K_p = \frac{9.2}{t_s}\cdot\frac{1}{V};\quad T_i = \frac{t_s\xi^2}{2.3}$$

A Practical PLL for single-phase systems - dq PLL

- Another equivalent approach typically used for PLL implementation is the use of áâ-dq transformations

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = V \begin{bmatrix} \sin(\theta) \\ \cos(\theta) \end{bmatrix} \Rightarrow \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \begin{bmatrix} \cos(\theta_o) & \sin(\theta_o) \\ \sin(\theta_o) & -\cos(\theta_o) \end{bmatrix}$$

where Vd should be zero at synchronism and therfore it is used as input signal while Vq represents the amplitude of the voltage and is used for monitoring. A more precise estimation of the amplitude can be obtained by calculated the module of the orthogonal system, as shown bellow:

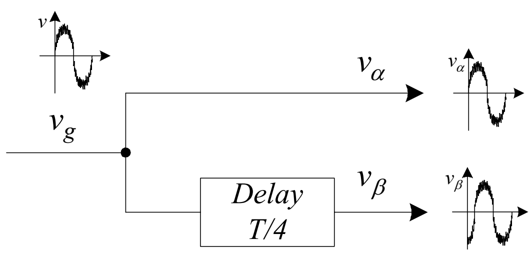


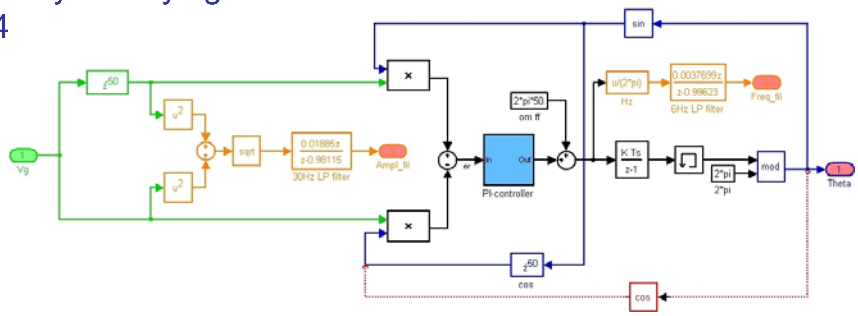
LP filters are used to smooth the frequency and amplitude estimation!

Methods to create the orthogonal component

- Transport Delay T/4 [5]

- The idea is that for sinusoidals systems a delay of T/4 will produce an orthogonal signal.
- This method works fine for fixed grid frequency. If the grid frequency is changing with for ex +/-1 Hz, then the PLL will produce an error
- In order to overcome this, the cosinus funtion of the PLL angle is calculated by delaying the sin(θ) with T/4





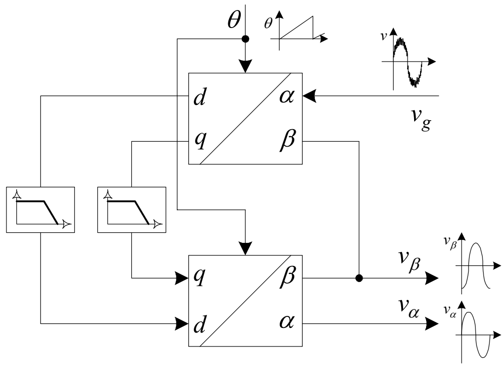
Methods to create the orthogonal component

- Another method is Inverse Park Transformation [4]

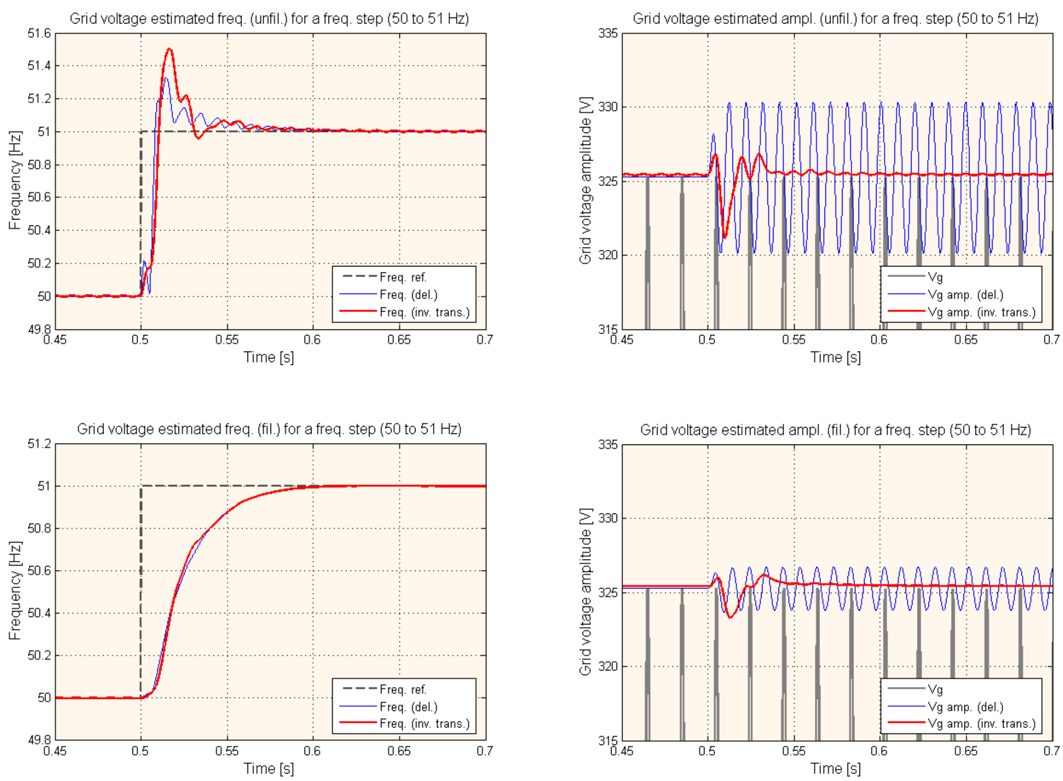
A singlephase voltage ($V\beta$) and an internally generated signal ($V\alpha$) are used as inputs to a Park transformation block ($\alpha\beta$-*dq*). The *d* axis output of the Park transformation is used in a control loop to obtain phase and frequency information of the input signal.

$V\alpha$ is obtained through the use of an inverse Park transformation, where the inputs are the *d* and *q*-axis outputs of the Park transformation (*dq*-$\alpha\beta$). fed through first-order pole blocks.

Although the algorithm of the PLL based on the inverse Park transformation is easily implemented, requiring only an inverse Park and two first-order low-pass filters, the tuning of its PI controller and the choice of the time constant of the filters is a more difficult process, as compared with the other PLL algorithms. This is due to the presence of the two interdependent nonlinear loops, which makes linearization and use of linear system analysis tools more troublesome processes.



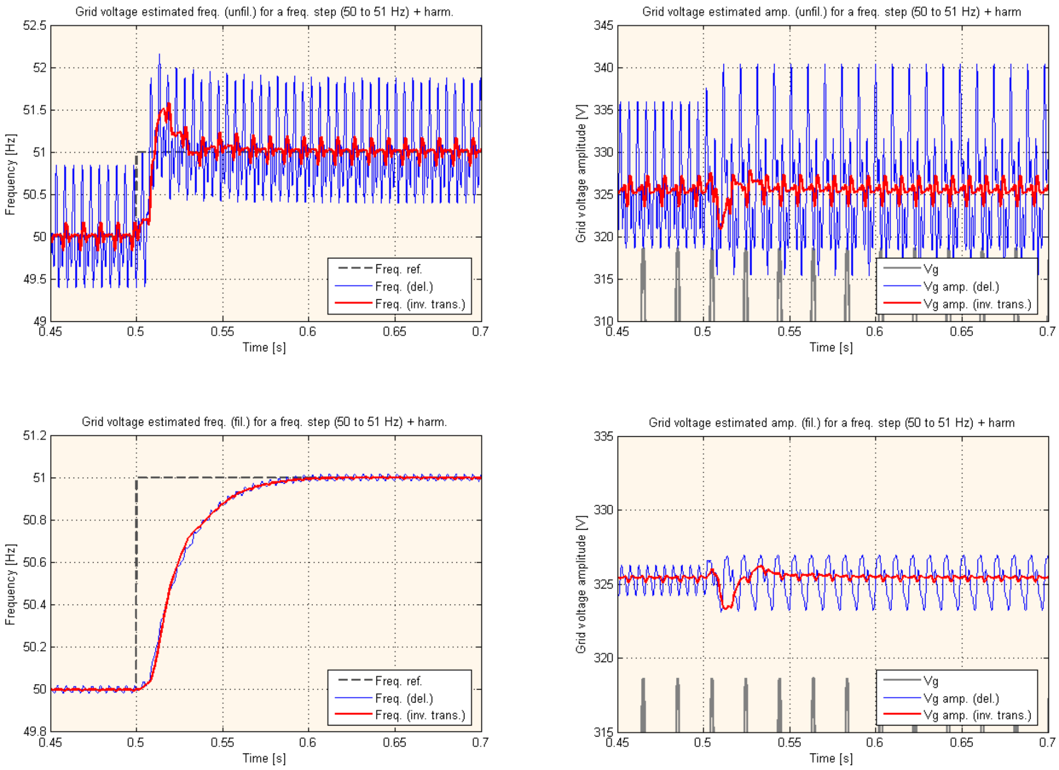
Experimental results - frequency step with ideal grid. Non filtered and 100ms filtered estimates of freq. and amp.



Institute of ENERGY TECHNOLOGY

Grid synchronization and monitoring

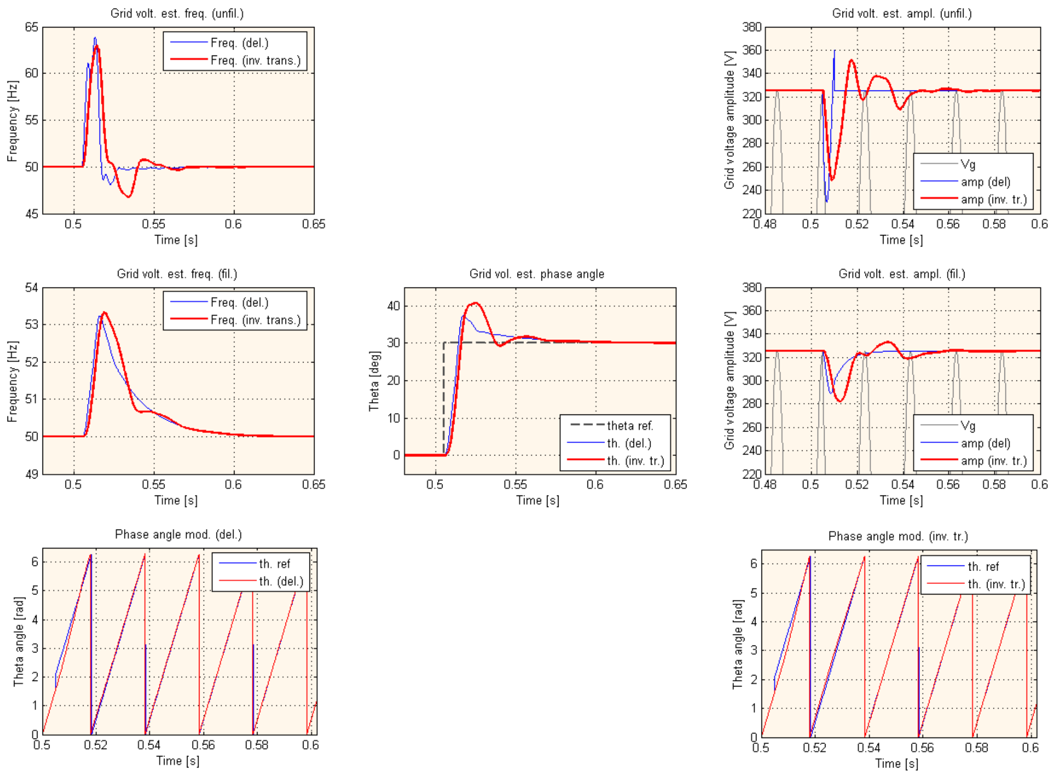
Experimental results - frequency step with real grid. Non filtered and 100ms filtered estimates of freq. and amp.



Institute of ENERGY TECHNOLOGY

Grid synchronization and monitoring

Experimental results - phase jump with ideal grid. Non filtered and 100ms filtered estimates of freq. and amp.



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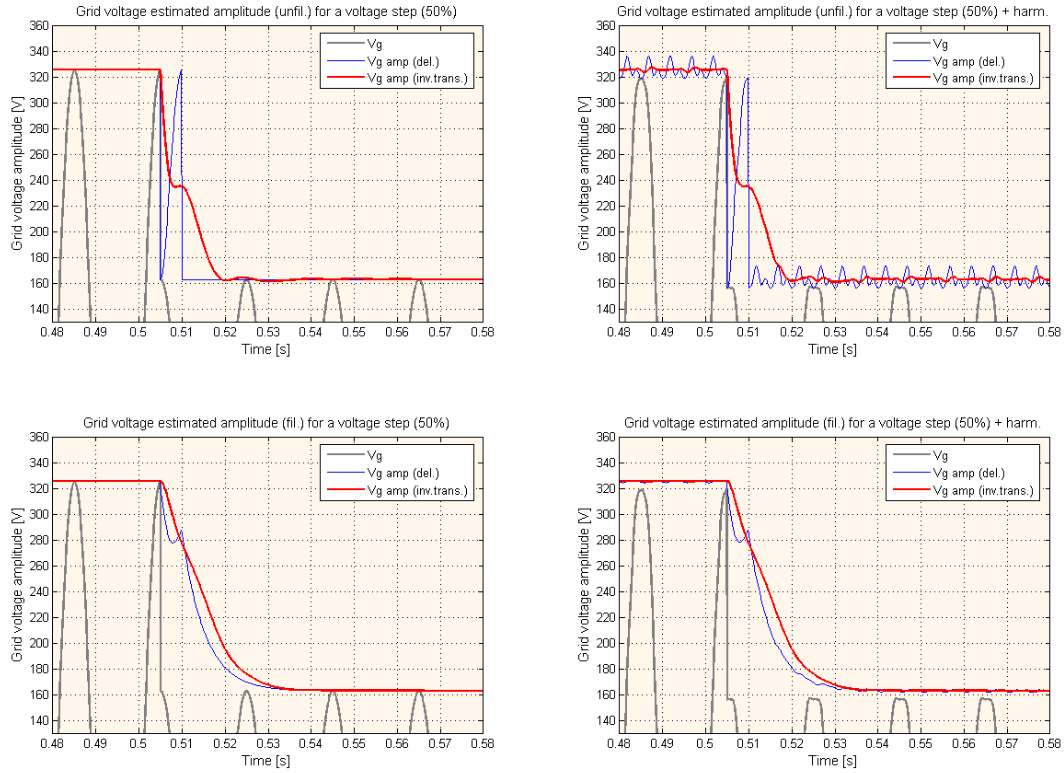
Grid synchronization and monitoring

Experimental results - amp step with ideal and real grid. Non filtered and 100ms filtered estimates amplitude



Institute of ENERGY TECHNOLOGY

Grid synchronization and monitoring

Conclusions

- PLL is a very useful method that enable the PV inverters to:
  - Create a "clean" current reference synchronized with the grid
  - Comply with the grid monitoring standards
- The PLL is able to track the frequency and phase of the input signal in a designed settling time
- By setting a higher settling time a "filtering" effect can be achieved in order to obtain a "clean" reference even with a polluted grid.
- The PLL needs two signals in quadrature at the input.
- For single-phase systems as there is only one signal available, the orthogonal signal needs to be created artificially.
- Two methods have been investigated: Transport Delay (T/4) and Inverse Park Transformation.
- Having the orthogonal components, the amplitude can be calculated
- Both methods requires LP filters on the estimated frequency and amplitude to get smooth signals and both pass IEC61727
- Inverse Park Transformation provides better performance under frequency changes but involves more calculations!

References

[1] IEC 61727 CDV Ed.2 – Characteristics of the Utility Interface for Photovoltaic (PV) Systems, 2002

[2] IEEE Std 929-2000 – IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,2000, ISBN 0-7381-1934-2

[3] Se-Kyo Chung - "A phase tracking system for three phase utility interface inverters" Power Electronics, IEEE Transactions on Volume 15, Issue 3, May 2000 Page(s):431 - 438

[4] Silva, S.M.; Lopes, B.M.; Filho, B.J.C.; Campana, R.P.; Bosventura, W.C. "Performance evaluation of PLL algorithms for single-phase grid-connected systems" Industry Applications Conference, 2004. 39th IAS Annual Meeting. Conference Record of the 2004 IEEE Volume 4, 3-7 Oct. 2004 Page(s):2259 - 2263 vol.4

[5] Ciubotaru, M, Teodorescu, R., Blaabjerg, F., "Improved PLL Structures for Single-Phase Grid Inverters" – Proceedings of International Conference on Poer Electronics and Intelligent Control for Energy Conservation, PELINCEC'05, Warsaw, 16-19 October 2005

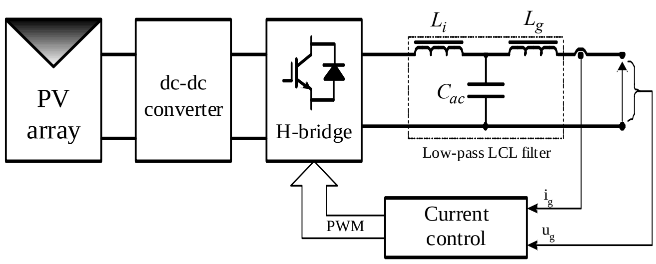
Agenda

- Control structures for single-phase PV systems
- Grid synchronization and monitoring
- **Current control design**
- MPPT strategies
- Anti-islanding strategies

Objectives

- Introduction
- Grid harmonics requirements for PV inverters
- LCL filter design
- Shortcomings of PI controller
- Generalized integrator
- PI and Proportional Resonant (PR) current control of single-phase PV inverters
- PR current control loop of single-phase PV inverter
- Discrete implementation of PR controller
- Experimental results
- Conclusions
- Reference papers

Introduction to current control for single-phase grid inverter with LCL filter



- The **LCL filter** is now commonly used to connect VSI-PWM inverters to the utility grid as it requires significantly less inductance as the L filter in order to achieve the same attenuation
- Special attention should pe payed when designing the **LCL filter + current controller** in order to avoid resonance in LCL filter and ensure stability.
- The **PI controller** commonly used to control the current in single-phase PV inverters exhibits stationary error and poor harmonic rejection.
- A new breed of controllers called **Proportional Resonant** (**PR**)can alleviate these shortcomings and can be successfully used in grid connected VSI-PWM inverters

Grid current harmonics and THD requirements for PV inverters

- In Europe the "draft" standard IEC61727 [1] is coming soon!
- In US there is already IEEE 929 [2] that have similar requirements!
- The following conditions should be met regarding grid current harmonic content.

ODD HARMONICS	DISTORTION LIMIT
3rd through 9th	less than 4.0%
11th through 15th	less than 2.0%
17th through 21st	less than 1.5%
23rd through 33rd	less than 0.6%

- The total THD of the grid current should not be higher than **5%**

- **Thus high performance current control is required including harmonic compensation in order to cope with the standard**

Shortcomings of PI controller

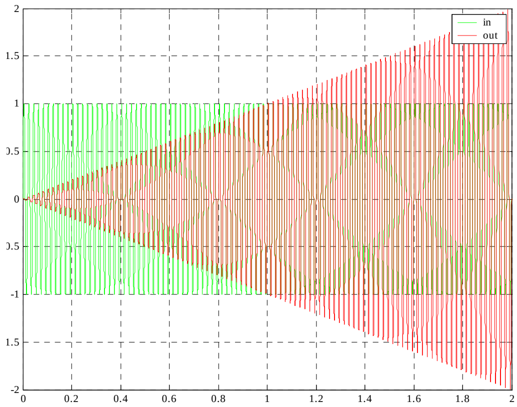
- Typically PI controllers are used for the current loop in single-phase grid inverters.
- The PI current control of a single-phase inverter has well known drawbacks:

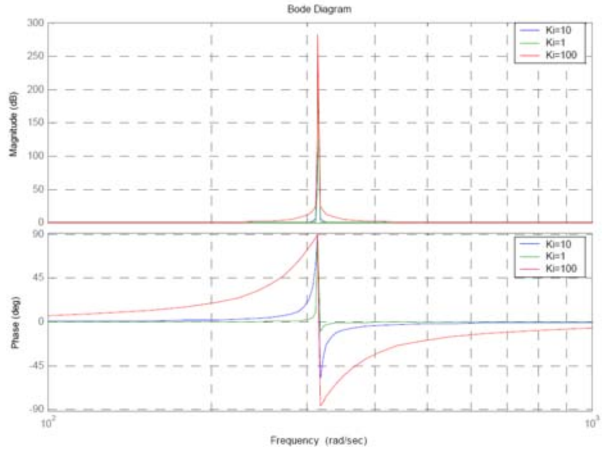
  - ☹ steady-state magnitude and phase error
  - ☹ limited disturbance rejection capability

$$G_{PI}(s) = K_P + \frac{K_I}{s}$$

- When the current controlled inverter is connected to the grid, the phase error results in a power factor decrement and the limited disturbance rejection capability leads to the need of **grid feed-forward compensation**.
- However the imperfect compensation action of the feed-forward control due to the **background distortion** results in high harmonic distortion of the current and consequently non-compliance with international power quality standards.

The generalized integrator GI [4]



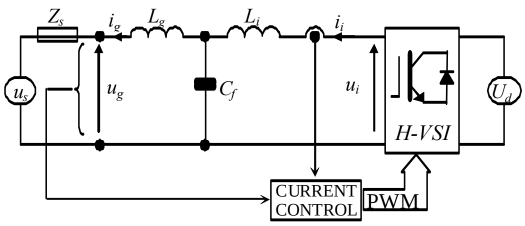


$$G_{GI}(s) = K_I \frac{s}{s^2 + \omega_o^2}$$

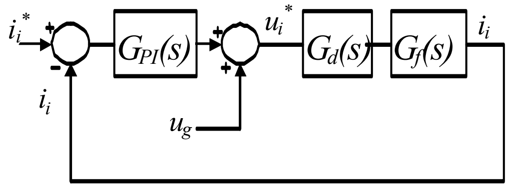
- The Generalized Integrator (GI) is a double integrator that achieves infinite gain at a certain frequency, called resonance frequency, and almost no attenuation outside this frequency.
- Thus, it can be used as a notch filter in order to compensate the harmonics in a very selective way
- The GI will lead to zero stationary error and improved and selective disturbance rejection as compared with PI controller

PI vs PR for single-phase grid inverter current control

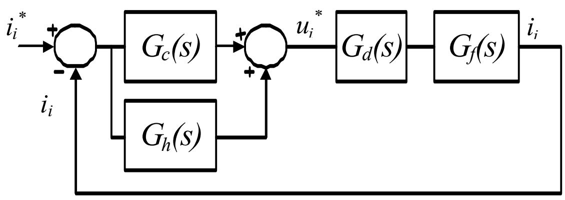
The H-bridge PV inverter connected to the grid through an LCL filter



The current loop of PV inverter with PI controller



The current loop of PV inverter with PR controller and HC



PI $G_{PI}(s) = K_P + \frac{K_I}{s}$

PR $G_c(s) = K_P + K_I \frac{s}{s^2 + \omega_o^2}$

HC $G_h(s) = \sum_{h=3,5,7} K_{Ih} \frac{s}{s^2 + (\omega_o h)^2}$

Inverter $G_d(s) = \frac{1}{sT_s + 1}$

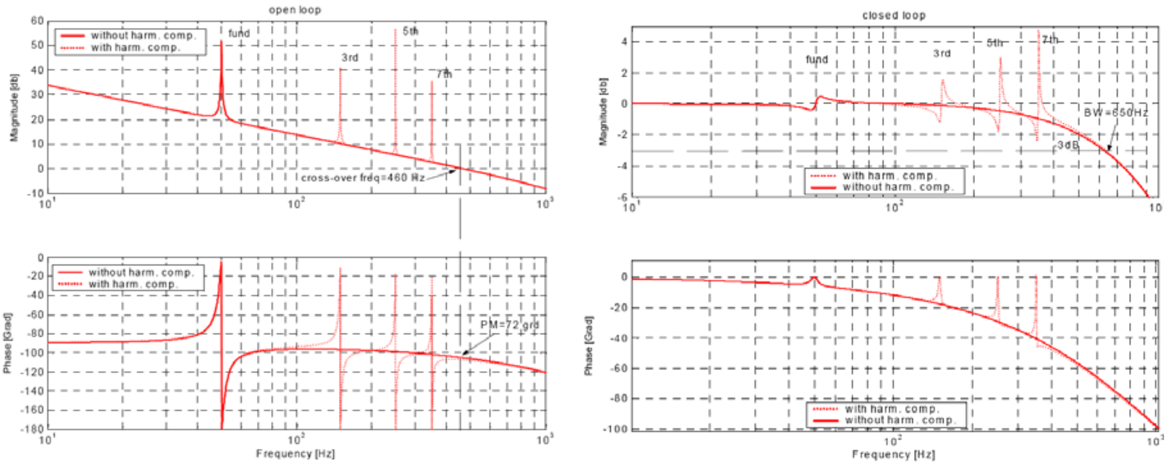
Plant $G_f(s) = \frac{i_i(s)}{u_i(s)} = \frac{1}{L_{fi} s} \frac{(s^2 + z_{LC}^2)}{(s^2 + \omega_{res}^2)}$ $\quad z_{LC}^2 = \frac{1}{L_g C_f}$ $\quad \omega_{res}^2 = \frac{(L_g + L_i) \cdot z_{LC}^2}{L_i}$

- No grid voltage feed-forward is required when using
- GIs tuned to the low harmonics can be used for selective harmonic compensation by cascading the fundamental component GI

PR current control for single-phase grid inverter
Frequency analysis

Open-loop PR current control system with and without harmonic compensator

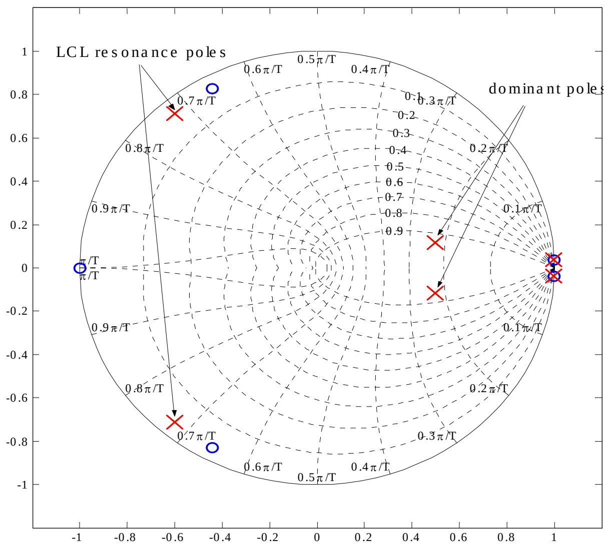
Closed loop PR current control system with and without harmonic compensator



- Having added the harmonic compensator, the open-loop and closed-loop bode graphs changes as it can be observed with dashed line. The change consists in the appearance of gain peaks at the harmonic frequencies, but what is interesting to notice is that the **dynamics** of the controller, in terms of **bandwidth** and **stability margin remains unaltered**.

PR current control for single-phase grid inverter
Frequency analysis

Pole-zeros placement of closed-loop current control system

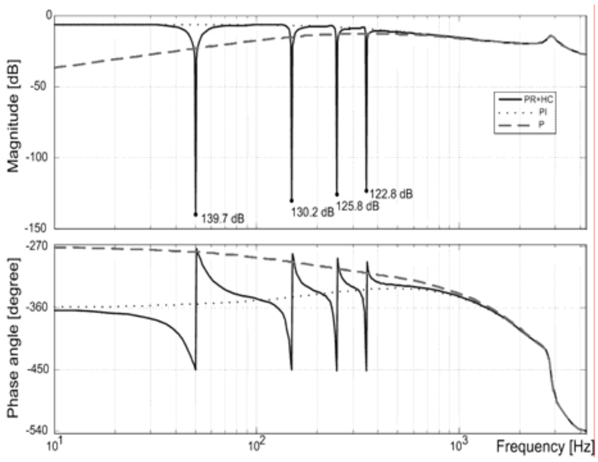


- The dominant poles of the controller should have a high damping (0.707) in order to ensure a smooth response during transients
- Also the high-frequency poles from the LCL-filter should be inside the unity-circle indicating stability. Sometime damping resistors in series with the capacitors can be required to ensure stability. The most desirable design will be without damping resistors as they produce losses. A good control design can achieve this!

- The one-sample delay of the system also increases the stability by pushing the LCL-filter poles toward the unity-circle centrum. The zero introduced is attracting the high-frequency poles!

PR current control for single-phase grid inverter
Frequency analysis

Disturbance rejection (current error ratio disturbance) of the PR+HC, PR and P



$$\left.\frac{\varepsilon(s)}{u_g(s)}\right|_{i_i^*=0} = \frac{G_f(s)}{1+\left(G_c(s)+G_c(s)\right)\cdot G_d(s)\cdot G_f(s)}$$

$$G_c(s) = K_P + K_I \frac{s}{s^2+\omega_o^2}$$

$$G_h(s) = \sum_{h=3,5,7} K_{Ih} \frac{s}{s^2+(\omega_o h)^2}$$

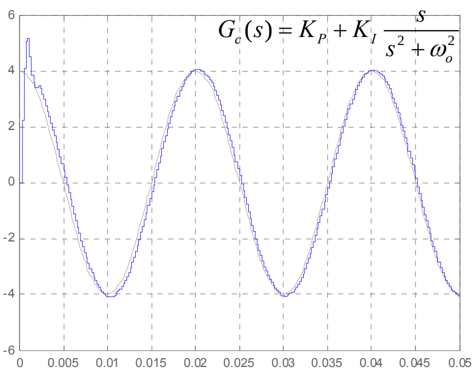
$$G_f(s) = \frac{i_i(s)}{u_i(s)} = \frac{1}{L_{fi}s}\frac{\left(s^2+z_{LC}^2\right)}{\left(s^2+\omega_{res}^2\right)}$$

$$\omega_{res}^2 = \frac{(L_g+L_i)\cdot z_{LC}{}^2}{L_i} \qquad z_{LC}^2 = \frac{1}{L_g C_f}$$

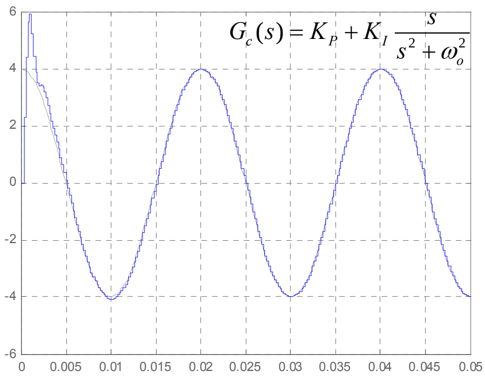
- Around the 5th and 7th harmonics the PR attenuation being around 125 dB and the PI attenuation only 8 dB. The PI rejection capability at 5th and 7th harmonic is comparable with that one of a simple proportional controller, the integral action being irrelevant.
- PR +HC exhibits high performance harmonic rejections leading to very low current THD!

PR current control for single-phase grid inverter
Tuning

- The gain Kp is founded by ensuring the desired bandwith using either rlocus Matlab function or SISOTOOL.
- The integral constant *Ki* acts to eliminate the steady-state phase error.



Ki = 100



Ki = 500

- A higher Ki will "catch" the reference faster but with higher overshoot.
- Another aspect is that *Ki* determines the bandwidth centred at the resonance frequency, in this case the grid frequency, where the attenuation is positive. Usually, the grid frequency is stiff and is only allowed to vary in a narrow range,typically ± 1%.

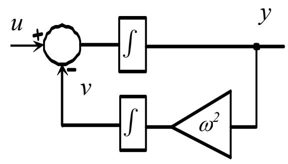
Discretization of generalized integrators Frequency analysis

GI integrator decomposed in two simple integrators

$$\frac{y(s)}{u(s)} = \frac{s}{s^2+\omega^2} \Leftrightarrow \begin{cases} y(s) = \frac{1}{s}\left[u(s)-v(s)\right] \\ v(s) = \frac{1}{s}\cdot\omega^2\cdot y(s) \end{cases}$$

Forward integrator for direct path and backward for feedback path

$$\begin{cases} y_k = y_{k-1} + T_s\cdot(u_{k-1}-v_{k-1}) \\ v_k = v_{k-1} + T_s\cdot\omega^2\cdot y_k \end{cases}$$



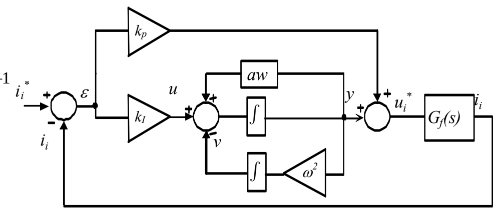
The inverter voltage reference

$$u_i^*(s) = \varepsilon(s)\cdot\left(K_p + \frac{K_I\cdot s}{s^2+\omega^2}\right)$$

Difference equations

$$\begin{cases} y_k = y_{k-1} + T_s\cdot K_I\cdot\varepsilon_{k-1} - T_s\cdot v_{k-1} \\ u_{i,k}^* = K_p\cdot\varepsilon_k + y_k \\ v_k = v_{k-1} + T_s\cdot\omega^2\cdot y_k \\ \varepsilon_{k-1} = \varepsilon_k \\ y_{k-1} = y_k \\ v_{k-1} = v_k \end{cases}$$

Control diagram of PR implementation



$$aw = \begin{cases} y_{max} - y & , y > y_{max} \\ -y_{max} - y & , y < -y_{max} \end{cases}$$

Another discretization using delta operator is presented in the Laboratory Handbook PV Systems Lab 3 - Appendix and will be demonstrated in the lab

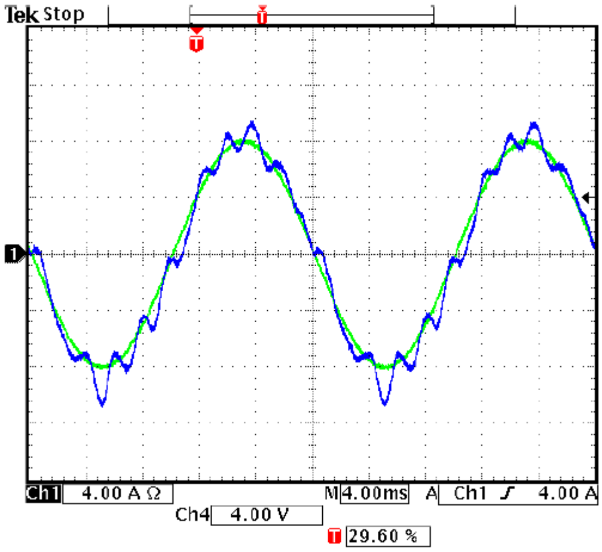
Experimental results

- 1.5 kW IGBT full-bridge inverter
- dSPACE 1103 controller
- LCL filter (1.4mH, 2uF, 0.7mH)
- Ud = 450 V
- Ug = 230 V rms
- Kp=10, Ki=1000,
- fs = 10kHz

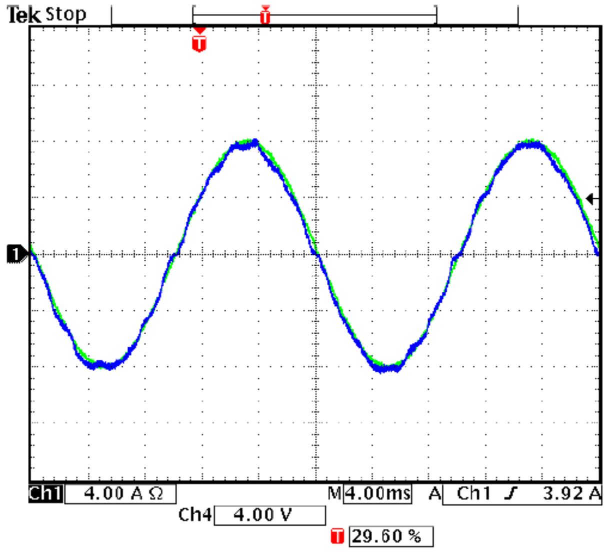
Inverter + LCL dSPACE

Experimental results - current harmonics in stationary

PI + Voltage-Feed-Forward (Kp=10, Ti=4Ts)
THD = 12%,

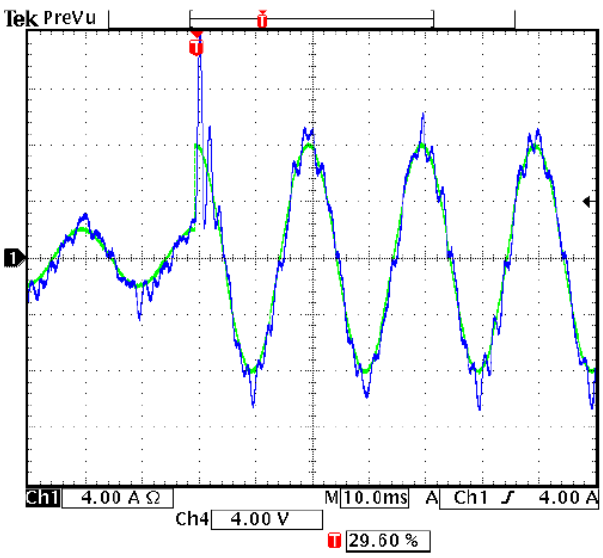


PR+HC (Kp=10, Ki=1000, Ki3,5,7=1000)
THD = 1.0%.

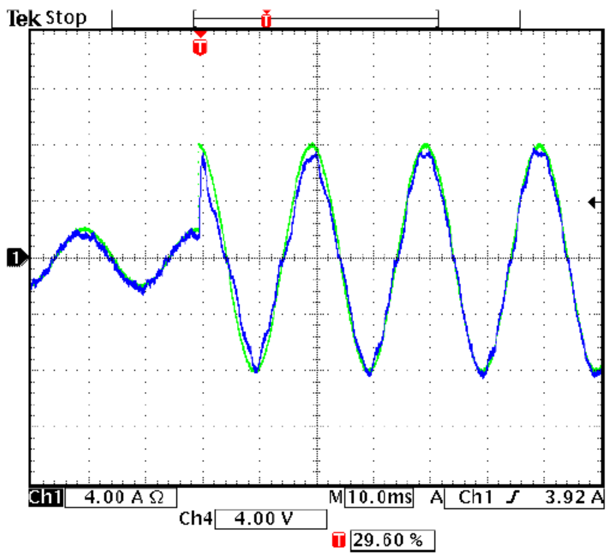


Experimental results - current response at reference step

PI + Voltage-Feed-Forward (Kp=10, Ti=4Ts),
Overshoot = 100%



PR+HC (Kp=10, Ki=1000, Ki3,5,7=1000)
Overshoot = 0!



Conclusions

- A new current control strategy called Proportional Resonant (PR) suitable for PWM grid-connected VSI has been successfully developed and tested.
- Unlike PI, the PR uses Generalized Integrators (GI) that are double integrators achieving very high gain in a narrow frequency band centred on the resonant frequency and almost null outside.
- This makes the PR controller to act as a notch filter at the resonance frequency and thus it can track a sinusoidal reference without having to increase the switching frequency or adopting a high gain, as it is the case for the classical PI controller.
- Several GI can be been added in order to achieve selective Harmonic Compensation (HC) without influencing the dynamics of the controller.
- A modest computation burden of around 40 ms was achieved for PR+HC on a 16-bit fixed-point TMS320F24xx DSP platform due mainly to a novel discretization method.
- Considerable lower current THD in comparison with the classical stationary PI controller and compliance with IEC 61727/IEEE 929 standards is achieved.

References

[1] IEC 61727 CDV Ed.2 – Characteristics of the Utility Interface for Photovoltaic (PV) Systems, 2002

[2] IEEE Std 929-2000 – IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,2000, ISBN 0-7381-1934-2

[3] Teodorescu,R., Blaabjerg,F., Liserre.M., Borup,U.,-" A New Control Structure for Grid-Connected PV Inverters with Zero Steady-State Error and Selective Harmonic Compensation" – Proceedings of APEC'04, Anaheim, CA

[4] Teodorescu,R., Blaabjerg,F., Liserre.M.- "Proportional-Resonant Controllers. A New Breed of Controllers Suitable for Grid-Connected Voltage-Source Converters" Proceedings of OPTIM'04, 20-21 may 2004, Brasov, vol. III pp 9-14

Agenda

- Control structures for single-phase PV systems
- Grid synchronization and monitoring
- Current control design
- **MPPT strategies**
- Anti-islanding strategies

Objectives

- Introduction to MPPT
- Incremental conductance strategy
- Perturb & Observe strategy
- Constant Voltage
- Conclusions
- Reference papers

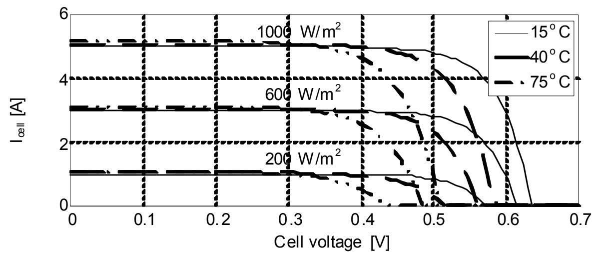
Introduction to Maximum Power Point Tracking - MPPT

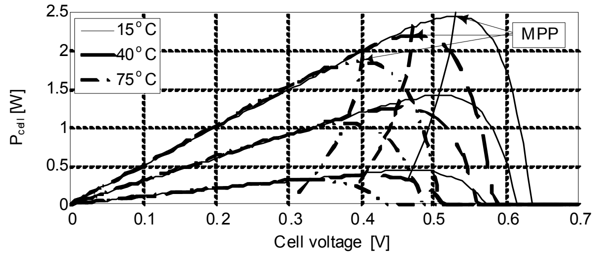
The MPP is affected by temperature and irradiance.

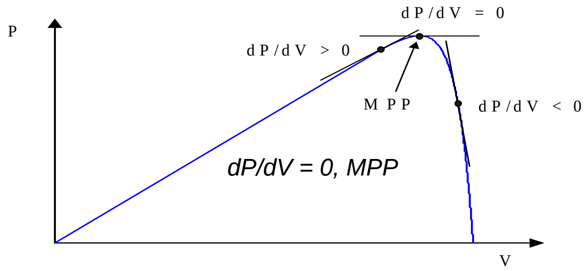
The task of MPPT is to track this MPP regardless of weather or load conditions so that the PV system draws maximum power from the solar array.

The MPPT is a nonlinear and time-varying system that has to be solved.

All algorithms are based on the fact that, looking at the power characteristic, at the left of the MPP the dP/dV > 0, at the right dP/dV < 0 and at MPP dP/dV = 0



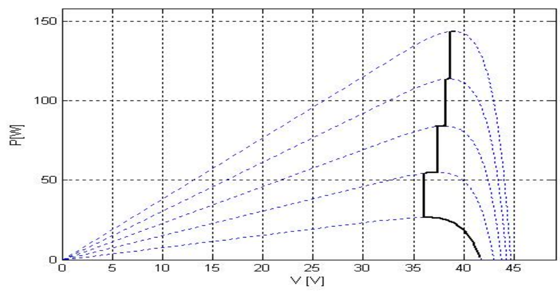


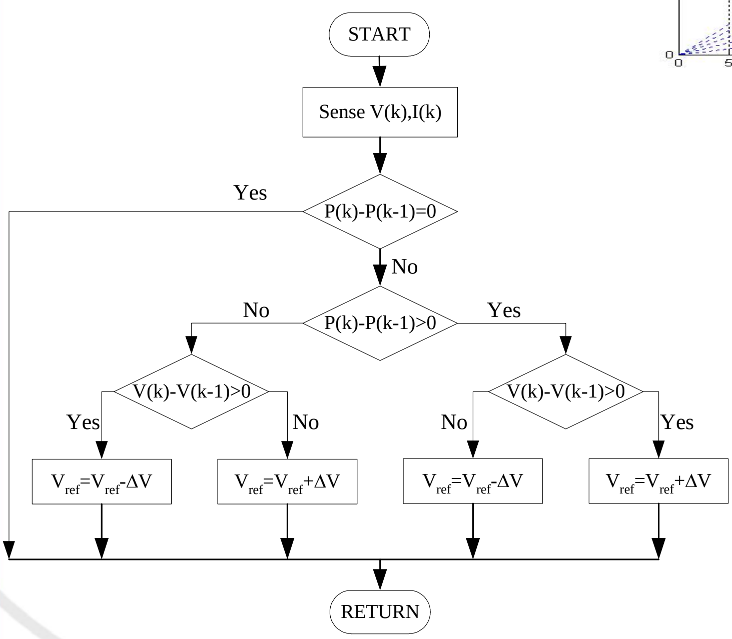


MPPT strategies – Perturb and Observe (P&O)

Advantages: easy to implement

Disadvantages: oscillation around MPP





$$\left.\begin{matrix} dP > 0 \\ dV > 0 \end{matrix}\right\} \Rightarrow \frac{dP}{dV} > 0 \Rightarrow increase\ V$$

$$\left.\begin{matrix} dP > 0 \\ dV < 0 \end{matrix}\right\} \Rightarrow \frac{dP}{dV} < 0 \Rightarrow decrease\ V$$

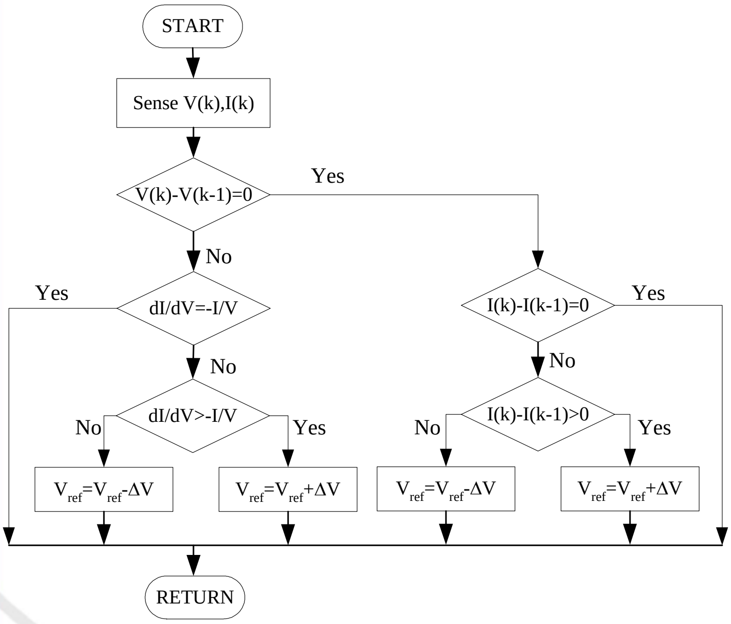
$$\left.\begin{matrix} dP < 0 \\ dV > 0 \end{matrix}\right\} \Rightarrow \frac{dP}{dV} < 0 \Rightarrow decrease\ V$$

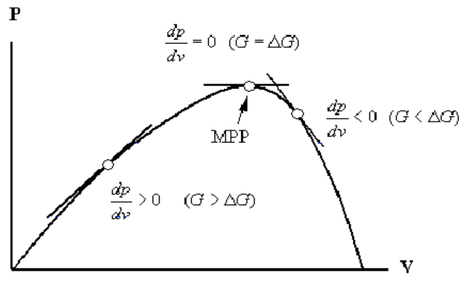
$$\left.\begin{matrix} dP < 0 \\ dV < 0 \end{matrix}\right\} \Rightarrow \frac{dP}{dV} > 0 \Rightarrow increase\ V$$

MPPT strategies – Incremental Conductance (INC)

Advantages: no more perturbations when MPP is reached

Disadvantages: increased complexity over P&O





dP/dV > 0, if G > -dG

dP/dV = 0, if G = -dG

dP/dV < 0, if G < -dG

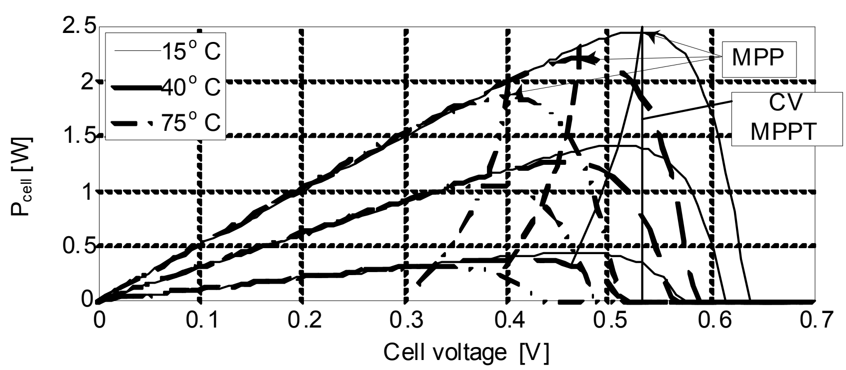
$$P = VI \Rightarrow \frac{dP}{dV} = I + V\frac{dI}{dV}$$

$$MPP: \frac{dP}{dV} = 0 = \frac{I}{V} + \frac{dI}{dV} = G + dG$$

MPPT strategies - Constant Voltage (CV)

Constant Voltage

This algorithm makes use of the fact that the MPP voltage changes only slightly with varying irradiance, The ratio of VMP/VOC depends on the solar cell parameters, but a commonly used value is 76%. In this algorithm the MPPT momentarily sets the PV array current to zero to allow a measurement of the array's open circuit voltage. The array's operating voltage is then set to 76% of this measured value. This operating point is maintained for a set amount of time and then the cycle is repeated. A problem with this algorithm is the available energy is wasted when the load is disconnected from the PV array, also the MPP is not always located at 76% of the array's open circuit voltage.



Conclusions

- Preliminary results indicate that perturb and observe compares favorably with incremental conductance and constant voltage.

	P&O	INC	CV
Array	96.5%	98.2%	88.1%
Simulator	97.2%	98.5%	92.7%

- Although incremental conductance is able to provide marginally better performance, the increased complexity of the algorithm will require more expensive hardware, and therefore may have an advantage over perturb and observe only in large PV arrays

References

[1] D.P.Hohm, M.E.Ropp – "Comparative Study of MPPT Algoithms Using Experimental, Programmable MPPT Test Bed", Proc. of Photovoltaic Specialists Conference, 2000, pp.1699 - 1702

Agenda

- Control structures for single-phase PV systems
- Grid synchronization and monitoring
- Current control design
- MPPT strategies
- **Anti-islanding strategies**

Objectives

- What in the earth is anti-islanding?
- Anti-islanding requirements
- Anti-islanding methods (passive/active)
- Positive feedbcak method
- Harmonic injection
- Conclusions
- Reference papers

Understanding anti-islanding

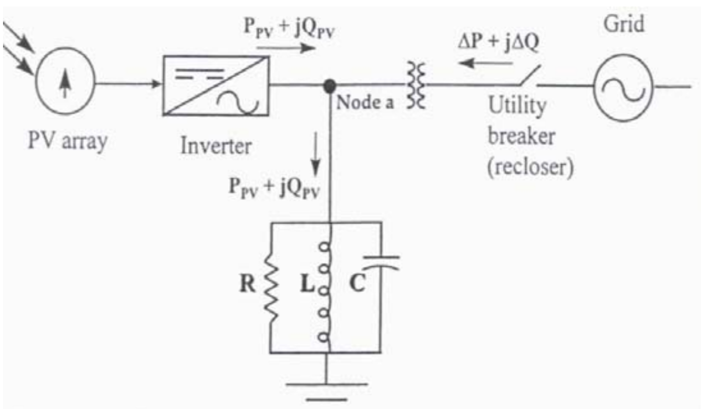
- Islanding for a distribute power generation system (DPGS) is defined when the DPGS does not cease to operate when the grid is disconnected, i.e. is continuing to operate with local load
- We can have desired islandings, for example in power systems when a section containing DPGS and load is running without conenction to the grid and undesired islanding when it can pose danger for grid maintainance people!
- In PV, WT and other Distribute power generation systems (DPGS) there are anti-islanding features required by standards!

Rationale for anti-islanding requirements

- The utility cannot control voltage and frequency in the island, creating the possibility of damage to customer equipment in a situation over which the utility has no control.
- Utilities, along with the PV distributed resource owner, can be found liable for electrical damage to customer equipment connected to their lines that results from voltage or frequency excursions outside of the acceptable ranges
- Islanding may create a hazard for utility lineworkers by causing a line to remain energized that may be assumed to be disconnected from all energy sources.
- Reclosing into an island may result in retripping the line or damaging the distributed resource equipment, or other connected equipment, because of out-of-phase closure.
- Islanding may interfere with the manual or automatic restoration of normal service by the utility.

IEEE929 [1] / IEC61727[2]

anti-islanding requirements



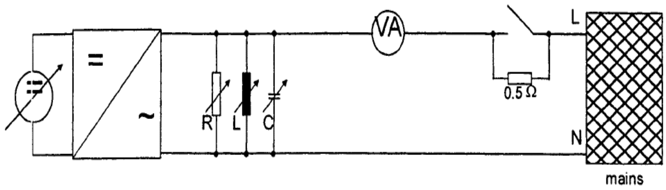
The inverter shoud cease to energize the utility in 10 cycles (200ms for 50Hz) having an RLC local load with Q=2.5 (Q=2.5P!)

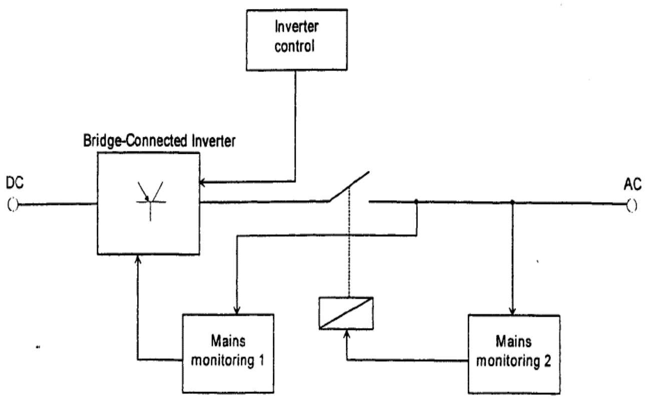
The test should be repeated for 25, 50, 75 and 100% P with a perfect balanced power (igrid=0)

In US IEEE929 was incorporated in the new standard IEEE 1574 [3] - which applys to all distributed power generation systems up to 30 kW (PV, FC, etc).

In EU, the IEC61727 is still a “draft” but most of the countries require similar demands.

EN 50330 (ENS) requirements for PV [4]





Having a perfect balanced local loading (Igrid=0) the PV must isolate from the grid within <u>5 seconds</u> at a change of impedance of <u>0.5 ohms</u> resistive.

The test should be repeated for different grid impedance angles

The automatic disconnecting facility consists in two independent mains monitoring devices (redundance)

Anti-islanding methods [5]

Passive methods

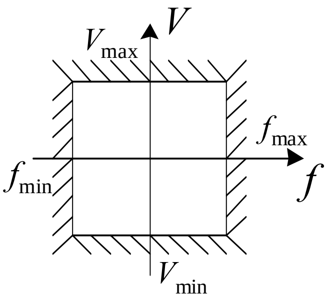
- Under/Over Voltage (UV/OV) and Under/Over Frequency (UF/OF)
- Voltage phase jump detection
- Detection of voltage harmonics

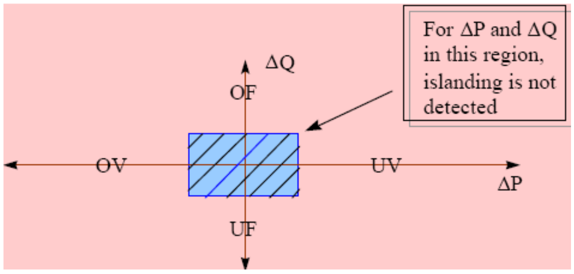
Active methods - resident in the inverter

- Output power variation
- Active Frequency Drift (AFD)
- Slip-Mode frequency-Shift (SMS)
- Positive feedback of frequency or voltage
- Impedance measurement using external device or harmonic injection

Under / Over Voltage and Under / Over Frequency

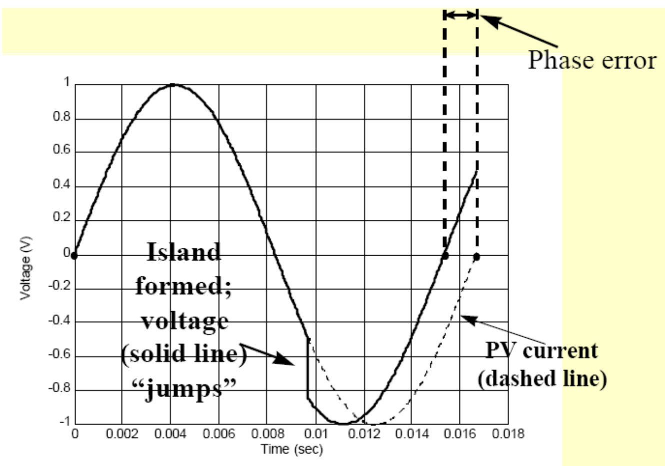
- **Description:** Inverter operation is only allowed within a selected amplitude/frequency window. If the amplitude or frequency of the PCC voltage leaves the window, the PV system is disconnected from the utility.
- **Strengths**: low cost, equivalent to utility protection, is used in conjunction with other anti-islanding methods
- **Weaknesses**: Large NDZ, slow reaction times
- **NDZ**: dependent on impedances, power ratings, operating point





Voltage phase jump detection

- **Description:** monitor the phase difference between the inverter and the utility for a sudden jump
- **Strengths**: easy to implement, does not affect the output power quality or system transient response
- **Weaknesses**: difficult to choose thresholds that detect islanding without false trips
- **NDZ**: unity power factor loads produce no phase error!



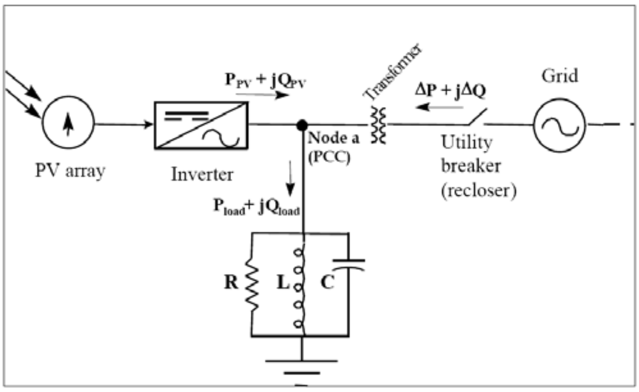
Detection of voltage harmonics

- **Description:** detect the increase of THD in the PCC voltage that can occur in islanding mode due to switching harmonics

– **Strengths**: should not be dependent on power factor, good for multi-inverter applications

– **Weaknesses**: not always possible to select a threshold that guarantees non-islanding without causing excessive false trips. Also som inductive load could attenuate the switching harmonics below the threshold.

– **NDZ**: difficult to evaluate!



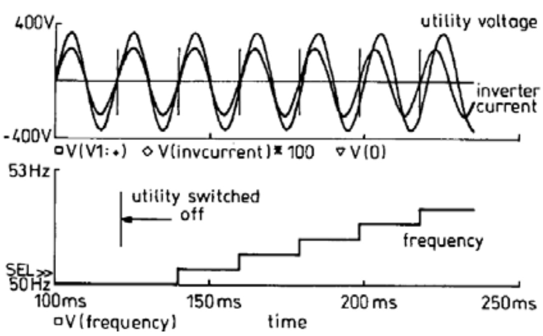
Active frequency drift [6]

- **Description**: output waveform is slightly distorted so islanding causes a drift in frequency

– **Strengths**: very easy to implement with microprocessor based inverters

– **Weaknesses**: small degradation in output power quality

– **NDZ**: relatively large relative to other active methods, depends on the value of the chopping fraction used, small (<1% then same as SMS), larger causes NDZ to shift toward capacitive.



Ipv goes to zero before or after the PCC voltage.

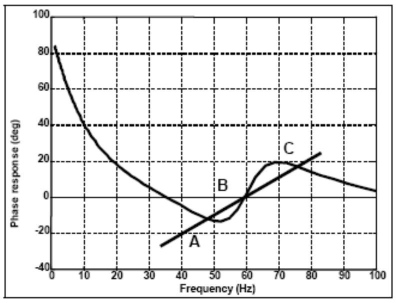
Slip-mode Phase Shift (SMS) [6]

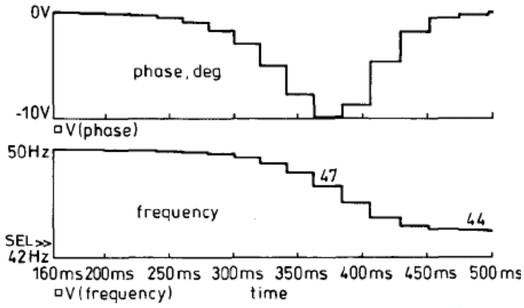
- **Description**: the current-voltage phase is changed as funtion of frequency so islanding causes a drift in frequency

– **Strengths**: very easy to implement with microprocessor based inverters, works with multi-inverter applications

– **Weaknesses**: some RLC loads (high-Q loads with resonant frequencies very near the line frequency) have phase response curves such that the phase of the load increases faster than the phase of the PV inverter

– **NDZ**: relatively small.





Positive feedback methods

RLC load characteristics:

$$P = V^2 / R$$

$$Q = V^2(\omega C - 1/\omega L)$$

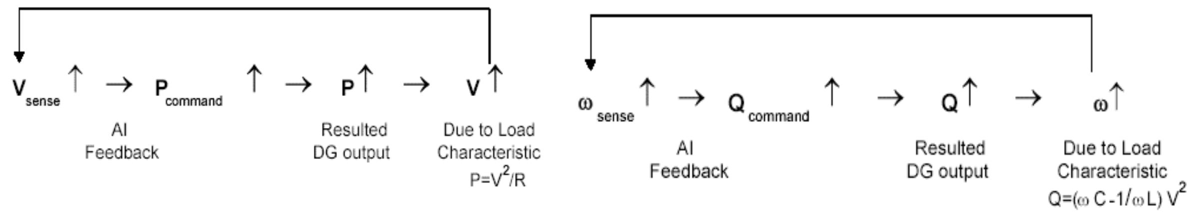
Two mechanisms

Voltage feedback – when inverter output voltage is increasing, the AI feedback will command the inverter output power to increase. In order to balance the power, the voltage will keep increase… As a result the voltage will be eventually out of nominal ranges so the islanding can be detected! Similar but opposite destabilization occurs when the sensed voltage is decreasing

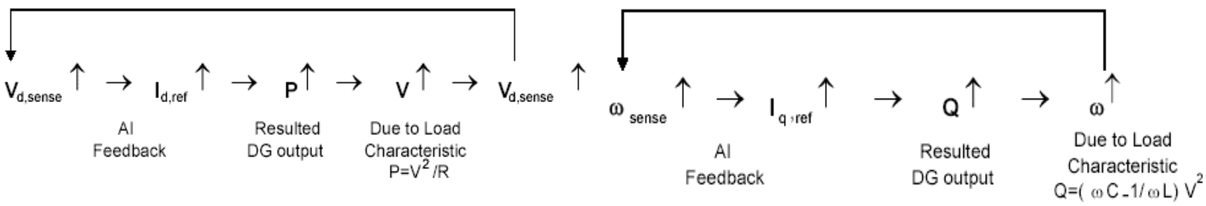
Frequency feedback – when the inverter-sensed frequency is increasing, the AI feedback will command the inverter reactive-power output to increase. Due to load characteristic, the frequency will keep increasing in order to balance the reactive power. The increased frequency will further drive the inverter reactive power up, and as result, the frequency will increase more…Eventually the frequency will be driven out of range and the inverter will trip.. Similar results occurs when the frequency is initially decreasing.

Frequency positive feedback implementation

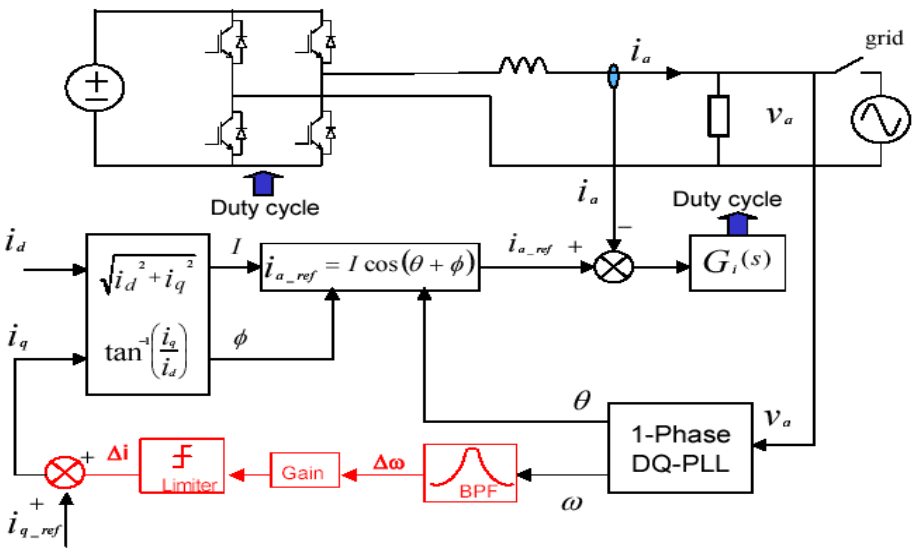
Concept



DQ implementation



Frequency positive feedback



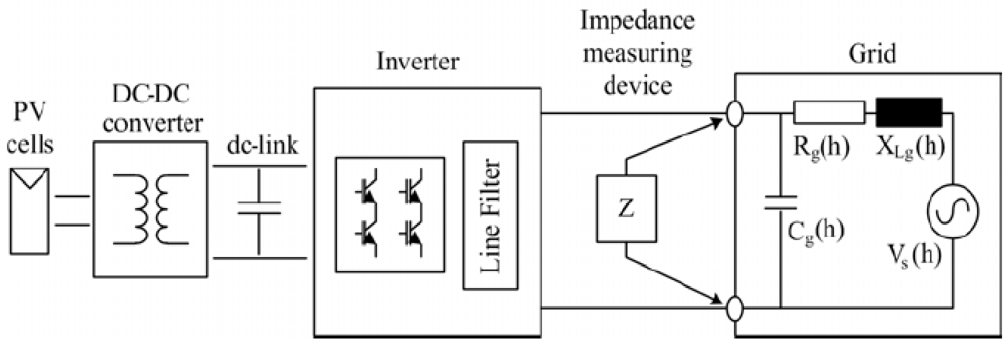
DQ pll using Inverse Park Transformation can be used in single-phase systems to create the dq components!

BPF 1-10Hz needed to remove noise and dc-offset! Gain should be high enough to make the system unstable in islanding but stable in non-islanding mode

For Voltage positive feedback, *Vd* (amplitude og *Vgrid*) is feedforwarded to *id_ref*

Impedance measurement - external device

Classical solution - using external device that produces an transient

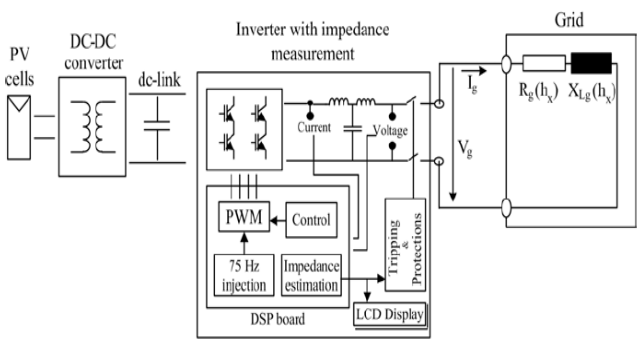


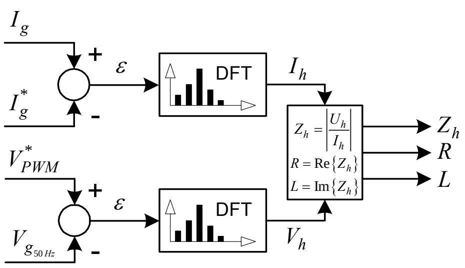
For ex. A capacitor is switched in and the grid voltage zero-crossing shift is measured. Thus the grid impedance is estimated

The disadvantage is that it requires extra hardware!

Impedance measurement - harmonic injection

New solution - using extra SOFTWARE! [7]





$$\underline{Z}(h) = \frac{\underline{V}(h)}{\underline{I}(h)}$$

$$\underline{Z}(h) = \frac{V \cdot e^{j\varphi_V}}{I \cdot e^{j\varphi_I}} = Z \cdot e^{j\varphi_Z}$$

$$\underline{Z}(h) = R_g + j \cdot \omega_h \cdot L_g$$

$$\underline{Z}(50Hz) = R_g + j \cdot \omega_{50} \cdot L_g$$

A non-characteristic harmonic current is injected in the grid by through the PWM. The resulting harmonic voltage will depend on the grid impedance. The voltage and current at this frequency are computed using DFT. The impedance is calulated by dividing the voltage to the current. The real part is Rg and the imaginary part is Lg

Impedance measurement - harmonic injection

DFT Implementation

$$\overline{\Lambda}_h = \sum_{n=0}^{N-1} v(n)\cdot\cos\left(\frac{2\pi\cdot h\cdot n}{N}\right) - j\cdot\sum_{n=0}^{N-1} v(n)\cdot\sin\left(\frac{2\pi\cdot h\cdot n}{N}\right)$$

$$\overline{\Lambda}_h = \lambda_{hr} + j\cdot\lambda_{hi}$$

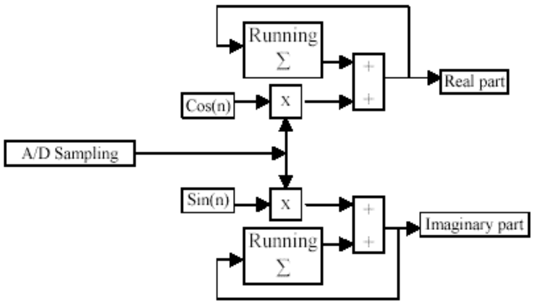
N is the number of samples per fundamental period;

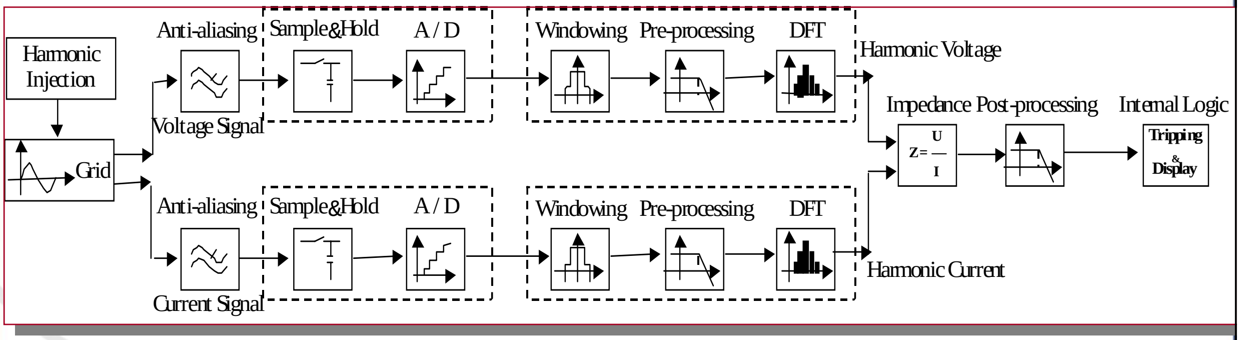
$v(n)$ is the input signal (voltage or current) at point n;

Λ_h is the complex Fourier vector of the h^{th} harmonic of the input signal;

λ_{hr} is the real part of Λ_h,

λ_{hi} is the imaginary part of Λ_h.

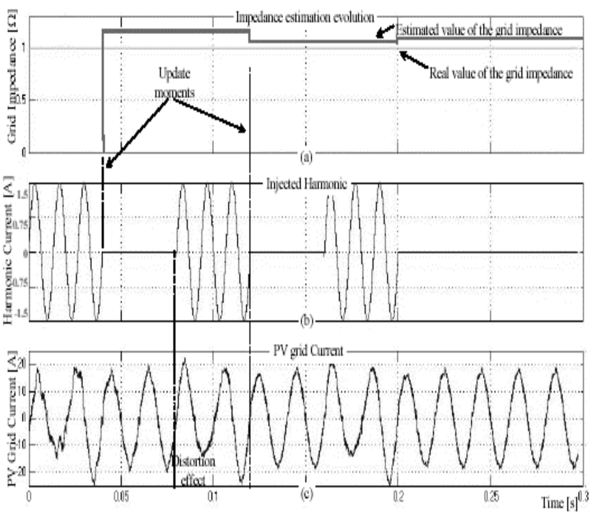


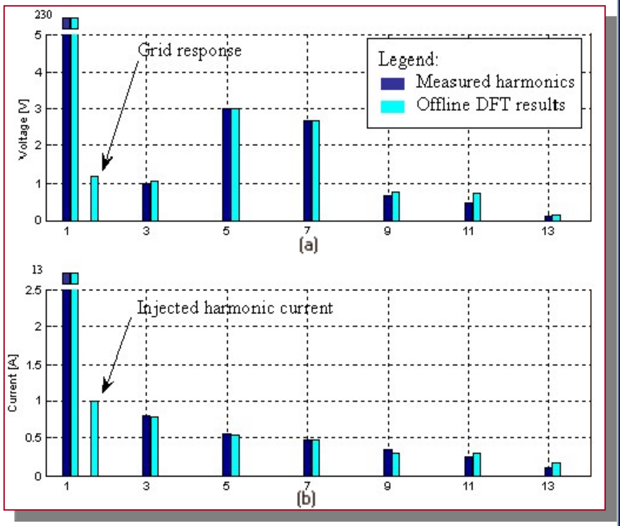


Principle of harmonic detection and calculation of the grid impedance.

Simulation results

Impedance measurement - harmonic injection 75Hz



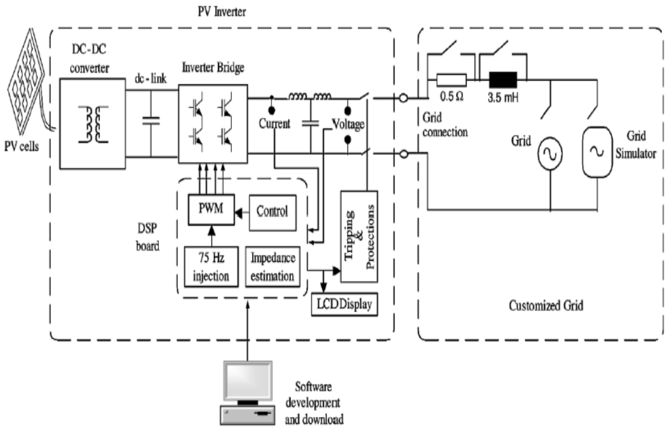


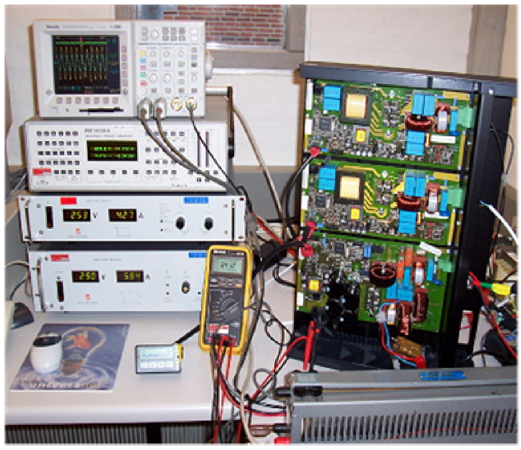
Comparison of spectra with and without harmonic injection a) Grid voltage. b) Grid current. The PV power is 3 kW.

A current transient in the current is introduced together wth the injection resulting in impedance estimation error!

Experimental results

Test setup

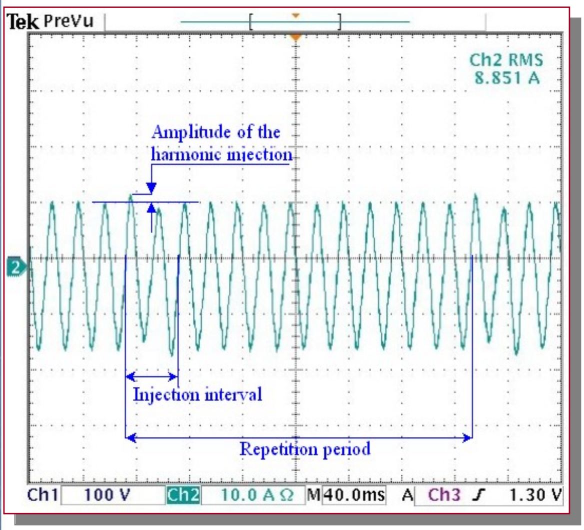




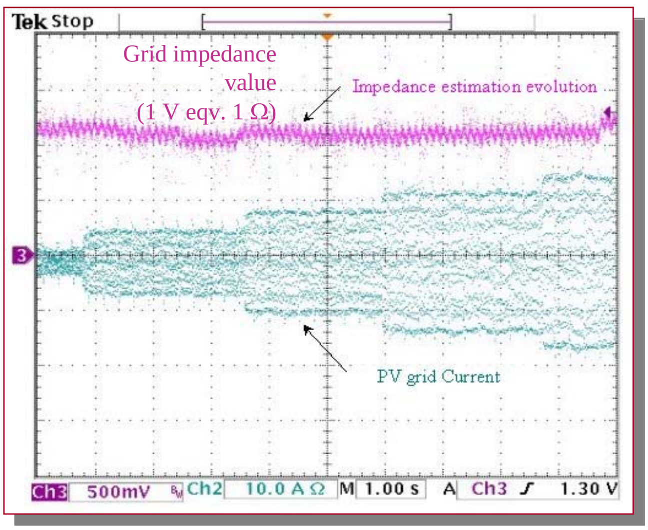
3 kW IGBT full-bridge inverter, TMS430F24xx DSP controller (40µs computation time) LCL filter resonance freq = 4.25kHz, Ud = 370 V, Ug = 230 V rms, Kp=2, Ki=300, fs=8.5kHz

Experimental results

3 kW PV inverter



Non-continuous injection of the harmonic into the grid.



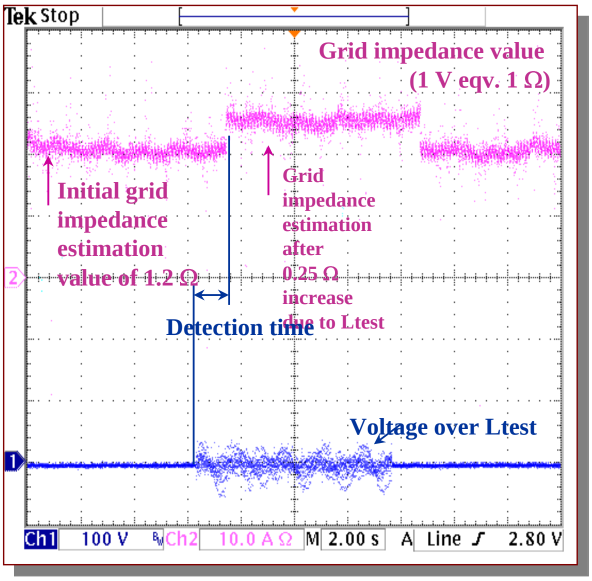
Impedance estimation when the PV current is changing from P=0.3 kW to P=3 kW. The result is filtered every 1 s

Non-continuous injection of the harmonic. Estimation is checked for different power levels

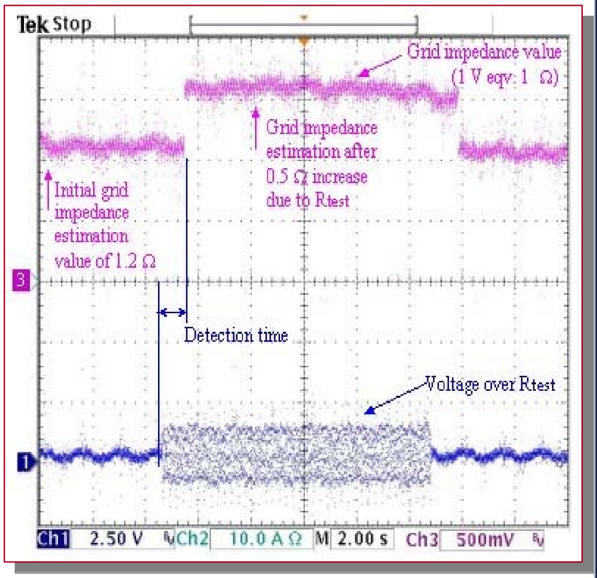
Experimental results

3 kW PV inverter

Detection of both resistive and inductive impedance jump!



Dynamic response of the method detecting a 0.8 mH inductive increase of the grid impedance.



Dynamic response of the method detecting 0.5 Ω resistive increase.

Experimental results

TABLE III. Evaluation of impedance measurements with different amplitudes and repetition rates for a PV-inverter power of 1 kW. The real grid impedance is 1.2 Ω.

Amplitude of the injection I_h [A]	Repetition rate [injection periods / total periods]	Required power for ENS measurement P [W]	ENS measurement result Z [Ω]	ENS measurement error [%]
3.5 A	2/7	2.1 W	1.20 Ω	- 0.0 %
3.5 A	2/13	1.1 W	1.14 Ω	- 5.0 %
1.3 A	2/7	0.29 W	1.17 Ω	- 2.5 %
1.3 A	2/13	0.15 W	1.12 Ω	- 6.5 %
0.7 A	2/13	0.04 W	1.53 Ω	+ 44.5 %

The error is increasing at lower harmonic levels. But still can detect 0.5 ohms jump!

Conclusions

Anti-islanding is a **requirement** for DPGS

Software Anti-islanding methods are possible

The algorithm can be easilly implemented in the ”existing” DSP control platform and is not requiring extra hardware

For Anti-Islanding standard (IEC61727/IEEE929 frequency or voltage feedback methods can be used in both single-phase or three-phase systems in combination with passive methods to obtain minnimum NDZ.

For ENS standard, harmonic injection can be used

References

[1] IEEE Std 929-2000 – IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,2000, ISBN 0-7381-1934-2

[2] IEC 61727 CDV Ed.2 – Characteristics of the Utility Interface for Photovoltaic (PV) Systems, 2002

[3] IEEE Std 1547 – IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems,2003, ISBN 0-7381-3720-0

[4] EN 50330-1 – Utility Interactive Faile Save Protective Interface for PV-Line Commutated Converters, Copyright OVE/ON, 1999

[5] Evaluation of Islanding Detection Methods for Photovoltaic Utility Interactive Power Systems - Task V, Report IEA-PVPS T5-09: 2002 March 2002, www.iea.org

[6] G.A.Smith, I?A.Onions and D.G. Infield, "Predicting islanding operation of grid connected PV inverters", IEE Proc.-Electr. Power Appl., Vol. 147, No. 1. January 2000

[7] Asiminoaie L.,Teodorescu,R., Blaabjerg,F., Borup,U. – “A Digital Controlled PV-Inverter with Grid Impedance Estimation for ENS Detection ” IEEE Trans on PE 2005.

A Distributed Power Generation System: Wind Power Generation Systems

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Outline

Wind turbine system

Power Conversion

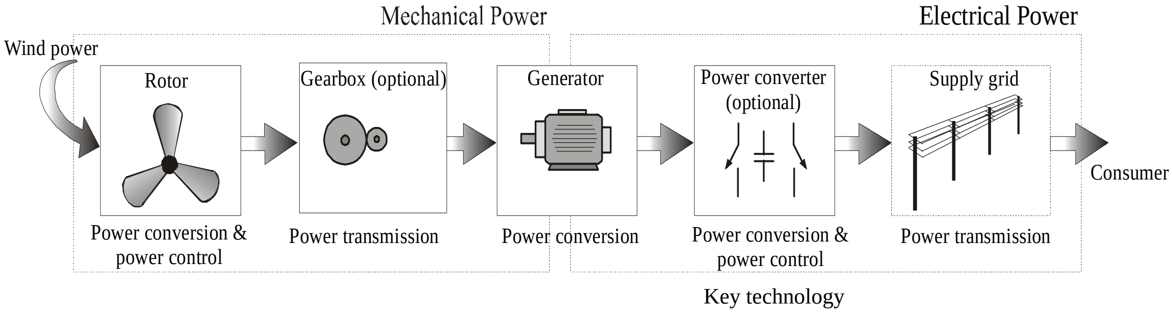
- Fixed speed system
- Variable speed system

Power Converters

Requirements of connecting wind power systems

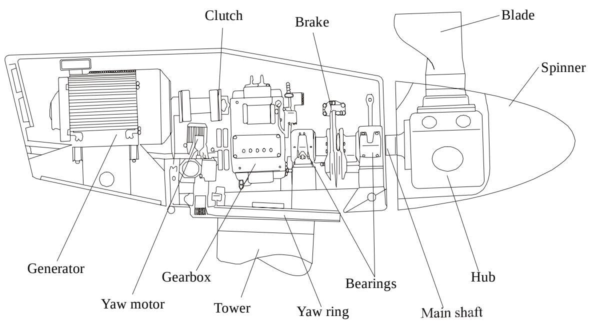
Wind turbine system

Basic power conversion:

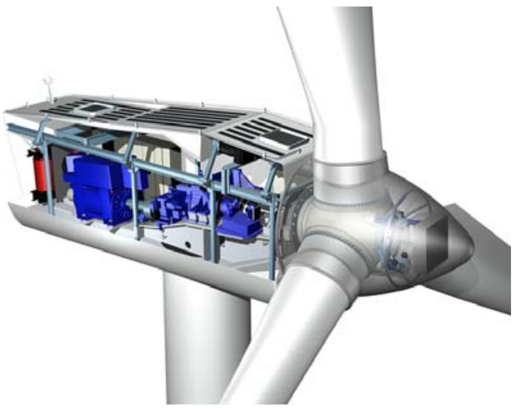


Wind turbine systems

Nacelle in wind turbine



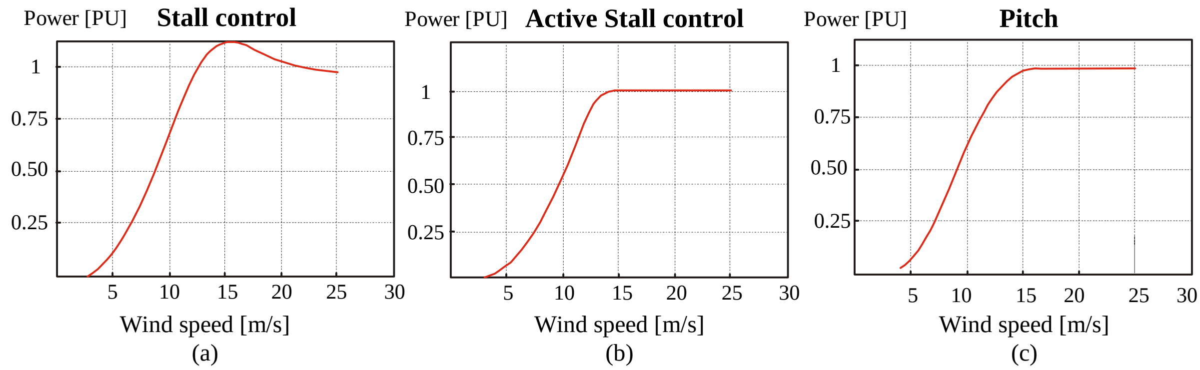
Vestas V80-2 MW



- **Example of technology**

Wind turbine system

Power Control



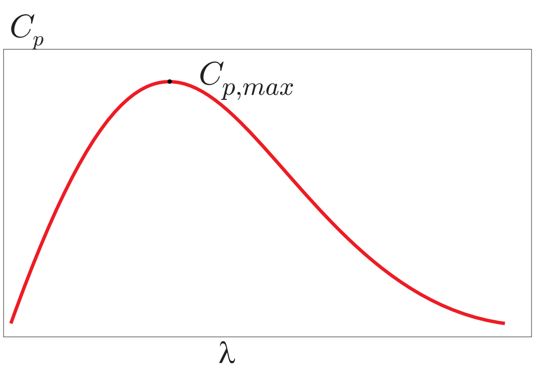
Power curves from different wind turbines

Wind turbine system

Power curve - Aerodynamic

- Power to the generator- shaft is given by:

$$P_{tur} = \frac{1}{2} C_p \rho A_v v_{wind}^3$$

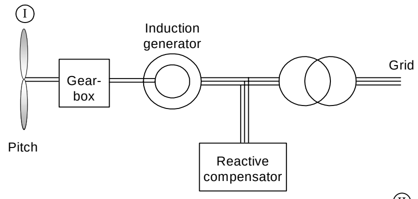


$$\lambda = \frac{v_{tip}}{v_{wind}} = \frac{r_{rt}\omega_{rt}}{v_{wind}}$$

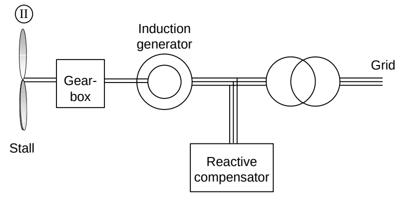
= *ratio between tip-speed and wind speed*

Wind turbine systems

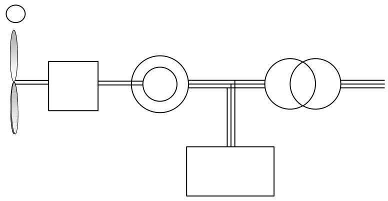
Basic topology for wind turbine (I, II, III)



(a)



(b)



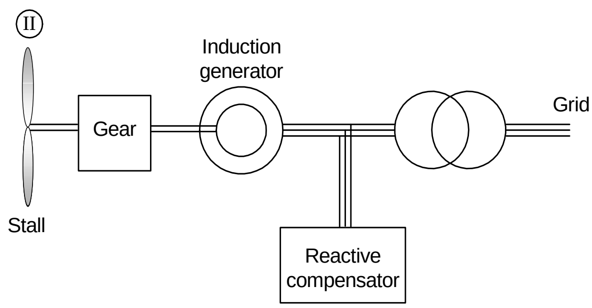
- Fixed speed with capacitor bank (Reactive power)

Wind turbine systems

Two-generator principle (exists in many systems): (System II)

- **Shift between number of poles**
    - **"Variable speed with 1 bit resolution"**
    - **No reduction in mechanical load**
    - **No reduction in power pulsations to the grid**

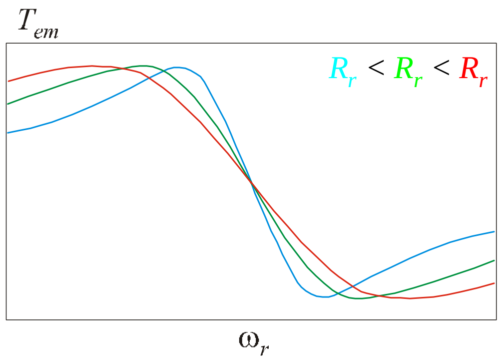
Poles	50 Hz grid (rpm)
2	3000
4	1500
6	1000
8	750
10	600
12	500

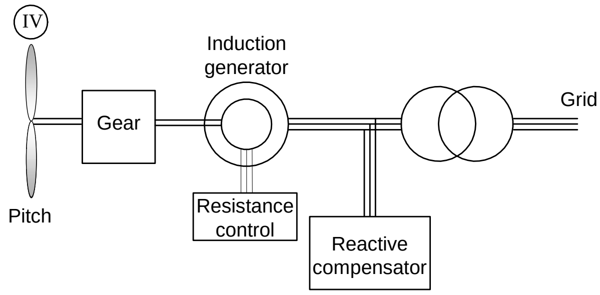


Wind turbine systems

Rotor resistance control (System IV):

- Higher speed range
- Lower mechanical stress
- Less grid pulsations
- Improvement in Optislip (no rings)
- Still reactive power compensation
- Use basically slip-rings
- Speed range still limited to 5-10 % of nominal speed (above synchronous speed)
- Higher power losses in the rotor

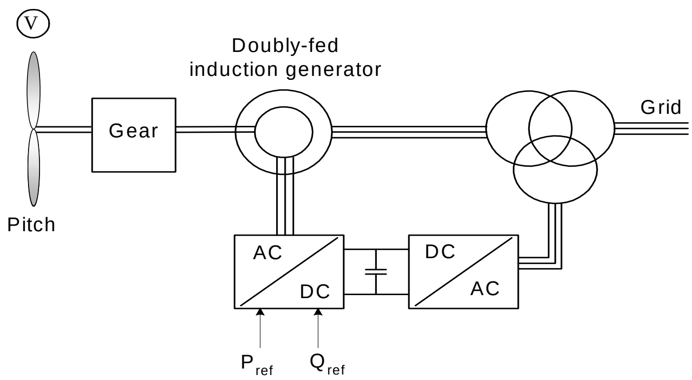




Wind turbine systems

Doubly-fed induction generator - wounded rotor (System V)

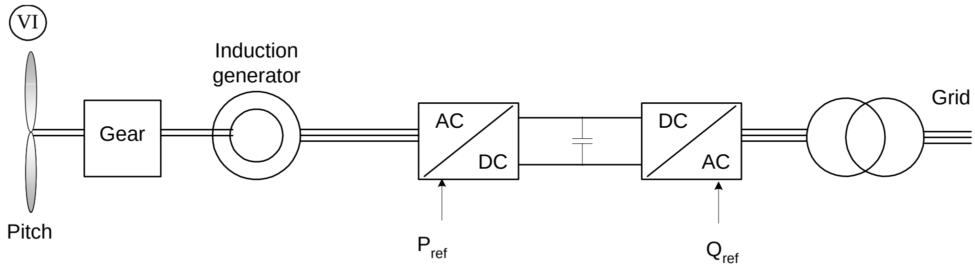
- Limited speed range (-30% to +20%, typical)
- Small-scale power converter (Less power losses, price)
- Complete control of active P_{ref} and reactive power Q_{ref}
- Need for slip-rings
- Need for gear



Wind turbine systems

Induction generator - Squirrel cage rotor (System VI)

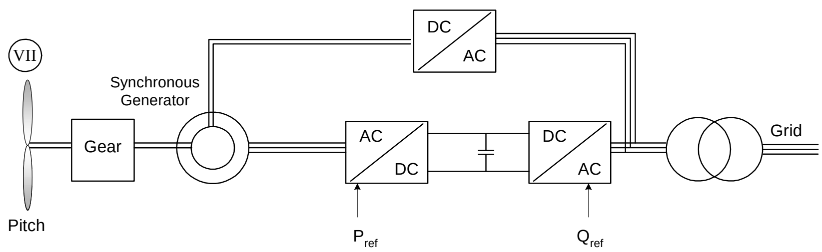
- ➢Full speed range
- ➢No brushes on the generator
- ➢Complete control of active og reactive power
- ➢Proven technology
- ➢Full-scale power converter
- ➢Need for a gear



Wind turbine systems

Synchronous generator - External magnetized (System VII)

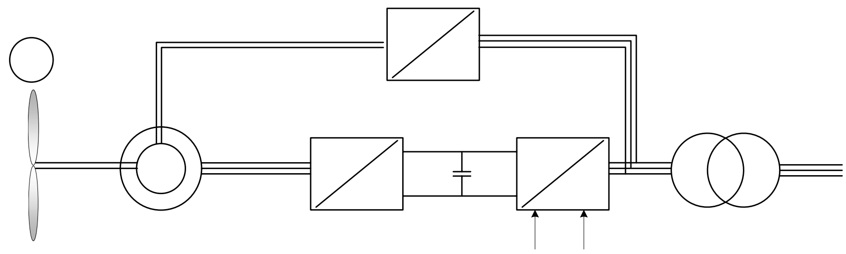
- ➢Full speed range
- ➢Possible to avoid gear (multi-pole generator)
- ➢Complete control of active and reactive power
- ➢Small converter for field
- ➢Need of slip-rings
- ➢Full scale power converter
- ➢Multi-pole generator may be big and heavy



Wind turbine systems

Multi-pole synchronous generator - External magnetized (System VII)

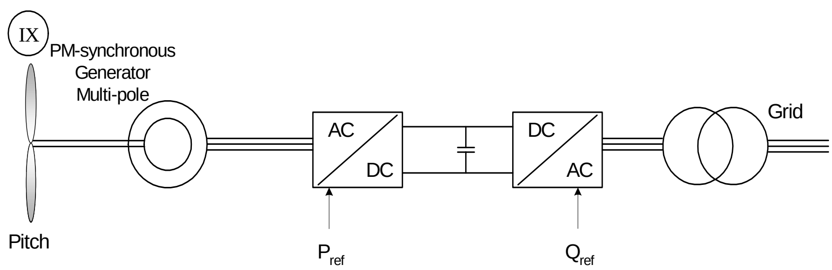
- ➢Full speed range
- ➢Without gear (multi-pole generator)
- ➢Complete control of active and reactive power
- ➢Small converter for field
- ➢Need of slip-rings
- ➢Full scale power converter
- ➢Multi-pole generator may be big and heavy



Wind turbine systems

Permanent magnets synchronous generator - (System IX)

- ➢Full speed range
- ➢Multi-pole generator
- ➢Complete control of active and reactive power
- ➢Brushless (reduced maintenance)
- ➢No power converter for field (higher efficiency)
- ➢Full scale power converter
- ➢Multi-pole generator big and heavy
- ➢Permanent magnets needed



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Wind turbine systems

Comparison of topologies

System comparison of wind turbines									
System	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
Variable speed	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Control active power	Limited	No	Limited	Limited	Yes	Yes	Yes	Yes	Yes
Control reactive power	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Short circuit (fault-active)	No	No	No	No	No/Yes	Yes	Yes	Yes	Yes
Short circuit power	contribute	contribute	contribute	contribute	contribute	limit	limit	limit	limit
Control bandwidth	1-10 s	1-10 s	1-10 s	100 ms	1 ms	0.5-1 ms	0.5-1 ms	0.5-1 ms	0.5-1 ms
Standby function	No	No	No	No	Yes +	Yes ++	Yes ++	Yes ++	Yes ++
Flicker (sensitive)	Yes	Yes	Yes	Yes	No	No	No	No	No
Softstarter needed	Yes	Yes	Yes	Yes	No	No	No	No	No
Rolling capacity on grid	Yes, partly	No	Yes, partly	Yes, partly	Yes	Yes	Yes	Yes	Yes
Reactive compensator (C)	Yes	Yes	Yes	Yes	No	No	No	No	No
Island operation	No	No	No	No	Yes/No	Yes/No	Yes/No	Yes/No	Yes
Investment	++	++	++	++	+	0	0	0	0
Maintenance	++	++	++	++	0	+	+	+	+

- **Power electronics now enables wind energy as a power source**

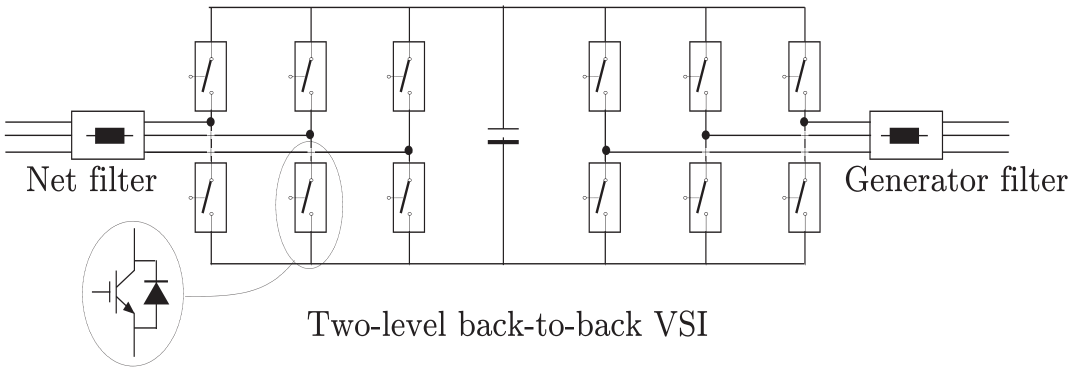
Market share of 2001

Design Concept	World-Market Share	Market Share Germany
Fixed speed (Stall or active stall regulation, fixed speed operation, gearbox, pole-switchable asynchronous	23%	22%
Dynamic slip control (Limited variable speed, pitch regulation, gearbox, pole-switchable asynchronous generators with variable slip)	11%	0%
Doubly-fed generator (Variable speed operation, pitch control, gearbox, double-fed generator utilizing power electronics in the inverter)	50%	49%
Direct-driven variable speed synchronous (generators with large-diameter synchronous ring generator, including pitch control, but no gearbox, utilizing power electronics in the inverter)	16%	29%
Total	**100%**	**100%**

Power Converters

Topologies for IG & DFIG:

➢Back-to-back two-level voltage source converter

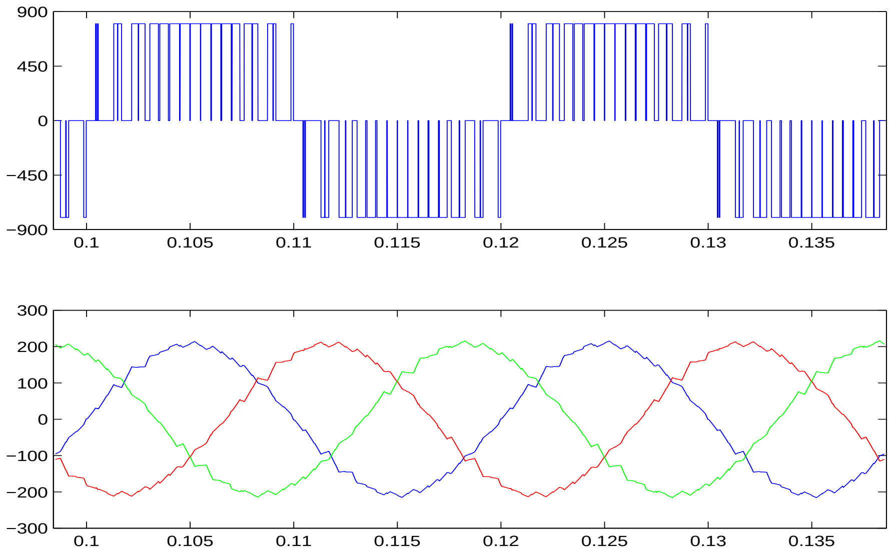


Proven technology from ASD

Power Converters

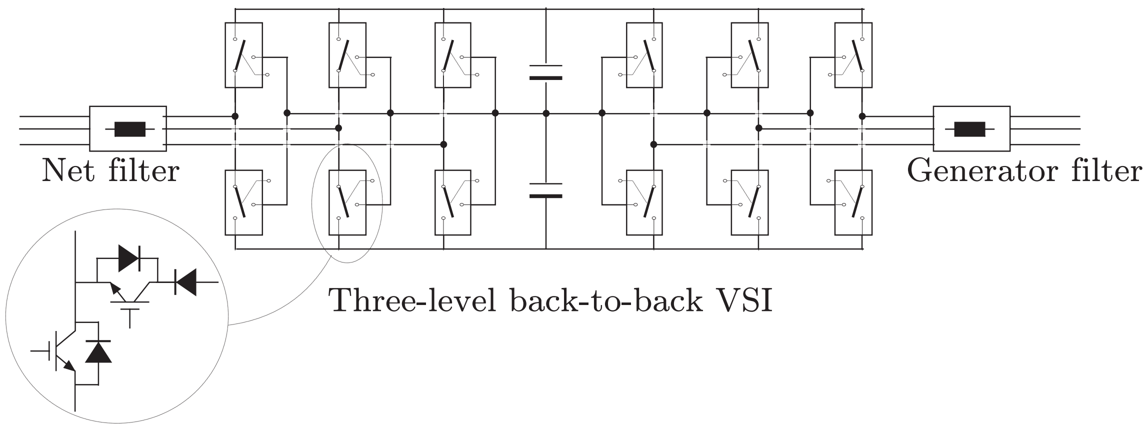
Topologies for IG & DFIG:

Voltage and currents



Power Converters

Topologies for IG & DFIG:

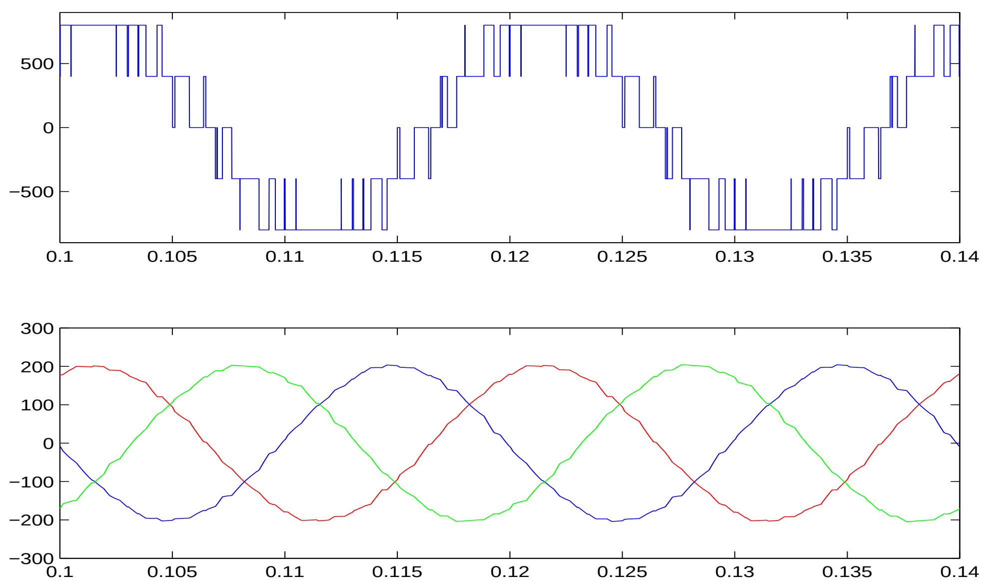


- ➢Back-to-back three-level voltage source converter

Power Converters

Topologies for IG & DFIG:

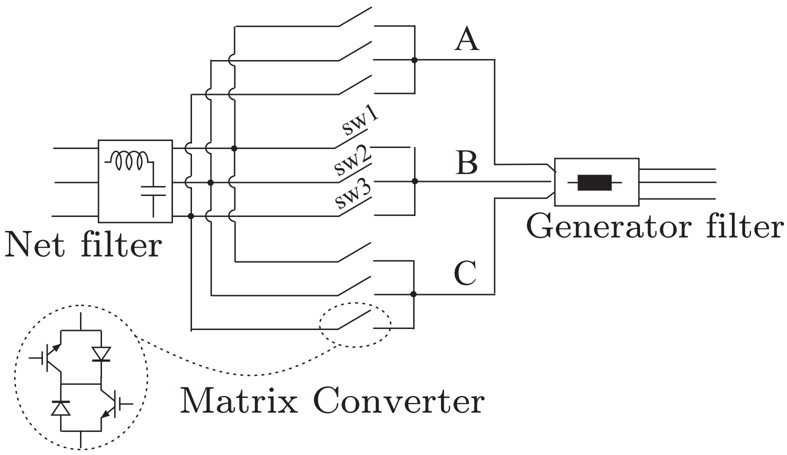
Voltage and currents of three-level voltage source converter



Power Converters

Topologies for IG & DFIG:

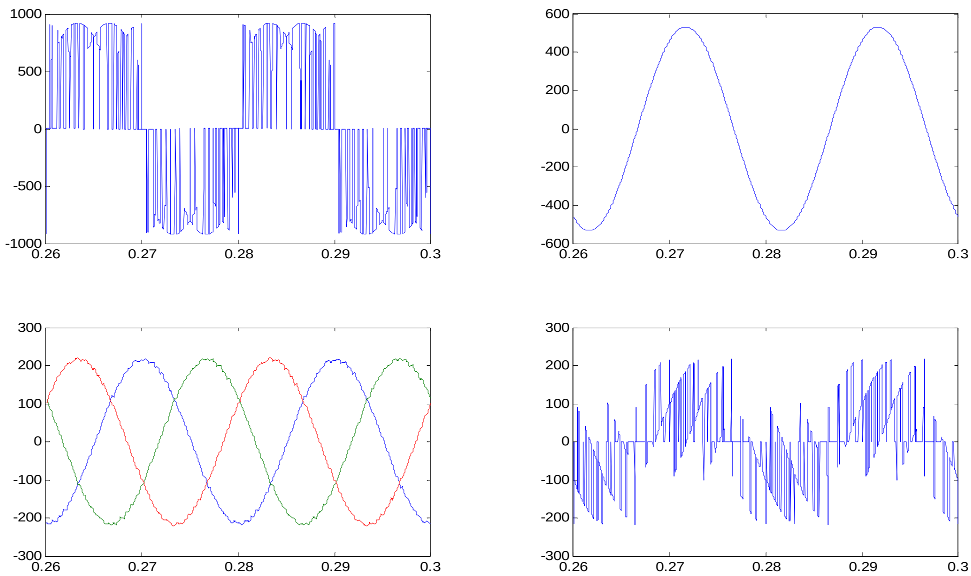
- Matrix converter



Power Converters

Topologies for IG & DFIG:

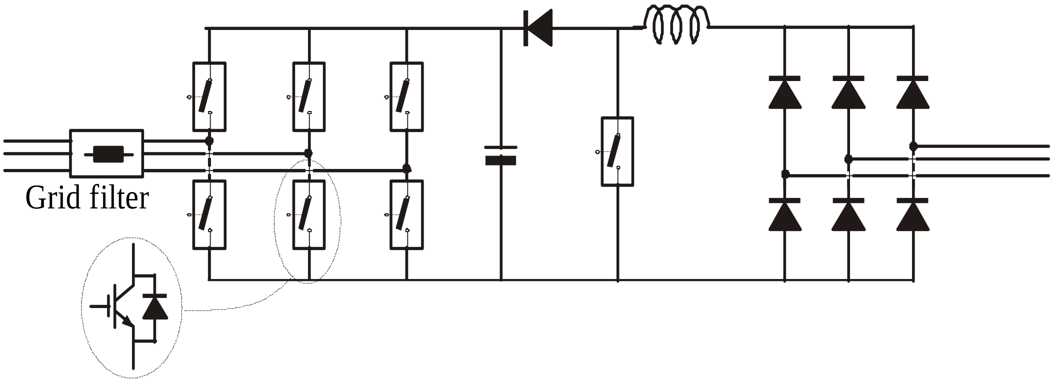
Input and output voltages and currents of matrix converter



Power Converters

Topologies for SG & PMSG:

➢Two-level inverter and boost-rectifier



Requirements to wind turbines

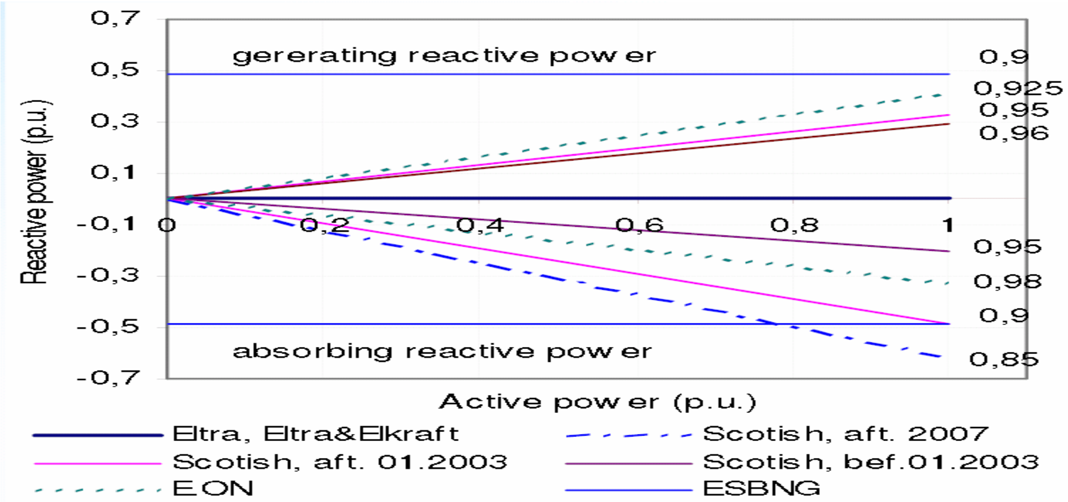
Operate a wind farm/wind turbine like a power station/plant

Grid Code: Technical document containing the rules governing the operation, maintenance, & development of the system

- Steady state
  - ***Voltage support/reactive power compensation***
  - ***Frequency /Power control***
    - ***Low/high frequency support***
  - ***Power Quality, flicker, harmonics***
- Transient /dynamic state
  - ***Fault ride through, to stay connected during low voltage on the grid***
  - ***Ramp rate***
- Communication /power dispatch
  - ***Reliable communication***
  - ***Wind forecasting***
  - ***Participate power market***

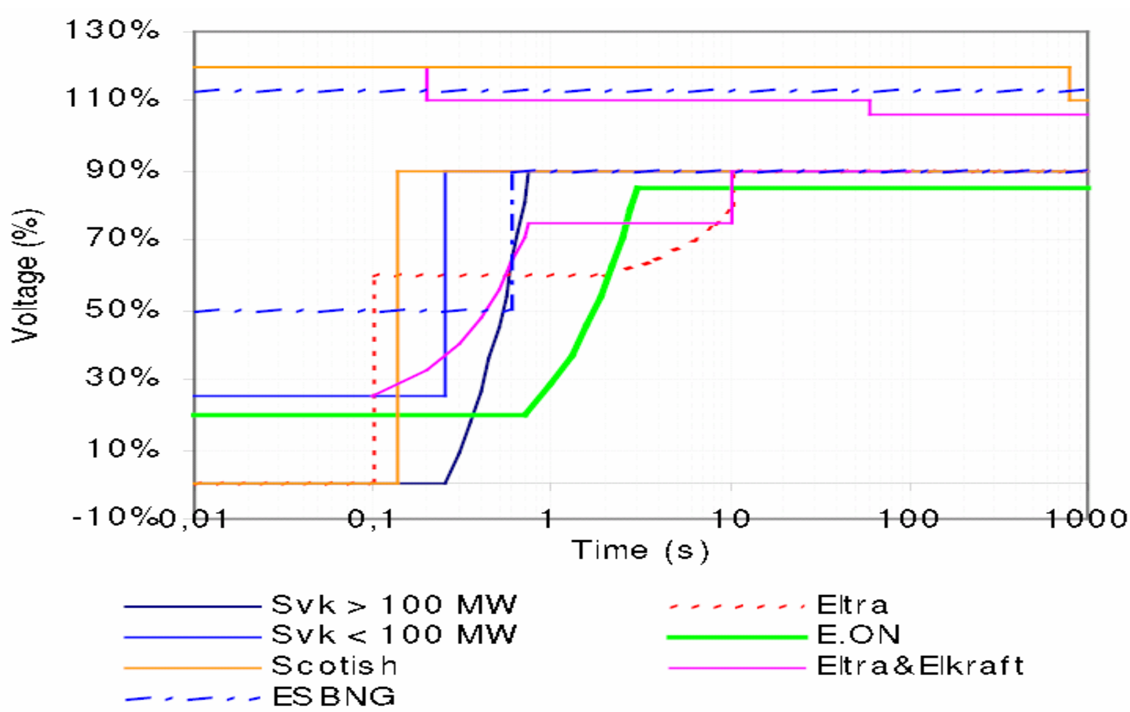
Requirements to wind turbines

Reactive power control

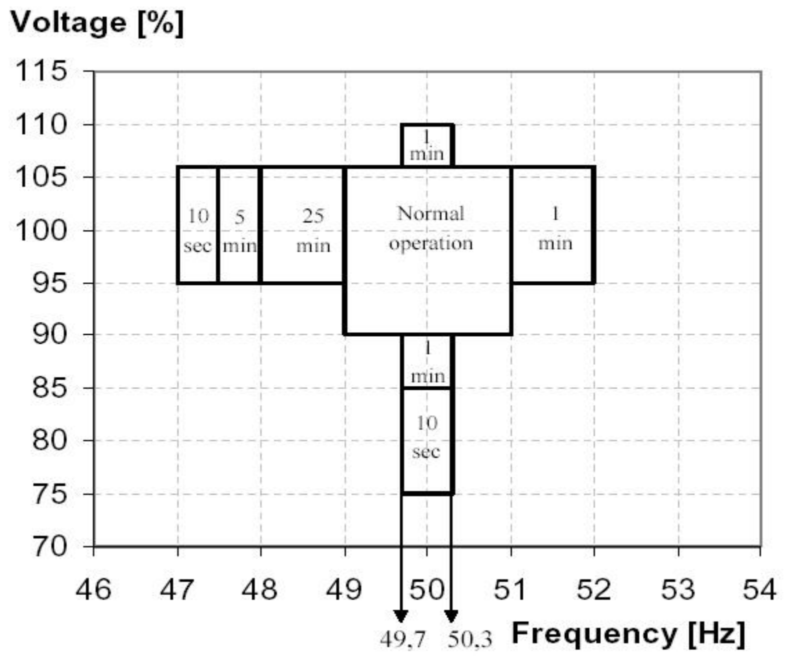


Requirements to wind turbines

Voltage tolerance

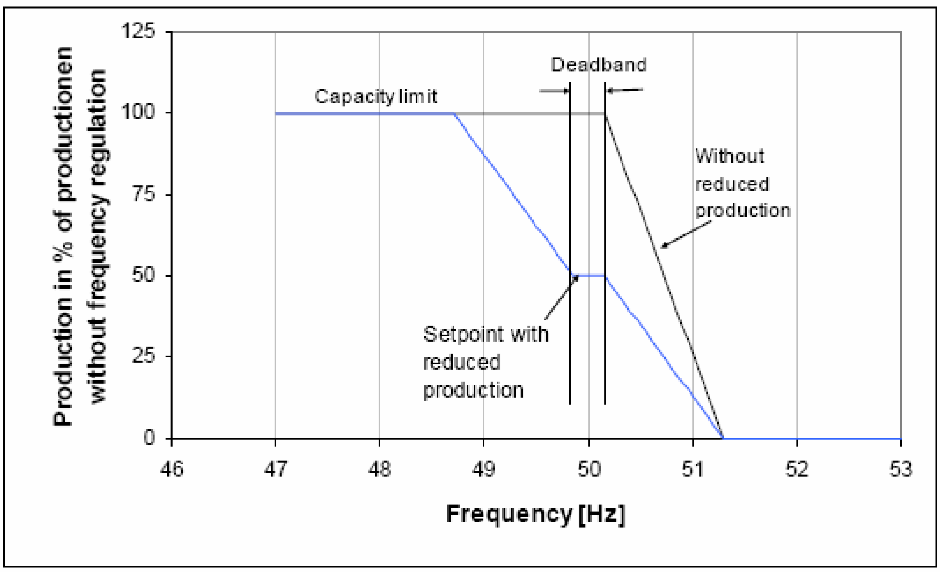


Voltage and frequency requirements



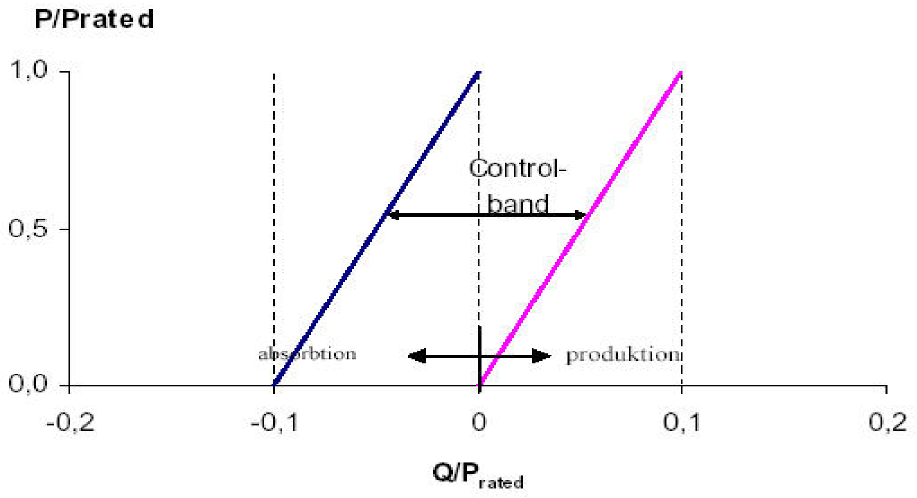
Techincal Regulations TF 3.2.6 (Eltra, Elkraft)

Frequency and power control



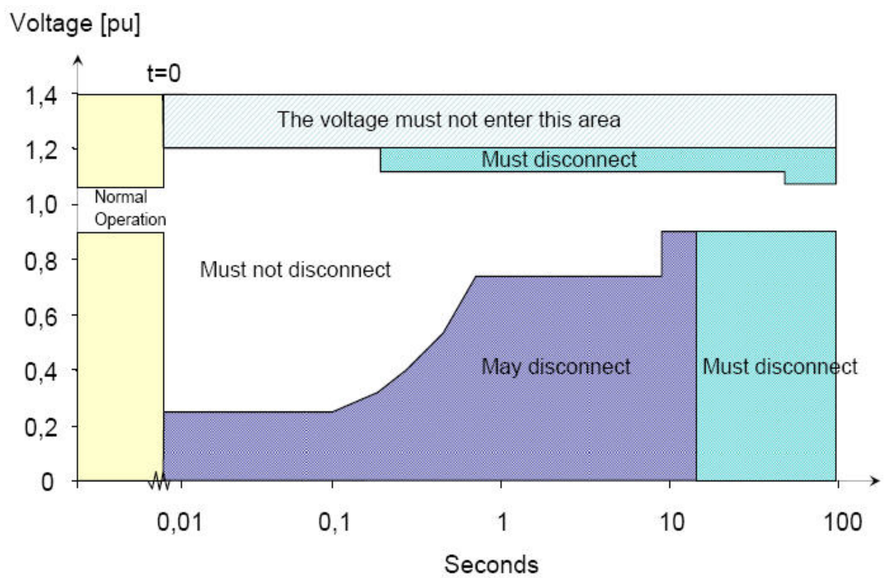
Techincal Regulations TF 3.2.6 (Eltra, Elkraft)

Reactive power



Techincal Regulations TF 3.2.6 (Eltra, Elkraft)

Requirements for wind turbine interaction with the grid during grid faults



Techincal Regulations TF 3.2.6 (Eltra, Elkraft)

Requirements for wind turbine interaction with the grid during grid faults

In all operational situations the wind farm shall be able to withstand the following faults sequences without being disconnected (does not apply to radial connected wind turbines):

- Three-phase fault on a random line or transformer with definitive disconnection without any attempt at reclosing.
  - T=0 3-phase short circuit
  - T=100 ms typical disconnection of the fault
- Two-phase fault on a random line with unsuccessful reclosing
  - T=0 2-phase short circuit
  - T=100-150 ms Typical disconnection of fault and the line at transmission
  - T=400-450 ms automatic reclosing
  - T=500-950 ms disconnection of the fault (may be shorter around 100ms for distribution)
- Withstand 3 faults within 2 minutes
- Withstand 6 faults if delay between faults are 5 minutes

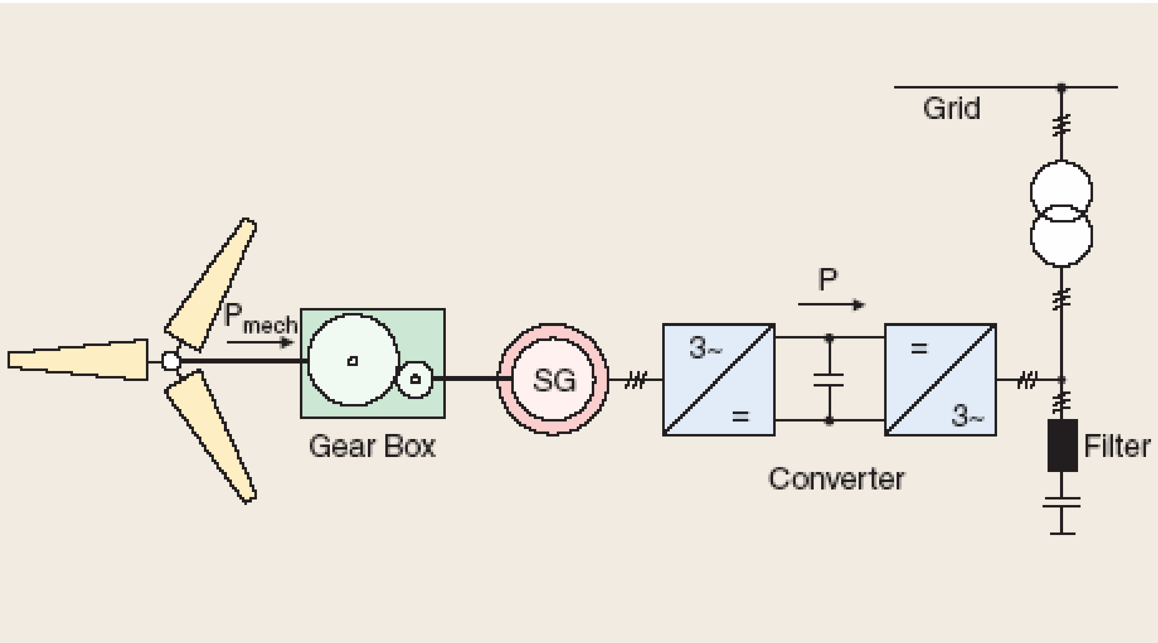
Control of three-phase inverters for wind systems

by Marco Liserre, Polytechnic of Bari, Italy

Agenda

- ✓ Current control of three-phase grid-side inverters
- ✓ Stability for a large set of grid impedance values
- ✓ Operation under unbalance condition or during voltage dips
- ✓ Grid synchronization

Power system



Control of three-phase inverters for wind systems

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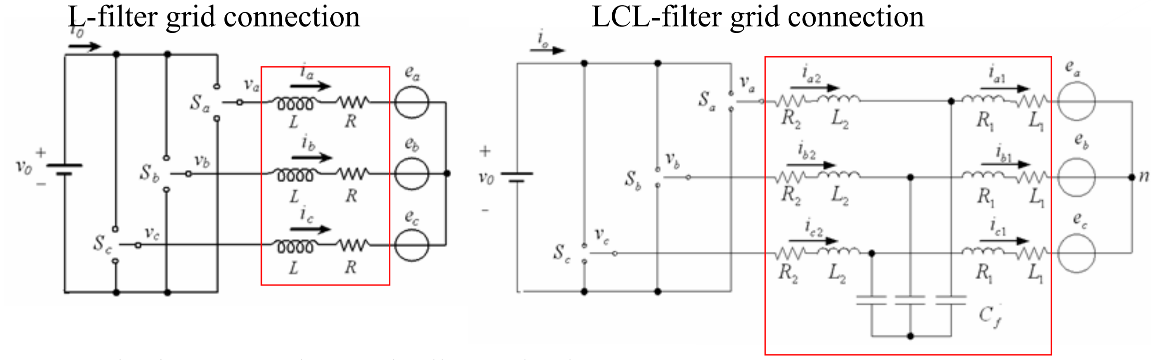
Agenda

- ✓ Current control of three-phase grid-side inverters
- ✓ Stability for a large set of grid impedance values
- ✓ Operation under unbalance condition or during voltage dips
- ✓ Grid synchronization

Grid connection issues

- ✓ Countries with background in renewable energy imposing more demands on grid connection
  - ✓ DPGS should run over small grid fluctuations
    - ✓ Voltage level
    - ✓ Frequency level
  - ✓ DPGS should sustain the grid when necessary
  - ✓ DPGS should contribute to reactive power control when requested

Grid filter, dq-frame model

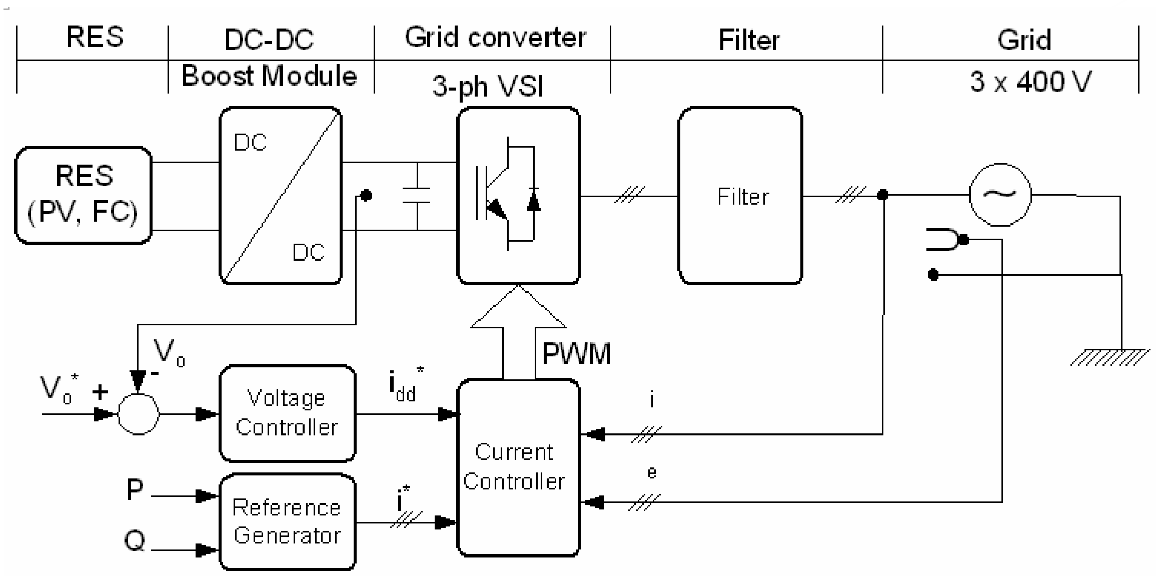


- In a dq-frame rotating at the line pulsation

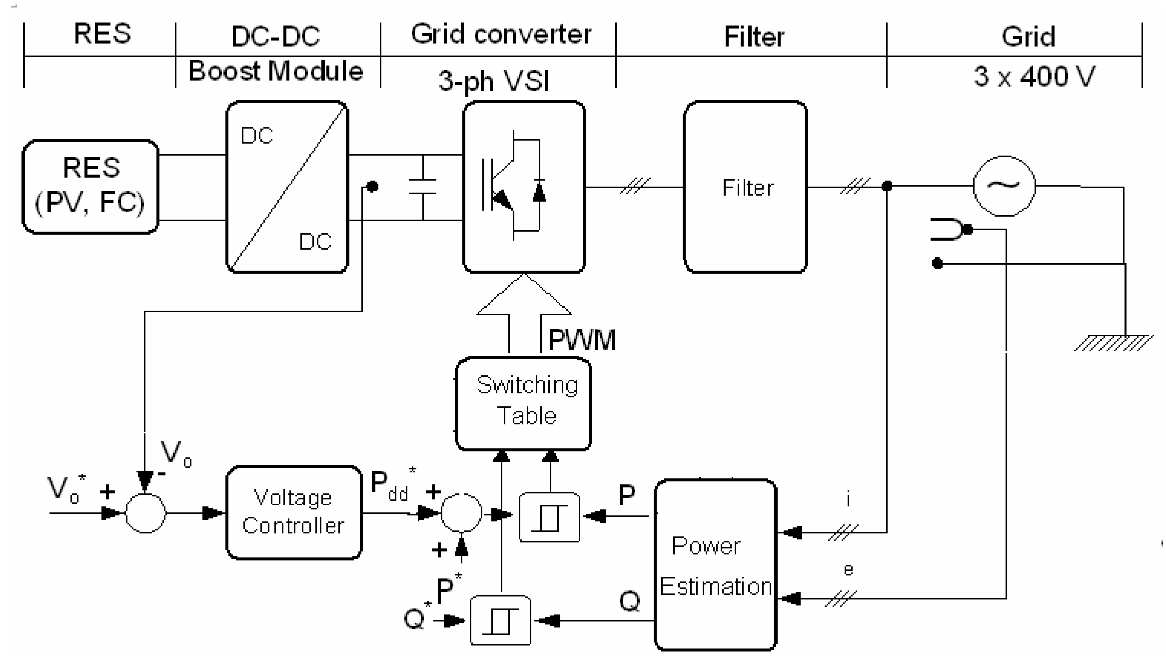
$$\begin{cases} \dfrac{di_d(t)}{dt} - \omega i_q(t) = \dfrac{1}{L}\left[-Ri_d(t) - e_d(t) + \dfrac{1}{2}p_d(t)v_o(t)\right] \\ \dfrac{di_q(t)}{dt} + \omega i_d(t) = \dfrac{1}{L}\left[-Ri_q(t) - e_q(t) + \dfrac{1}{2}p_q(t)v_o(t)\right] \end{cases}$$

$$\frac{d}{dt}\begin{bmatrix} i_{1d} \\ i_{1q} \\ v_{C_f d} \\ v_{C_f q} \\ i_{2d} \\ i_{2q} \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & \omega & -\frac{1}{L_1} & 0 & 0 & 0 \\ -\omega & -\frac{R_1}{L_1} & 0 & -\frac{1}{L_1} & 0 & 0 \\ \frac{1}{C_f} & 0 & 0 & \omega & -\frac{1}{C_f} & 0 \\ 0 & \frac{1}{C_f} & -\omega & 0 & 0 & -\frac{1}{C_f} \\ 0 & 0 & -\frac{1}{L_2} & 0 & -\frac{R_2}{L_2} & \omega \\ 0 & 0 & 0 & \frac{1}{L_2} & -\omega & -\frac{R_2}{L_2} \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \\ v_{C_f d} \\ v_{C_f q} \\ i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_1} & 0 \\ 0 & -\frac{1}{L_1} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e_d \\ e_q \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{L_2} & 0 \\ 0 & \frac{1}{L_2} \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

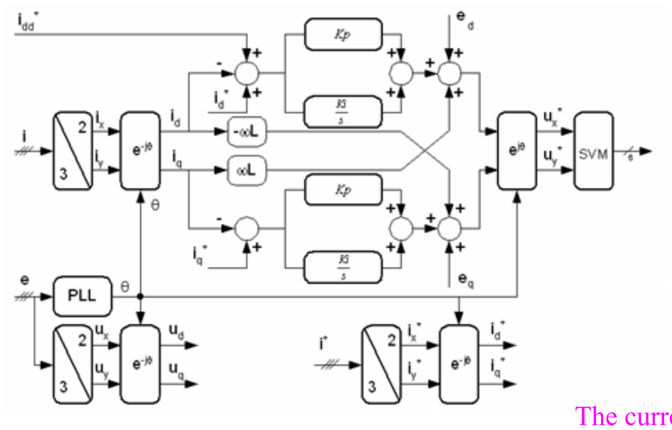
Cascade control

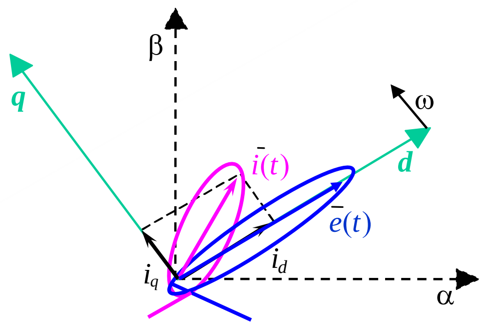


Direct Power Control



Current control in a rotating frame



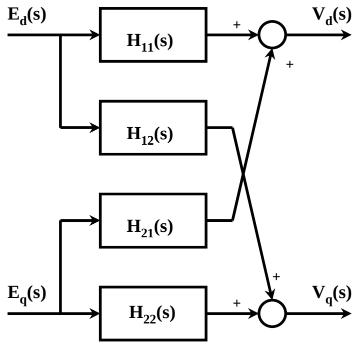


$$D_{PI}(s)_{dq} = \begin{bmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{bmatrix}$$

The current control can be performed on the grid current or on the converter current

The voltage used for *the dq-frame orientation* could be measured after a dominant reactance

From PI in a rotating-frame to P+res for each phase



In the hypothesis

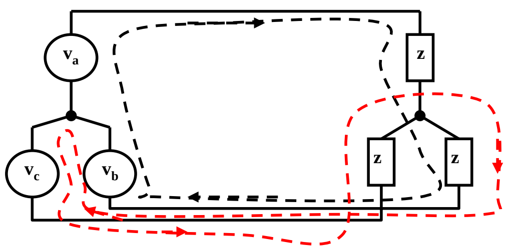
$$H_{11}(s)=H_{22}(s)= K_p+\frac{K_i}{s}$$

$$H_{12}(s)=H_{21}(s)=0$$

$$\begin{cases} v_d(t)=h_{11}(t)*e_d(t) \\ v_q(t)=h_{22}(t)*e_q(t) \end{cases}$$

$$G_c^{(d,q)}=\begin{bmatrix} K_p+\frac{K_i}{s} & 0 \\ 0 & K_p+\frac{K_i}{s} \end{bmatrix} \Leftrightarrow G_c^{(a,b,c)}(s)=\frac{2}{3}\cdot\begin{bmatrix} K_p+\frac{K_i s}{s^2+\omega_0^2} & -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} \\ -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & K_p+\frac{K_i s}{s^2+\omega_0^2} & -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} \\ -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & K_p+\frac{K_i s}{s^2+\omega_0^2} \end{bmatrix}$$

From PI in a rotating-frame to P+res for each phase



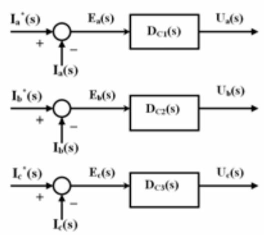
$$\frac{d}{dt}\begin{bmatrix} i_a(t) \\ i_c(t) \end{bmatrix}=\frac{1}{L}\begin{bmatrix} -R & 0 \\ 0 & R \end{bmatrix}\cdot\begin{bmatrix} i_a(t) \\ i_c(t) \end{bmatrix}+\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ 1 & 1 & 2 \end{bmatrix}\cdot\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix}$$

if $v_a(t)+v_b(t)+v_c(t)=0$

$$\frac{d}{dt}\begin{bmatrix} i_a(t) \\ i_c(t) \end{bmatrix}=\frac{1}{L}\begin{bmatrix} -R & 0 \\ 0 & R \end{bmatrix}\cdot\begin{bmatrix} i_a(t) \\ i_c(t) \end{bmatrix}+\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\cdot\begin{bmatrix} v_a(t) \\ v_c(t) \end{bmatrix}$$

each current is determined only by its voltage !

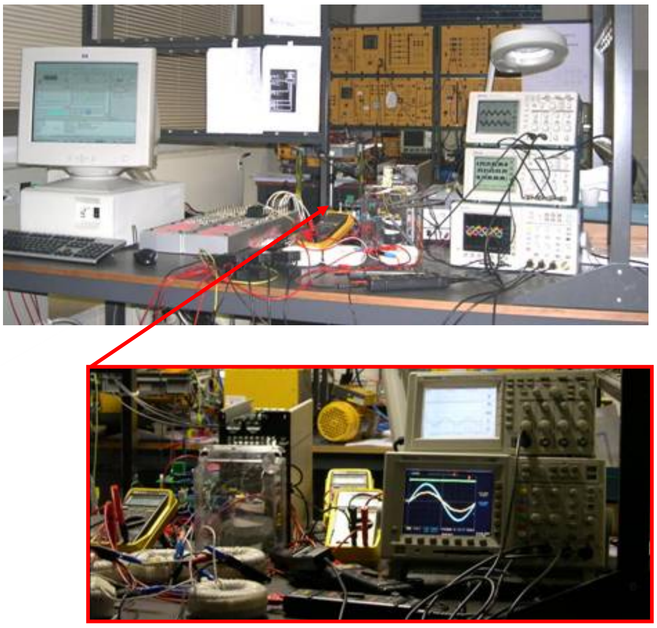
$$G_c^{(a,b,c)}(s)=\frac{2}{3}\cdot\begin{bmatrix} K_p+\frac{K_i s}{s^2+\omega_0^2} & -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} \\ -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & K_p+\frac{K_i s}{s^2+\omega_0^2} & -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} \\ -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_0}{2\cdot(s^2+\omega_0^2)} & K_p+\frac{K_i s}{s^2+\omega_0^2} \end{bmatrix} \Leftrightarrow G_{c1}^{(a,b,c)}(s)$$



Results

Three-phase prototype at Polytechnic of Bari

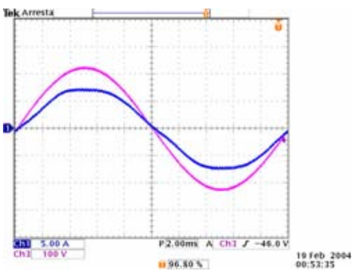
Tests made under ideal sinusoidal and balanced grid conditions

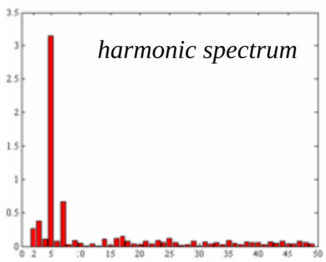


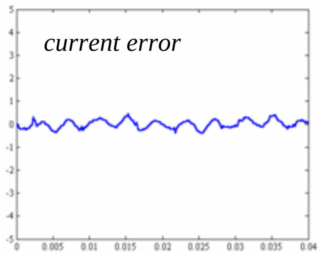
Grid Converters and their Control in DPGS, Tutorial IECON'05,
V-Control of three-phase inverters for wind systems

Results (ideal grid conditions)

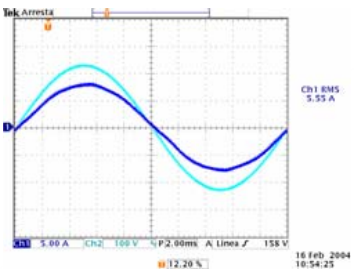
PI controller in a rotating frame

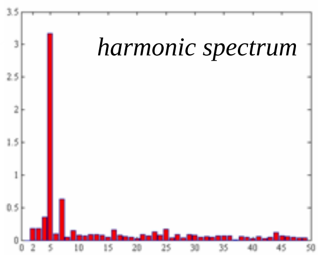


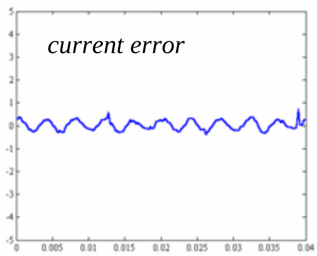




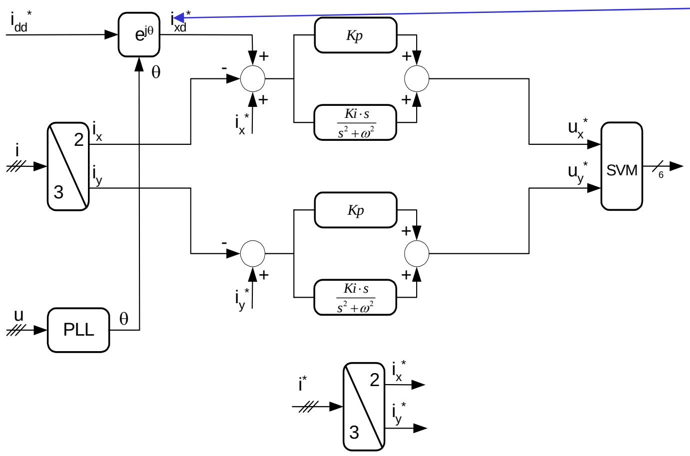
P+resonant controller for each phase



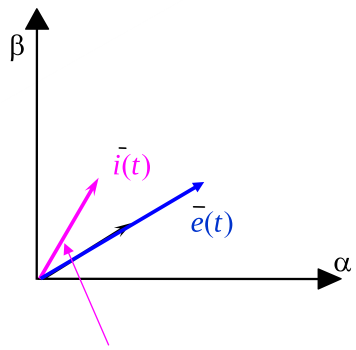




Current control in a stationary frame



The voltage used for *reference generation* could be measured after a dominant reactance



$$D_{PR}(s)_{\alpha\beta} = \begin{bmatrix} K_p + \frac{K_i s}{s^2+\omega_0^2} & 0 \\ 0 & K_p + \frac{K_i s}{s^2+\omega_0^2} \end{bmatrix}$$

The current control can be performed on the grid current or on the converter current

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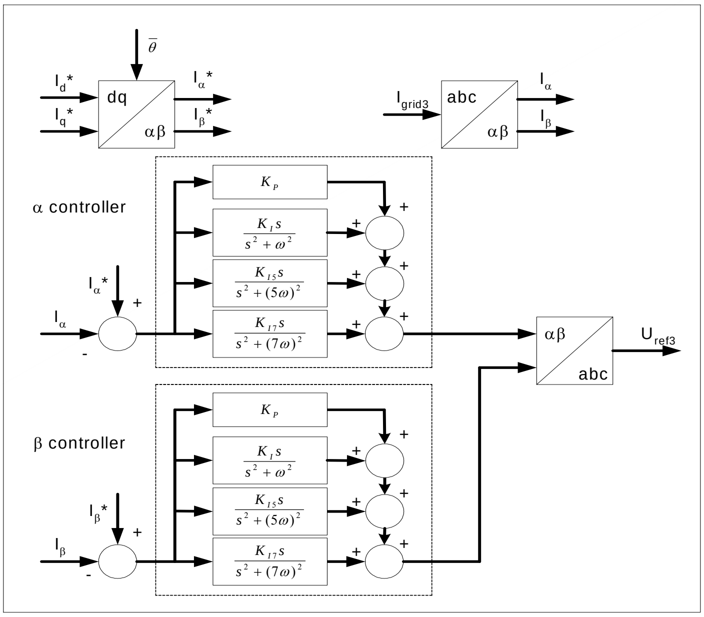
Use of grid voltage harmonic compensators

$$G_R(s)_{\alpha\beta} = \sum_{h=3,5,7} k_{ih} \frac{s}{s^2 + (\omega_0 \cdot h)^2}$$

the harmonics to be compensated should be within the bandwidth of the current controller otherwise stability problems may arise



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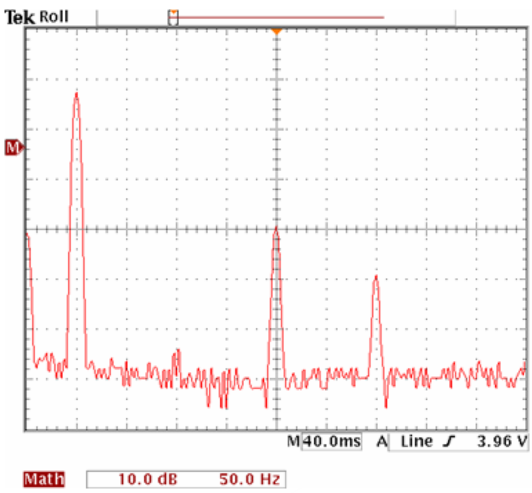
Results

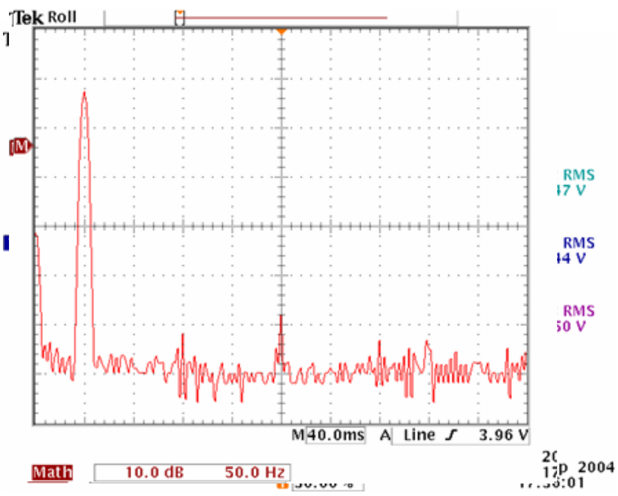
Three-phase prototype at Aalborg University

		Three-phase	
LCL-filter	Converter side (boost) inductance L	7 mH	3.4 %
	Filter capacitor C_f	1.6 µF	3.2%
	Grid side inductance L_g	3 mH	2.5 %
	Transformer inductance	2 mH	
CC-PWM	Sampling frequency	5 / 8 kHz	
	Type of modulation	space-vector	
	Switching frequency	5 / 8 kHz	
	Type of current controller	resonant with 5th and 7th harmonic compensators	
Voltage	Ac voltage level	230 V_{rms}	
	Dc voltage level	650 V	
	Rated power	2.5 kW	
Sensors position	Ac voltage sensors	on the transformer secondary side	
	Ac current sensors	on the LCL-filter converter side	

Results (grid voltage background distortion)



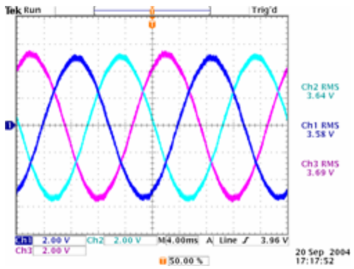
Effect of the grid voltage background distortion on the currents



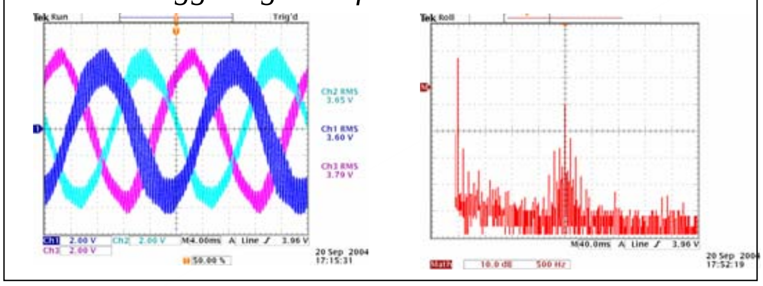
Use of harmonic compensators

Results (equivalence of PI in dq and P+res in αβ)

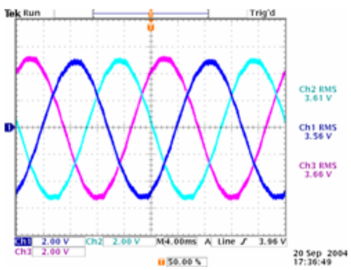
PI controller in a rotating frame



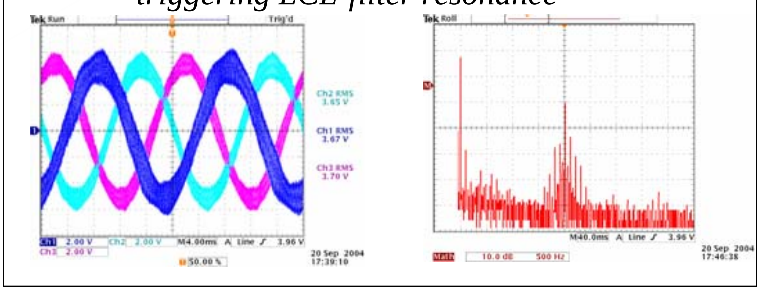
triggering LCL-filter resonance



P+resonant in stationary frame



triggering LCL-filter resonance



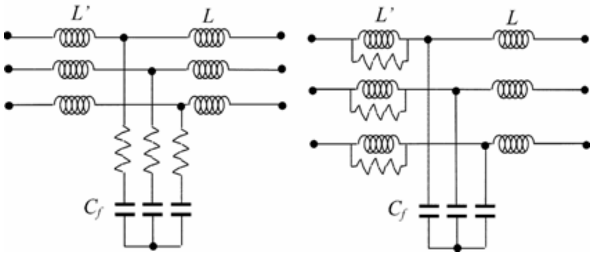
Damping of LCL-filter resonance

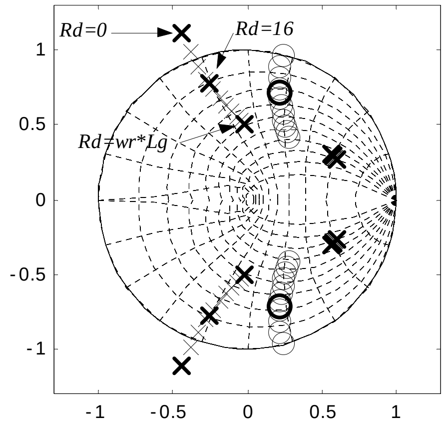
- ✓ If a LCL-filter is used the stability has to be verified

$$\frac{i(s)}{v(s)} = \frac{1}{L_2 s}\frac{\left(s^2 + z_{LC}^2\right)}{\left(s^2 + \omega_{res}^2\right)} \qquad \frac{i_g(s)}{v(s)} = \frac{1}{Ls}\frac{z_{LC}^2}{\left(s^2 + \omega_{res}^2\right)}$$

- ✓ To stabilize the current loop against LCL-filter resonance:
  - ✓ passive damping (resistor -> losses)
  - ✓ active damping:
    - ✓ multiloop (use of more sensors)
    - ✓ notch filter in cascade to the main controller

Damping of LCL-filter resonance: passive





f_{sw}	5 kHz	6 kHz	7kHz	8 kHz
abs value	32 W	20 W	13 W	10 W
% of rated power	0.8 %	0.5 %	0.3 %	0.2 %

- ✓ Increasing the switching/sampling frequency, the losses decrease but at the same time the damping becomes less effective

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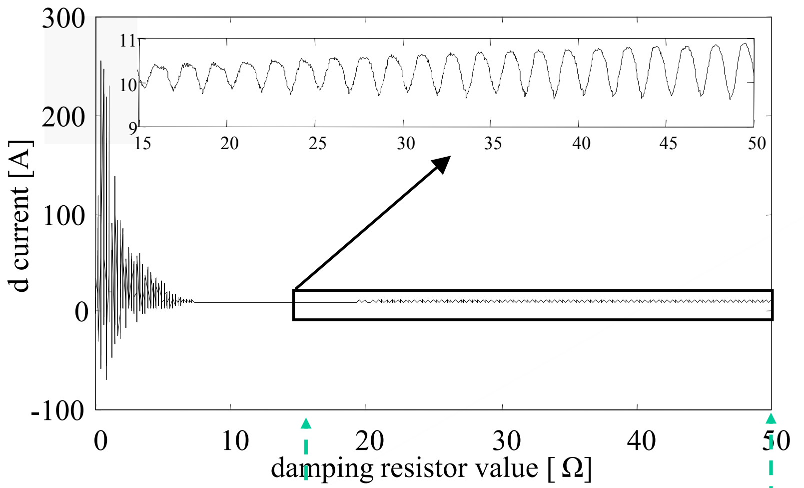
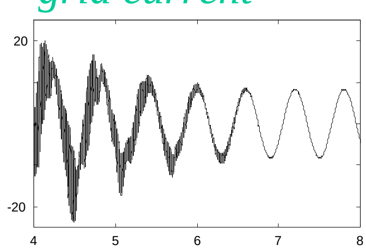
Damping of LCL-filter resonance: passive



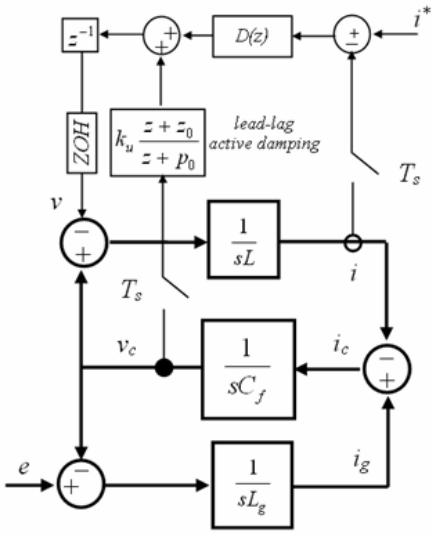


2.3 %	THD	4 %
0.8 %	THFHD	1.9 %
29 W	losses	67 W

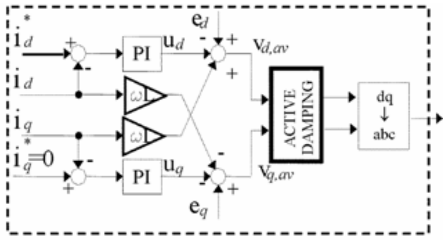
Excessive damping

Damping of LCL-filter resonance: active

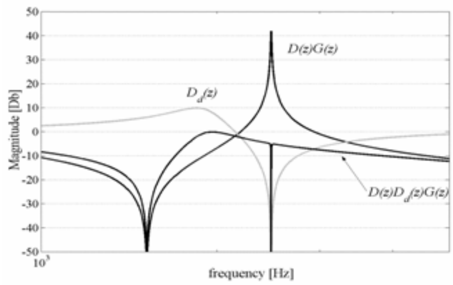
- ✓ multiloop (use of more sensors)



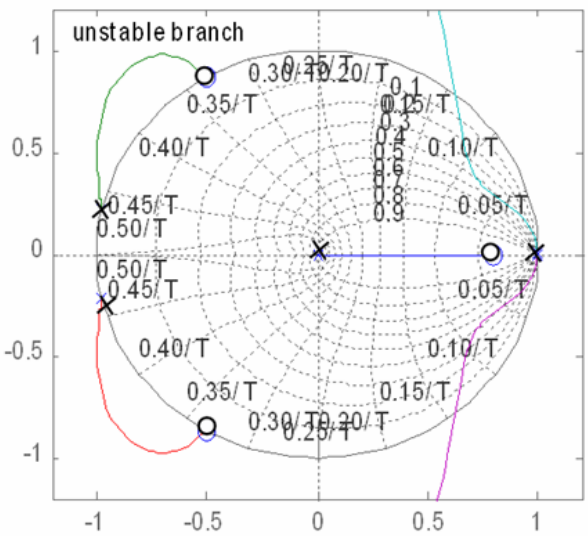
- ✓ notch filter in cascade



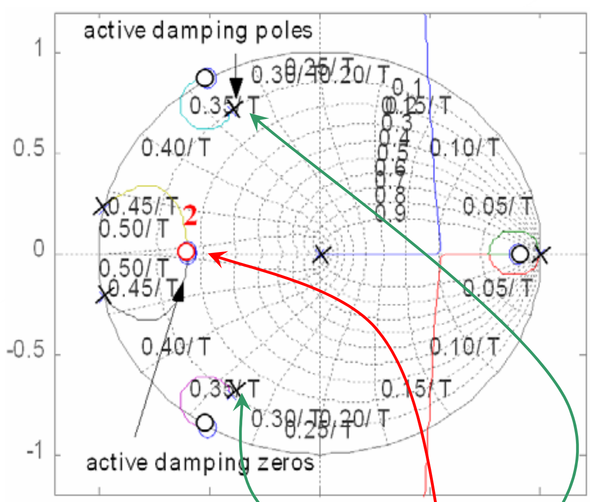
Current controller



Active damping with notch filter



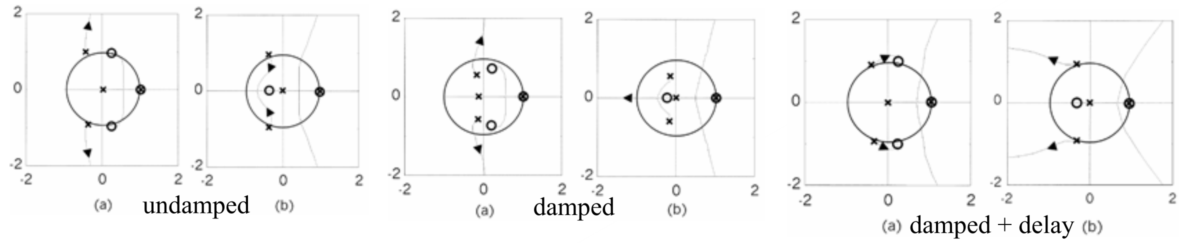
undamped



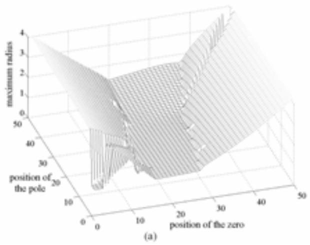
$$G_{AD}(z) = \left[\frac{z^2 - z_o^2}{z^2 - p_o^2}\right]$$

Tuning of the notch filter

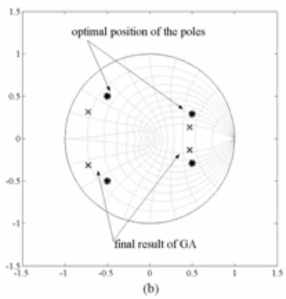
✓ different conditions makes the tuning procedure difficult



✓ Advanced procedures for the filter coefficient



GA tuning !



Results

Three-phase prototype at Aalborg University

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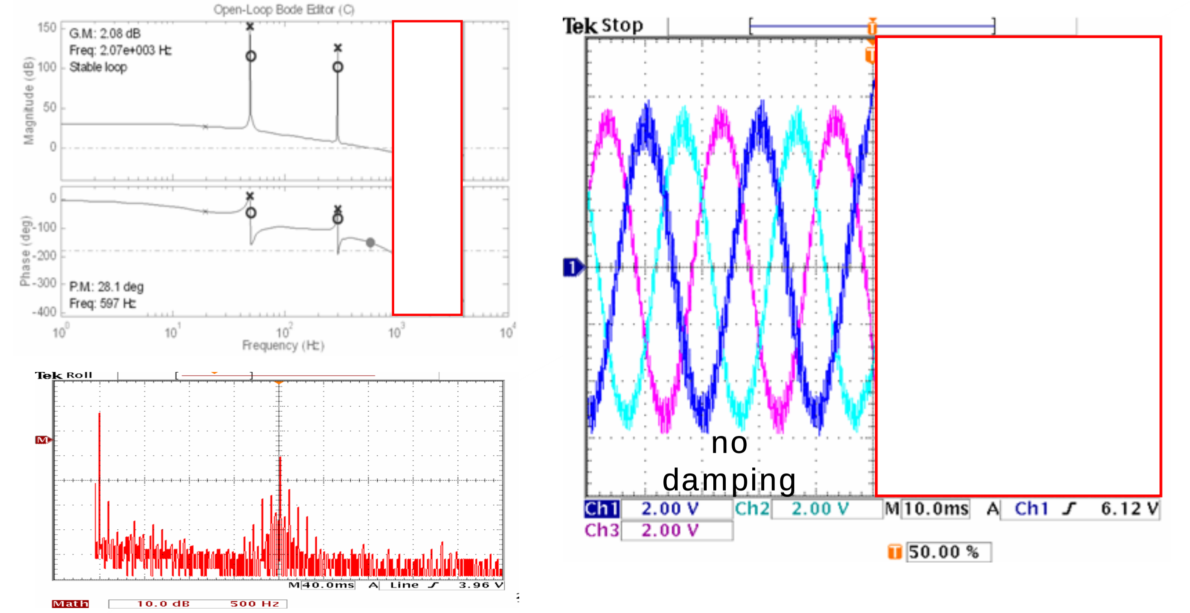
Results (LCL-filter resonance)



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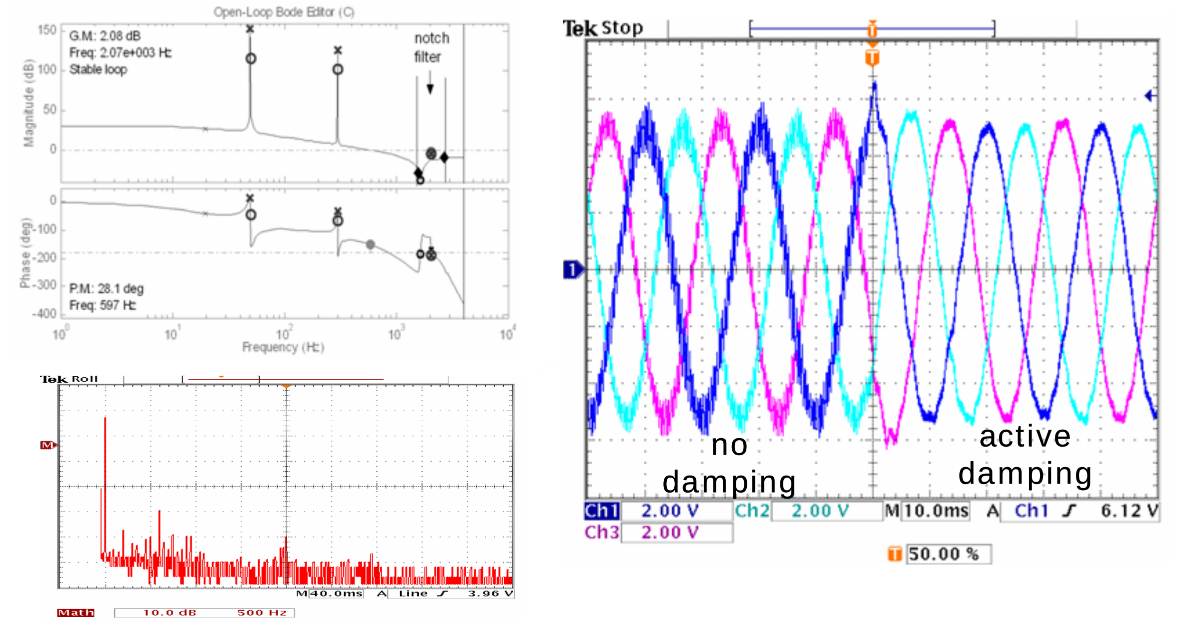
Results (LCL-filter resonance)



Other issues

- ✓ reduction of the number of sensors:
  - ✓voltage sensorless (DPC, VOC with PLL as an observer)
  - ✓current sensorless (overcurrent protection ?)
- ✓ non-ideal conditions:
  - ✓measurement of the grid voltage after a dominant reactance
  - ✓grid unbalance (*discussed in the following*)
- ✓ EMC issues:
  - ✓differential mode: IEC limitation and IEEE recommendations
  - ✓common mode: use of extra filter or modify LCL-filter

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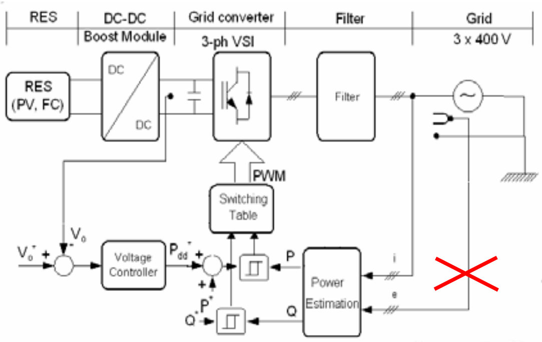
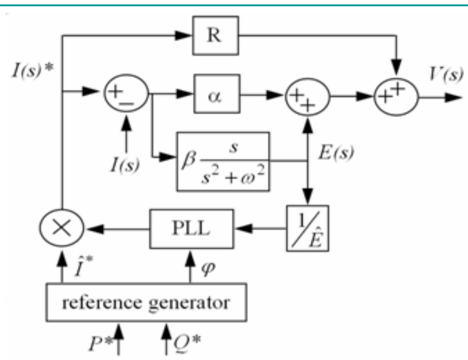
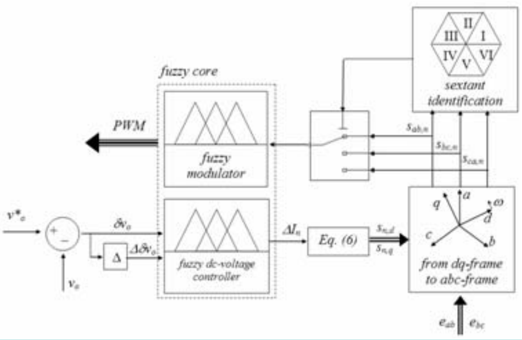
Reduction of the number of sensors







- ✓ Voltage sensorless is more reliable but need start-up procedures
- ✓ Current sensorless lacks in immunity to grid disturbance

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- ✓ B.K. Bose, Modern Power Electronics and A.C. Drives, 1st ed., Prentice Hall, 2001, ISBN 0-13-016743.
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- ✓ V. Blasko and V. Kaura, "A novel control to actively damp resonance in input LC filter of a three-phase voltage source converter", IEEE Trans. on Ind. App., vol. 33, 1997, pp. 542-550.
- ✓ I. Agirman and V. Blasko, "A novel control method of a VSC without AC line voltage sensors", IEEE Trans. on Ind. App., Vol. 39, March/April 2003, pp.519-524.
- ✓ C. Cecati, A. Dell'Aquila, M. Liserre, A. Ometto, "A Fuzzy Logic-Based Controller for Active Rectifier" IEEE Transactions on Industry Applications, Jan/Feb. 2003, vol. 39, no. 1.
- ✓ M. Liserre, R. Teodorescu, F. Blaabjerg "Stability of Photovoltaic and Wind Turbine Grid-Connected Inverters for a Large Set of Grid Impedance Values" IEEE Transactions on Power Electronics (in press).
- ✓ M. Malinowksi, M. P. Kazmierkowski, S. Hansen, F. Blaabjerg, G. Marques, "Virtual flux based direct power control of three-phase PWM rectifiers", IEEE Trans. on Ind. Applications, Vol. 37, July 2001, pp. 1019-1027.

Control of three-phase inverters for wind systems

by Marco Liserre, Polytechnic of Bari, Italy

Agenda

- ✓ Current control of three-phase grid-side inverters
- ✓ Stability for a large set of grid impedance values (PV and WT)
- ✓ Operation under unbalance condition or during voltage dips
- ✓ Grid synchronization

Stability for a large set of grid impedance values

- ✓ Complex controllers (e.g. multiple rotating dq-frames or resonant-based) are often required to compensate low frequency grid voltage background distortion and an LCL-filter is usually adopted for the high frequency one.
- ✓ The possible wide range of grid impedance values (distributed generation is suited for remote areas with radial distribution plants) challenge the stability and the effectiveness of the LCL-filter-based current controlled system.
- ✓ It has been found out and it will be discussed that the use of active damping helps to stabilize the system in respect to many different kinds of resonances.
- ✓ The use of active damping results in an easy plug-in feature of the generation system in a vast range of grid conditions and in a more flexible operation of the overall system able to manage sudden grid changes.
- ✓ The topic will be discussed both for PV and WT systems

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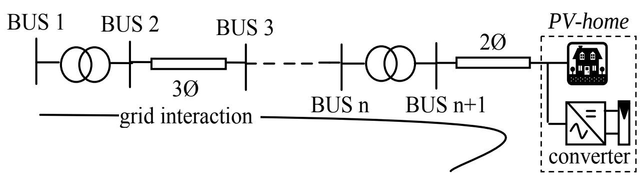
Photovoltaic system connection to the grid

- ✓ The High-Voltage/Medium-Voltage transformer as well as a three-phase cable to the MV transformer introduce only a small impedance.
- ✓ If the PV-house is located in a remote area the medium voltage line can be very extended (hundreds of km's) and its cables can introduce reactive reactance.
- ✓ The MV/LV transformer introduces a reactance that could be considerably higher in locations where the transformer rated power is considerable lower.
- ✓ Then the low voltage cable introduces a prevalently resistive impedance that varies with the distance of the PV-inverter from the transformer.
- ✓ Capacitive loads (e.g. refrigerators) could introduce a capacitive impedance that can create low frequency resonances



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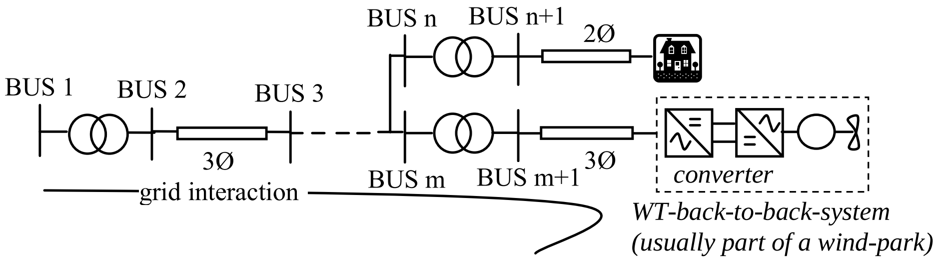
Wind turbine system connection to the grid

- ✓ The system is similar to the previous one (hence also in this case a radial plant typical of a rural zone can introduce a very high impedance) up to the MV/LV transformer, to which the wind turbine converter is connected.
- ✓ Hence the impedance seen by the grid connected inverter can be mainly inductive and can be different depending on the plant configuration.
- ✓ However, the system present less interaction with domestic loads, avoiding possible low frequency resonances.



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Dynamic and Stability problems

- ✓ The impedance variation leads to dynamic and stability problems:

<u>in the low frequency range</u> (around the current controller bandwidth frequency), it challenges the design of resonant controllers adopted to mitigate the effect of the grid harmonic distortion on the grid current. In fact if the proportional gain of the current loop is chosen such as the low frequency complex conjugate poles, that depend on the grid side time constant, are optimally damped, when the inverter is connected to a highly inductive grid, i.e. with a higher time constant, the selected proportional gain is insufficient, the system is too slow and the harmonic controllers stay outside the bandwidth, making the system unstable.

<u>in the high frequency range</u> (around the LCL-filter resonance frequency) it influences the frequency characteristic of the filter and the design of passive or active damping (to ensure stability) becomes more difficult

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Example of two systems: 500 kW WT and 3 kW PV

		500 kW WT system		3 kW PV-system	
LCL-filter	Boost inductance	0.2 mH	23 %	0.4 mH	1 %
	Grid side inductance	0.03 mH		0.2 mH	
	Filter capacitor	83 µF	1 %	5 µF	3 %
Grid impedance	Maximum value (weak grid)	0.03 Ω (inductive)	10 %	2.7 Ω (41% inductive)	15 %
	Minimum value (stiff grid)	0.003 Ω (inductive)	1 %	0.4 Ω (resistive)	2 %

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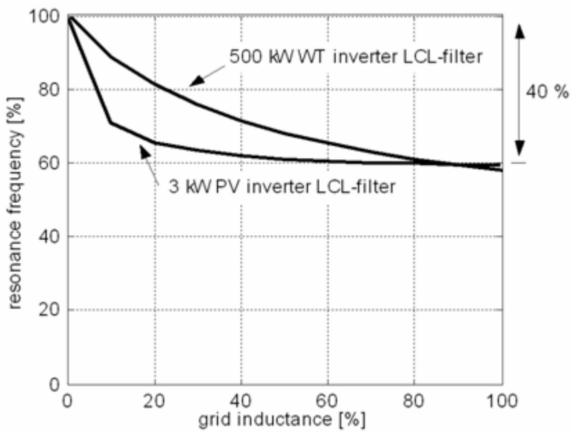
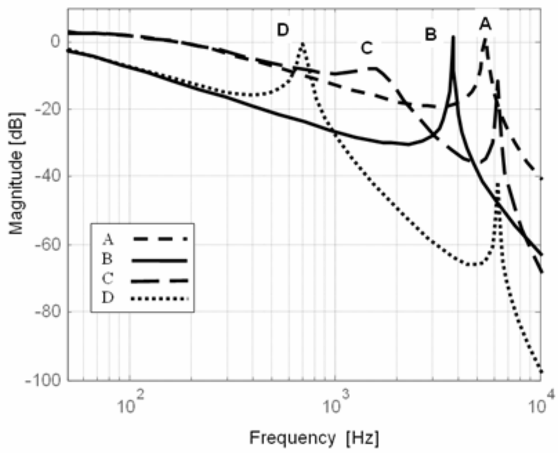
Example of two systems: 500 kW WT and 3 kW PV



variable inductance

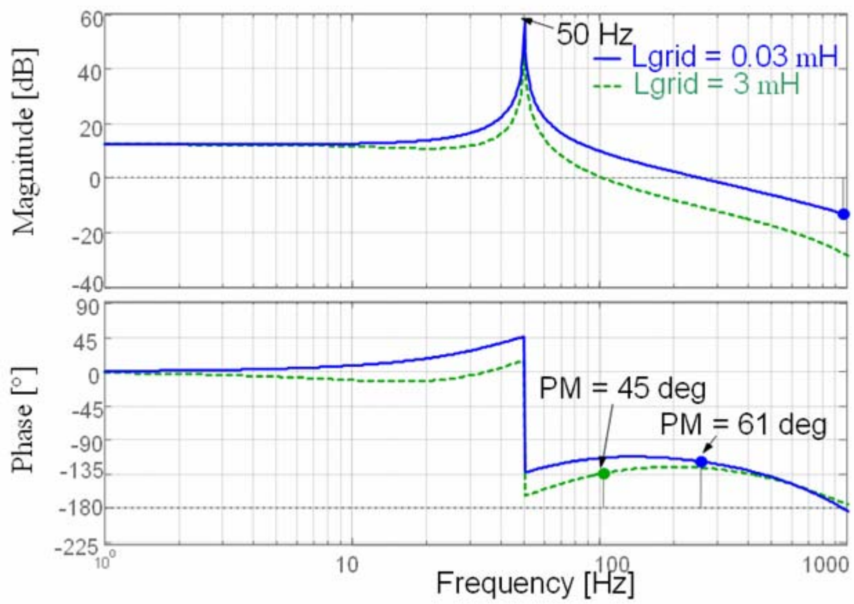


introduction of 100 µF capacitance

Considerations

- ✓ LCL-filter effectiveness changes with the grid stiffness
- ✓ Damping is difficult since the plant changes with the grid stiffness (active one is more flexible)
- ✓ The grid stiffness influence can be limited using more inductance in the filter but it leads to a bulky inverter and to packaging problems (i.e. the automatic mounting of the components is not possible) in case of PV systems
- ✓ The presence of capacitive loads create other resonance peaks, active damping can be effective also in these cases

Grid stiffness influence: low frequency



phase margin reduction

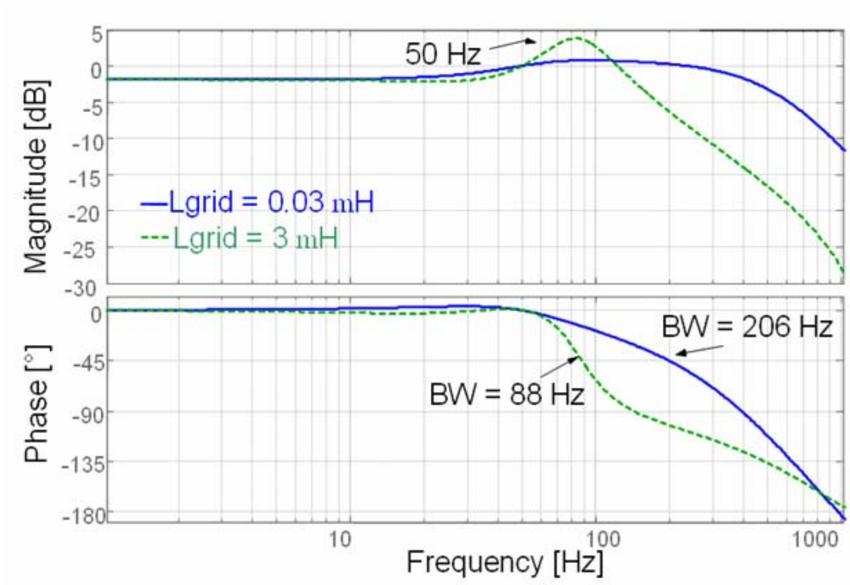
from

61°

to

45°

Grid stiffness influence: low frequency



bandwidth reduction

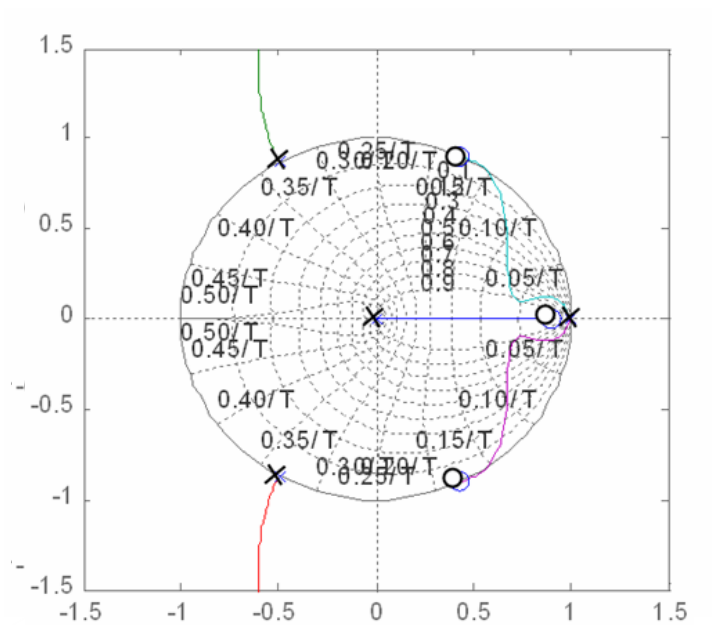
from

206 Hz

to

88 Hz

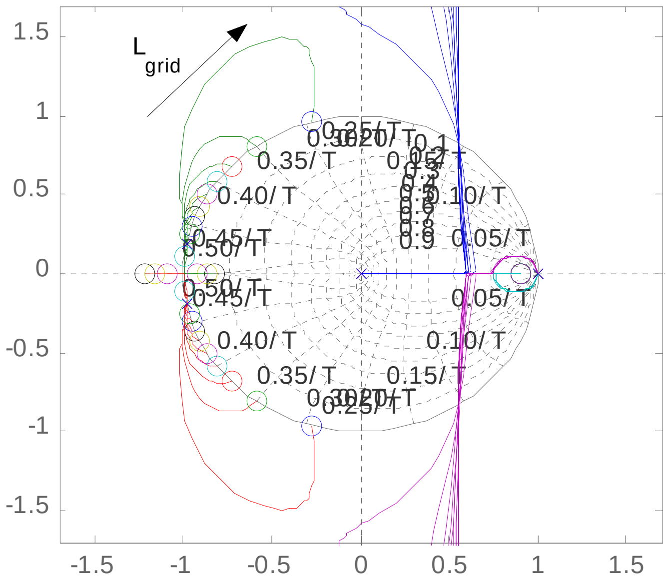
Grid stiffness influence: LCL-filter



weak grid

use active damping !

Grid stiffness influence: LCL-filter



In each grid condition the LCL-filter converter side impedance is adjusted such as the resonance frequency remains unchanged (the arrow indicates the root loci branches due to higher grid impedance)

Results

Three-phase prototype at Aalborg University

		Three-phase	
LCL-filter	Converter side (boost) inductance L	7 mH	3.4 %
LCL-filter	Filter capacitor C_f	1.6 µF	3.2%
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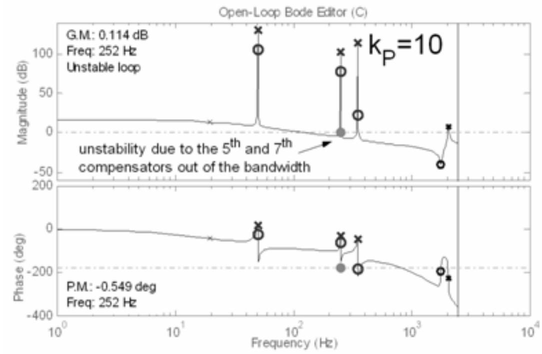
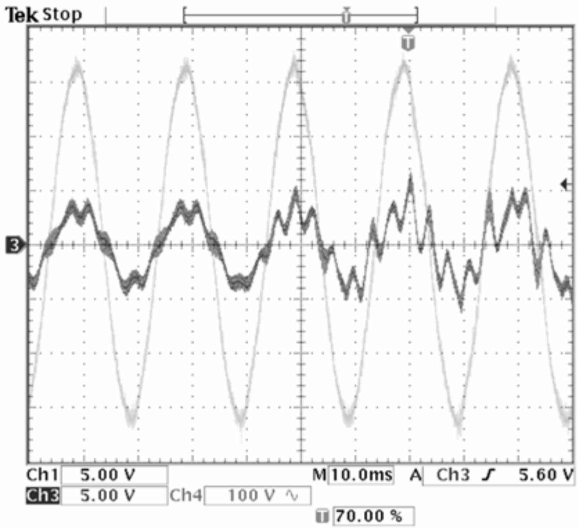
LCL-filter	Transformer inductance	2 mH	
CC-PWM	Sampling frequency	5 / 8 kHz	
CC-PWM	Type of modulation	space-vector	
CC-PWM	Switching frequency	5 / 8 kHz	
CC-PWM	Type of current controller	resonant with 5th and 7th harmonic compensators	
Voltage	Ac voltage level	230 V_{rms}	
Voltage	Dc voltage level	650 V	
Voltage	Rated power	2.5 kW	
Sensors position	Ac voltage sensors	on the transformer secondary side	
Sensors position	Ac current sensors	on the LCL-filter converter side	

Results (low frequency instability)



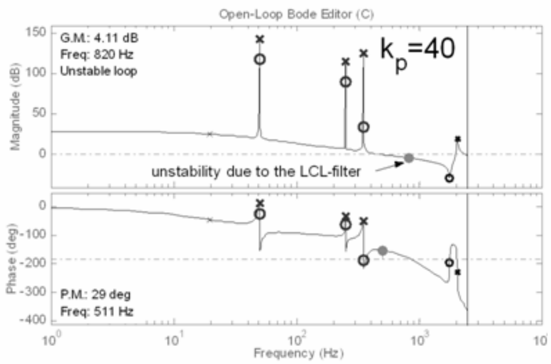


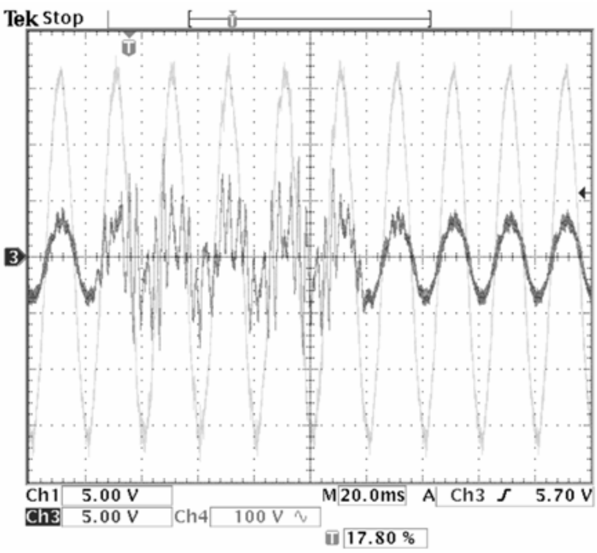
Three-phase system test:

Bode plot of the current controlled system,

test of the plug-in of the 5th harmonic compensator at t = 50 ms

Results (high frequency instability)





Three-phase system test:

Bode plot of the current controlled system,

and instability due to the high proportional gain that allows the use of 5th and 7th compensators

References

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V-Control of three-phase inverters for wind systems

Control of three-phase inverters for wind systems

by Marco Liserre, Polytechnic of Bari, Italy

Agenda

- ✓ Current control of three-phase grid-side inverters
- ✓ Stability for a large set of grid impedance values
- ✓ Operation under unbalance condition or during voltage dips
- ✓ Grid synchronization

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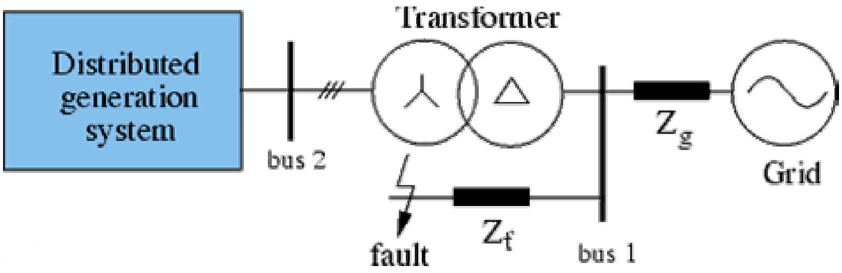
Voltage dips as consequence of grid faults

Grid codes

- ✓ DPGS connected through a transformer to the grid
- ✓ Faults propagation through the Delta/Y transformer



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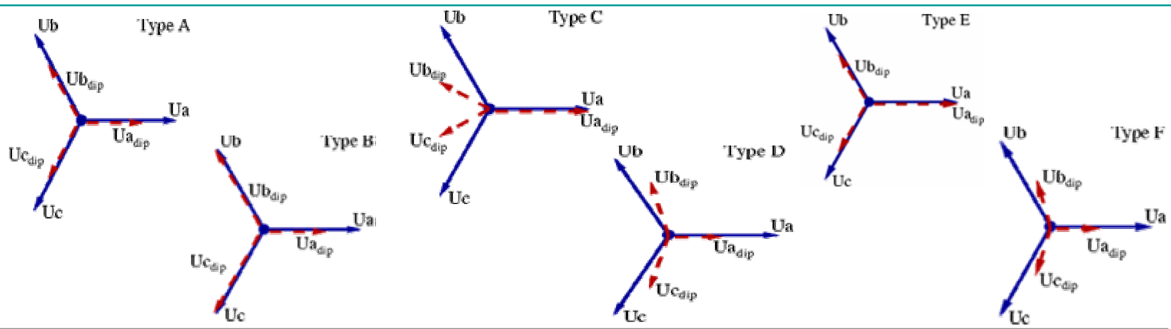
Review of voltage dip type



FAULTS	Dips seen at bus 1	Dips seen at bus 2
3-phase fault	type A	type A
1-phase fault	type B	type C
2 phase to ground fault	type E	type F
phase-to-phase fault	type C	type D

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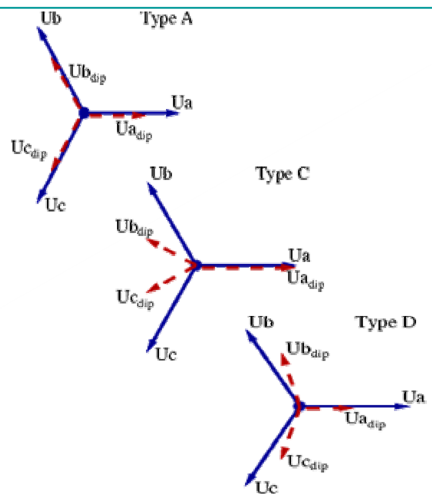
Considerations

- ✓ Faults type B and E need not being investigated, because they can never reach a wind turbine system
- ✓ Faults type F will not be investigated because extremely rare
- ✓ Faults type A are symmetrical. Voltage amplitude on all three phases will change in the same way, without any phase shift
- ✓ Faults type C and D are not symmetrical. Voltage amplitudes will change in different ways, and a phase shift can appear

Considerations

- ✓ Faults type A appear as a change in amplitude of U_1
- ✓ Faults type C appear as a drop in U_1 and the appearance of U_2, with $U_2>0$
- ✓ Faults type D appear as a drop in U_1 and the appearance of U_2, with $U_2<0$



In this analysis, there will never appear any U_0 voltage component.

In the event of perturbations of power injected to or drained from the grid, a change in grid frequency will appear. Voltages will keep nominal values.

Ride-through capability of the WT-system

- The capability of the system to allow ride-through grid disturbances is strictly related to the inverter rating (*voltage and current*) as well as its energy storage.
- Increasing the lifetime of the converter (decreasing the need of maintenance, crucial in off-shore installations) will require the exchange of the electrolytic capacitors with film capacitors, which involves a decrease of the dc-link capacitance due to a lower energy density.
- Therefore, the energy buffer in the dc-link becomes smaller and the conversion becomes *quasi-direct*

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Mathematical analysis of the effects of unbalance

$$
\begin{aligned}
i_o^p(t) = \frac{\sqrt{2}}{4} I_p \sum_{m=1}^{\infty} A_m \Big\{ & \cos[(m+1)\omega t + \varphi_p] + \cos[(m-1)\omega t + \varphi_p] + \\
& + \cos\left[(m+1)\omega t - (m+1)\omega t \frac{2\pi}{3} + \varphi_p\right] + \cos\left[(m-1)\omega t - (m-1)\frac{2\pi}{3} + \varphi_p\right] + \\
& + \cos\left[(m+1)\omega t + (m+1)\omega t \frac{2\pi}{3} + \varphi_p\right] + \cos\left[(m-1)\omega t + (m-1)\frac{2\pi}{3} + \varphi_p\right] \Big\}
\end{aligned}
$$

$$
\begin{aligned}
i_o^n(t) = \frac{\sqrt{2}}{4} I_n \sum_{m=1}^{\infty} A_m \Big\{ & \cos[(m+1)\omega t + \varphi_n] + \cos[(m-1)\omega t - \varphi_p] + \\
& + \cos\left[(m+1)\omega t - (m-1)\omega t \frac{2\pi}{3} + \varphi_n\right] + \cos\left[(m-1)\omega t - (m+1)\frac{2\pi}{3} - \varphi_n\right] + \\
& \cos\left[(m+1)\omega t + (m-1)\omega t \frac{2\pi}{3} + \varphi_n\right] + \cos\left[(m-1)\omega t + (m+1)\frac{2\pi}{3} - \varphi_n\right] \Big\}
\end{aligned}
$$

Mathematical analysis of the effects of unbalance

m =1

$$i_o(t) = \frac{3}{4}\sqrt{2}A_1\left[I_p\cos\varphi_p + I_n\cos(2\omega t + \varphi_n)\right] = I_o + I_{o2}\cos(2\omega t + \varphi_n)$$

$$I_o = \frac{3}{4}\sqrt{2}A_1 I_p\cos\varphi_p$$

$$I_{o2} = \frac{3}{4}\sqrt{2}A_1 I_n$$

Mathematical analysis of the effects of unbalance

$$v_{ar}(t) = \frac{1}{2}V_o\sum_{m=1}^{\infty}A_m\cos(m\omega t) + \frac{1}{4}\sum_{k=2}^{\infty}V_{ok}\left\{\sum_{m=1}^{\infty}A_m\left[\cos(m+k)\omega t + \varphi_k\right] + \sum_{m=1}^{\infty}A_m\left[\cos(m-k)\omega t - \varphi_k\right]\right\}$$

input voltage

m =1, k = 2

$$v_{ar}(t) = V_{ar1}\left[\cos(\omega t)\left(1+\cos(\varphi_2)\right) - \sin(\omega t)\sin(\varphi_2)\right] + V_{ar3}\cos(3\omega t + \varphi_2)$$

$$V_{ar1} = \frac{1}{4}A_1\left(\frac{1}{2}V_o + V_{o2}\right)$$

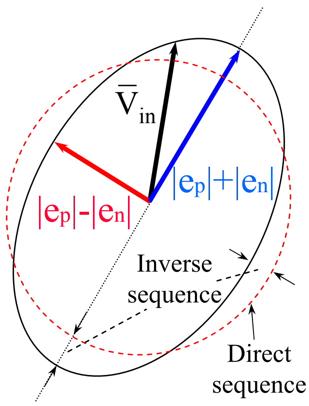
$$V_{ar3} = \frac{1}{4}V_{o2}A_1$$

Investigations of the Effects of Unbalanced Voltage Supply

Requirements

- ✓ Sinusoidal&balanced input currents ⇒ input current vector locus = circle
- ✓ Reduced energy storage capability (C_{dc} ⇒ 0) ⇒ P_{in}(which is constant) = P_{out}

⇒ **Increased sensitivity to power grid disturbances**



Possible fault-tolerant scenario:

Unbalance	small (<2-5%)	medium (5-15%)	high (>15 %)
Output power capability	Full	Full	Partial
Input currents	Should be sinusoidal & balanced	May be sinusoidal but unbalanced	May be not sinusoidal & unbalanced

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Investigations of the Effects of Unbalanced Voltage Supply

- ✓ The first requirement corresponds to normal operation
- ✓ In order to fulfill the second requirement, the size of the energy storage (dc-link capacitor) should be increased. The reason is that it is necessary to have an energy buffer to compensate for momentary ripple in the instantaneous input power
- ✓ The third requirement is suitable for implementation as a fault-tolerant feature, in order to allow the system to operate under extreme grid disturbances

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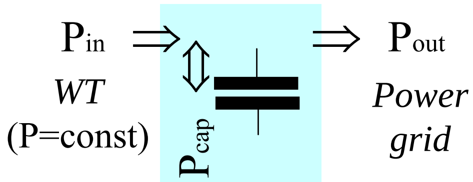
Minimizing the Effects of Unbalanced Supply Voltage

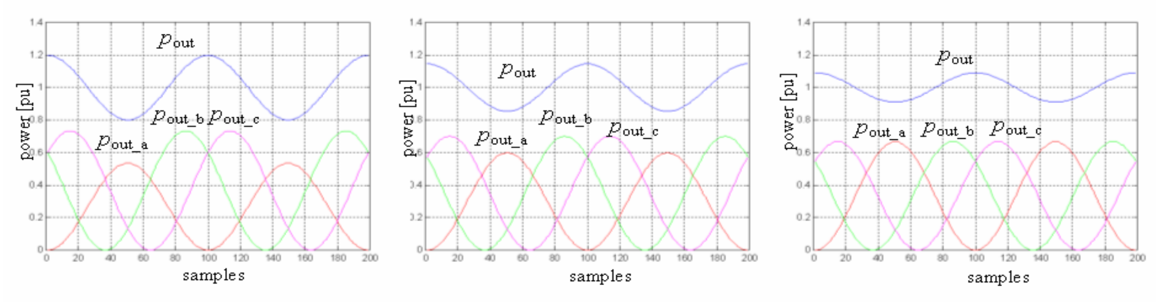


Normally, the DC-link cap will cover the gaps in P_{in} due to unbalance

If C_{dc} is very small, $P_{cap} << P_{in}$-P_{out}

⇒ Is necessary to investigate how reference input current influences the power ripple

Angle of the reference current = Angle of the grid voltage



$i^* = k \cdot e$ $\qquad$ $i^* = \text{const.}$ $\qquad$ $i^* = k / e$

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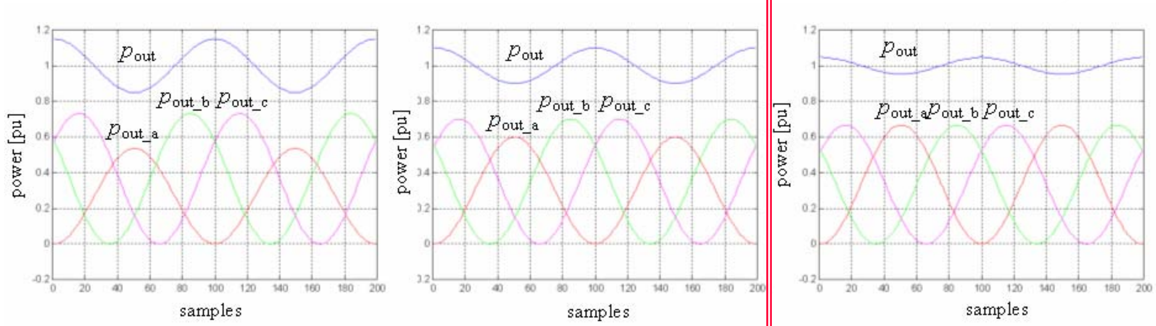
Minimizing the Effects of Unbalanced Supply Voltage

Angle of the reference current = Angle of the grid voltage *direct sequence*



$i^* = k \cdot e$ $\qquad$ $i^* = \text{const.}$ $\qquad$ $i^* = k / e$

As seen in all the six possible combinations, the most convenient situation is obviously the last one.

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Dc link voltage oscillation

$$\Delta E = 1/2 \cdot C \cdot (v_{o,MAX}^2 - v_{o,MIN}^2) = C \cdot V_o \cdot \Delta V_o$$

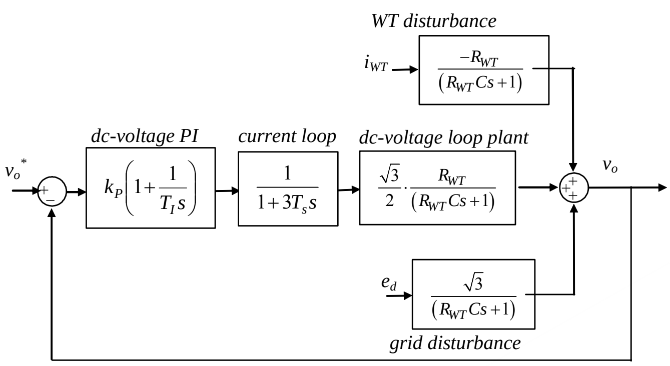
unbalance

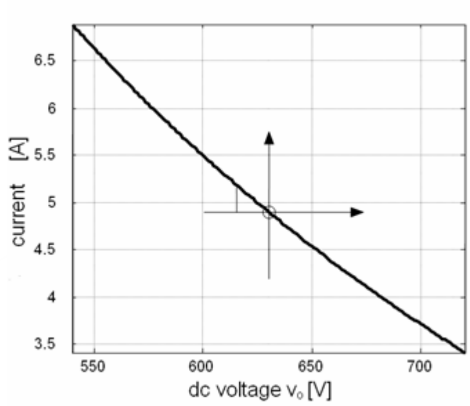
$$\Delta E = \frac{\Delta p_{pk-pk}}{2\pi \cdot 100} \quad \Rightarrow \quad \Delta V_o = \frac{\Delta p_{pk-pk}}{2\pi \cdot 100 \cdot C \cdot V_o}$$

sudden power changes

$$\Delta E = \frac{\Delta P(3+n)T_s}{2} \quad \Rightarrow \quad \Delta V_o = \frac{\Delta P(3+n)T_s}{2 \cdot C \cdot V_o}$$

Dc-voltage control stability analysis





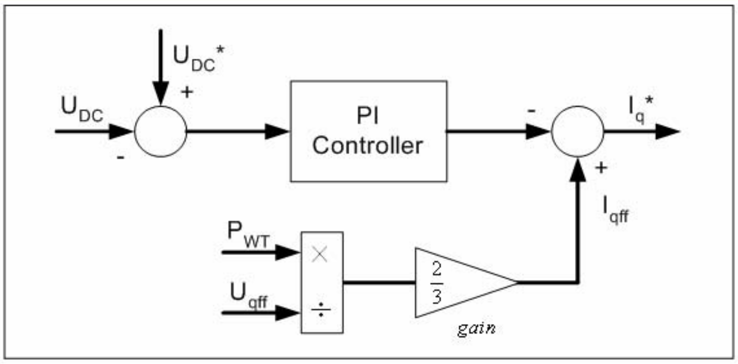
A negative R_{WT} implies that the system is more sensitive to the grid disturbances

Constant power operation

↓

negative resistance

Dc-voltage control with filtered feed-forward



$$I_{qff} = \frac{2}{3}\frac{P_{WT}}{U_{qff}}$$

The DC Voltage controller consists of a PI controller and a feedforward signal calculated from the input power and the grid voltage

Unfiltered grid voltage Feed-forward, transformed in dq system: this will be affected by a negative sequence component that will cause the Iqff to be affected by a periodical oscillation

Filtered grid voltage Feed-forward (quasi-constant, since the filtering cannot be perfect): this will produce a quasi-constant Iqff value.

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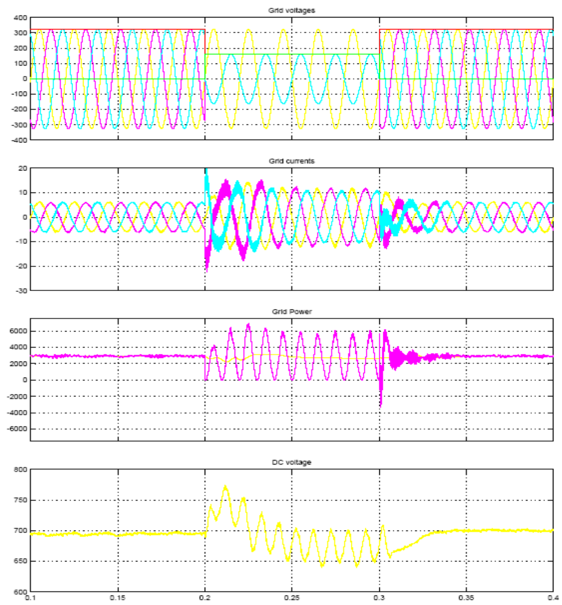
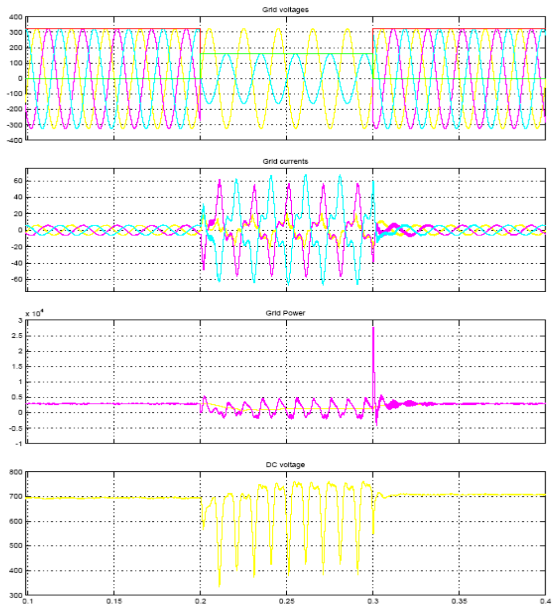
Test results: 100% C type Dip

Filtered: *Successful*



Unfiltered: *Unsuccessful*



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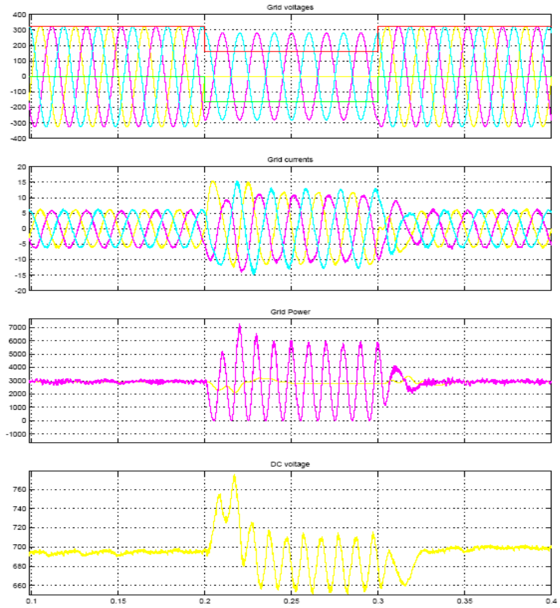
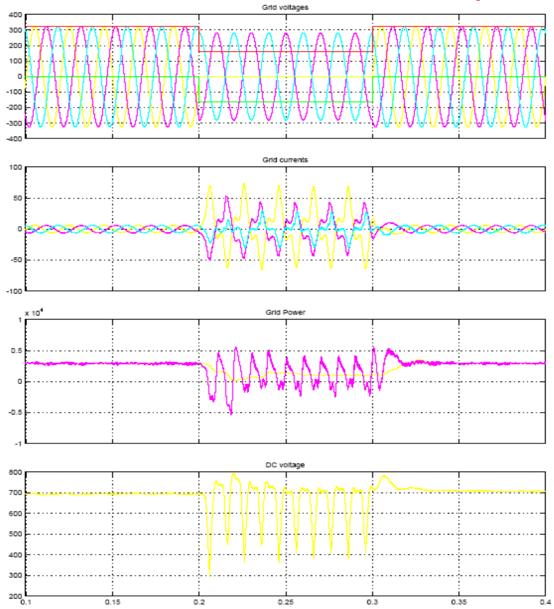
Test results: 100% D type Dip

Filtered: *Successful*



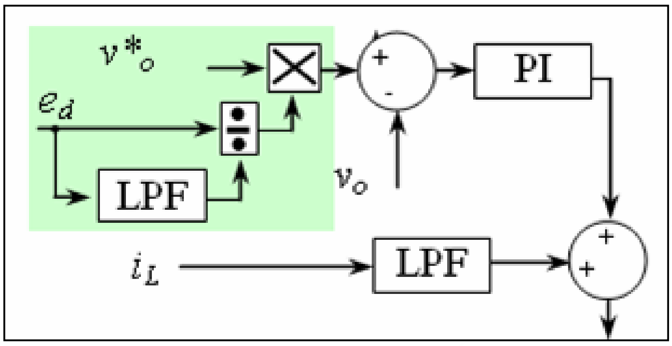
Unfiltered: *Unsuccessful*



Considerations

- ✓ In all symmetrical atypical conditions (Dips type A, frequency changes, power variations) the system shows an optimal reaction with both feed-forward strategies
- ✓ In asymmetrical conditions (Dips type C and D) the different FF strategies trigger different behaviors:
  - ✓ Filtered FF shows a very good output current waveform in all simulations.
  - ✓ Unfiltered FF produces unacceptable output current values for deep fault conditions.

Dc-voltage control with pre-compensation



$$v^*_{o,RF} = \frac{e_d}{E_d} \cdot v^*_o$$

This alterative solution, early developed for ASD, is an attempt to pre-compensate the dc-voltage oscillation, consequent to grid unbalance, modifying the dc-voltage reference signal

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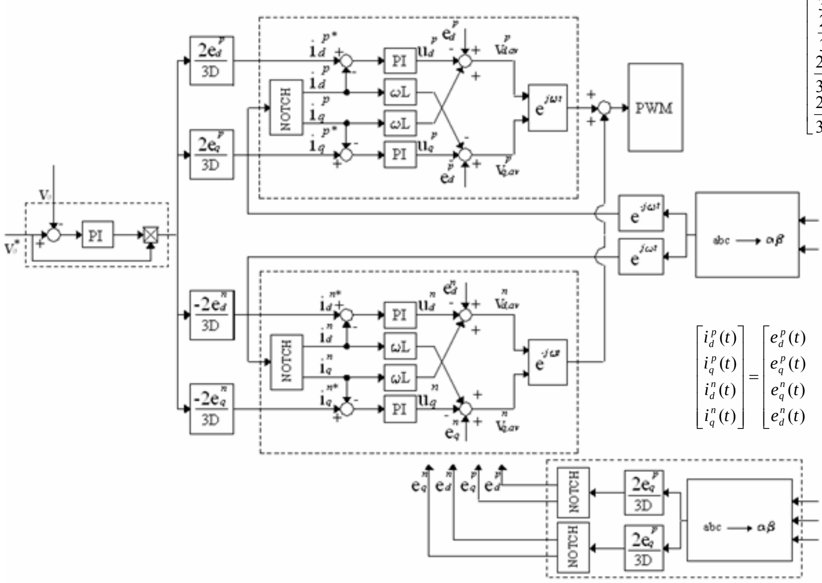
Dual current control



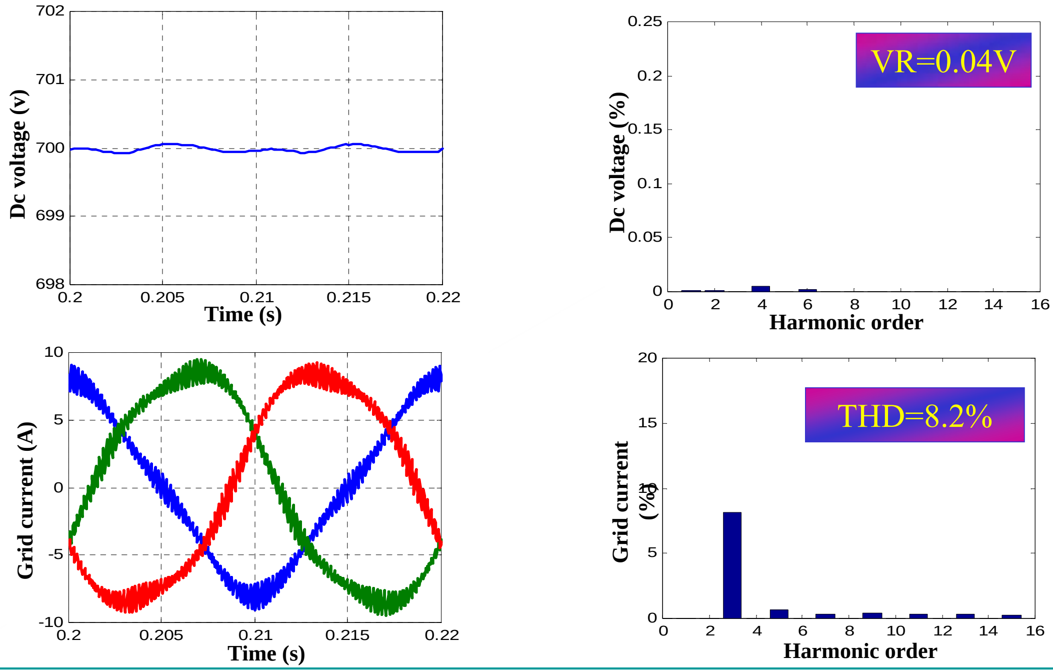
$$\begin{bmatrix} \frac{2}{3}p_0(t) \\ \frac{2}{3}q_0(t) \\ \frac{2}{3}p_{s2}(t) \\ \frac{2}{3}p_{c2}(t) \end{bmatrix} = \begin{bmatrix} e_d^p(t) & e_q^p(t) & e_d^n(t) & e_q^n(t) \\ e_q^p(t) & -e_d^p(t) & e_q^n(t) & -e_d^n(t) \\ e_q^n(t) & -e_d^n(t) & -e_q^p(t) & e_d^p(t) \\ e_d^n(t) & e_q^n(t) & e_d^p(t) & e_q^p(t) \end{bmatrix} \begin{bmatrix} i_d^p(t) \\ i_q^p(t) \\ i_d^n(t) \\ i_q^n(t) \end{bmatrix}$$

$$\frac{2}{3}\begin{bmatrix} p_o(t) \\ q_0(t) \\ p_{s2}(t) \\ p_{c2}(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} p_o(t) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

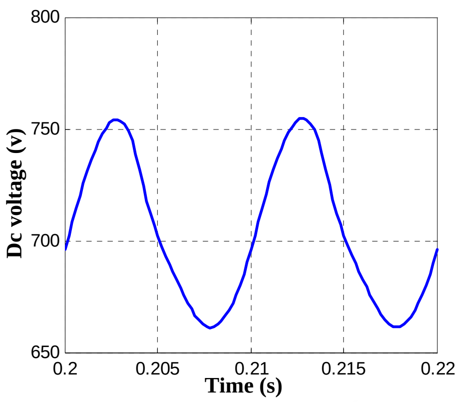
$$\begin{bmatrix} i_d^p(t) \\ i_q^p(t) \\ i_d^n(t) \\ i_q^n(t) \end{bmatrix} = \begin{bmatrix} e_d^p(t) & e_q^p(t) & e_d^n(t) & e_q^n(t) \\ e_q^p(t) & -e_d^p(t) & e_q^n(t) & -e_d^n(t) \\ e_q^n(t) & -e_d^n(t) & -e_q^p(t) & e_d^p(t) \\ e_d^n(t) & e_q^n(t) & e_d^p(t) & e_q^p(t) \end{bmatrix}^{-1} \begin{bmatrix} \frac{2}{3}p_0(t) \\ 0 \\ 0 \\ 0 \end{bmatrix} = \frac{2p_0}{3D}\begin{bmatrix} e_d^p(t) \\ e_q^p(t) \\ -e_d^n(t) \\ -e_q^n(t) \end{bmatrix}$$

$$D = \left[\left(e_d^p(t)\right)^2 + \left(e_d^n(t)\right)^2\right] - \left[\left(e_d^n(t)\right)^2 + \left(e_q^p(t)\right)^2\right] \quad \frac{3}{2}$$

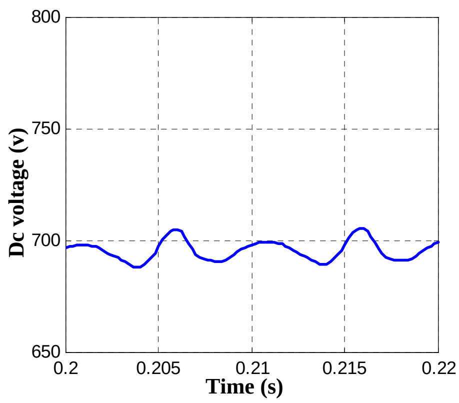
Unbalance condition



Voltage dip



only direct controller



direct/inverse controller

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Control of three-phase inverters for wind systems

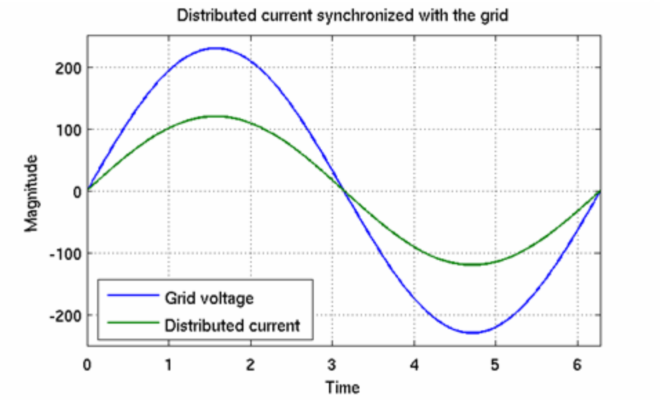
by Marco Liserre, Polytechnic of Bari, Italy

Agenda

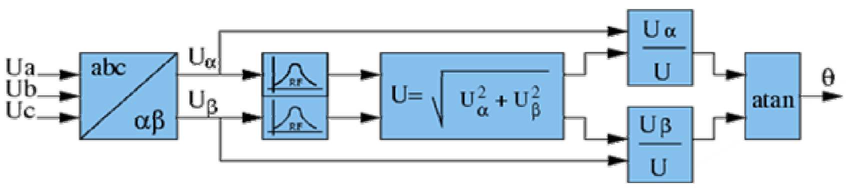
- Current control of three-phase grid-side inverters
- Stability for a large set of grid impedance values
- Fault conditions
- Grid synchronization

Zero crossing

- ✓How it works
  - ✓ method to detect when grid voltages cross zero
- ✓Implementation
  - ✓ hardware chip
  - ✓ software implemented
- ✓Dynamics
  - ✓ very low due to the low frequency of the grid voltages
- ✓Usage
  - ✓ maybe a solution for low cost applications



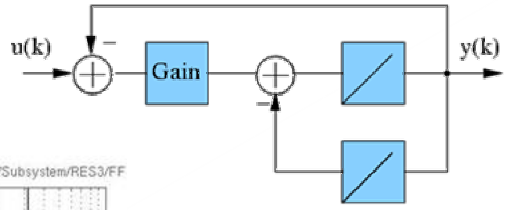
αβ Filtering

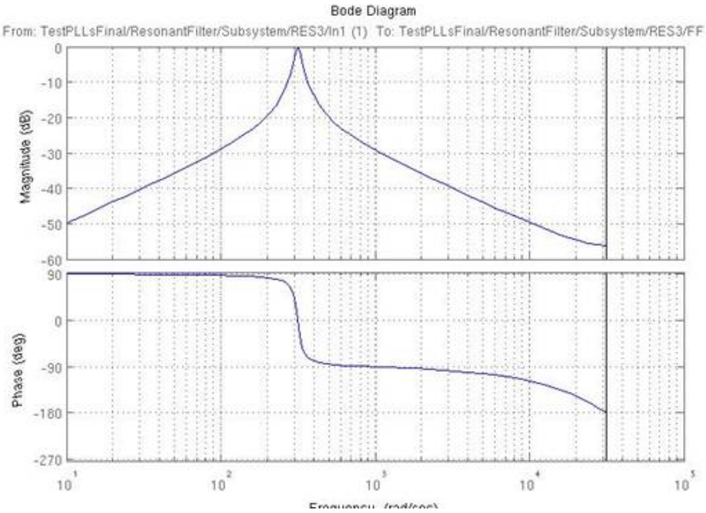


- ✓Method derived from drive applications
- ✓The filtering is applied on stationary reference frame
  - ✓ Different filtering techniques may be applied (notch filter, band pass filter, etc.)
  - ✓ Resonant filter applied
    - ✓no delay
    - ✓easy to design

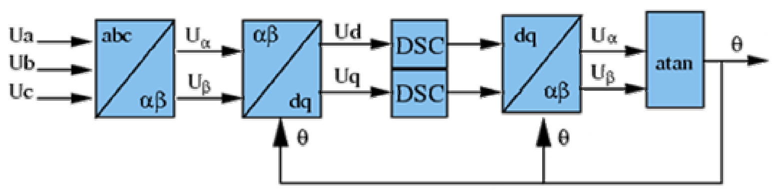
αβ Filtering

- Structure
- Bode plot for Gain = 0.1

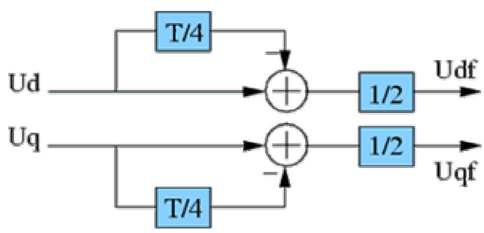




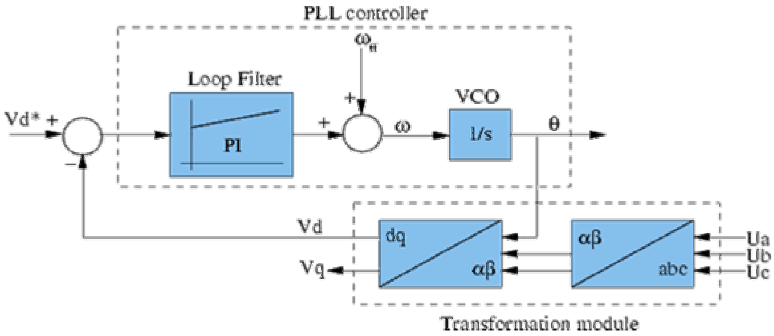
dq Filtering



- Filtering applied in synchronous rotating reference frame
  - Easier to filter dc signals
  - Many filter techniques might apply
  - Delay Signal Cancellation chosen here
    - no delay
    - easy to implement

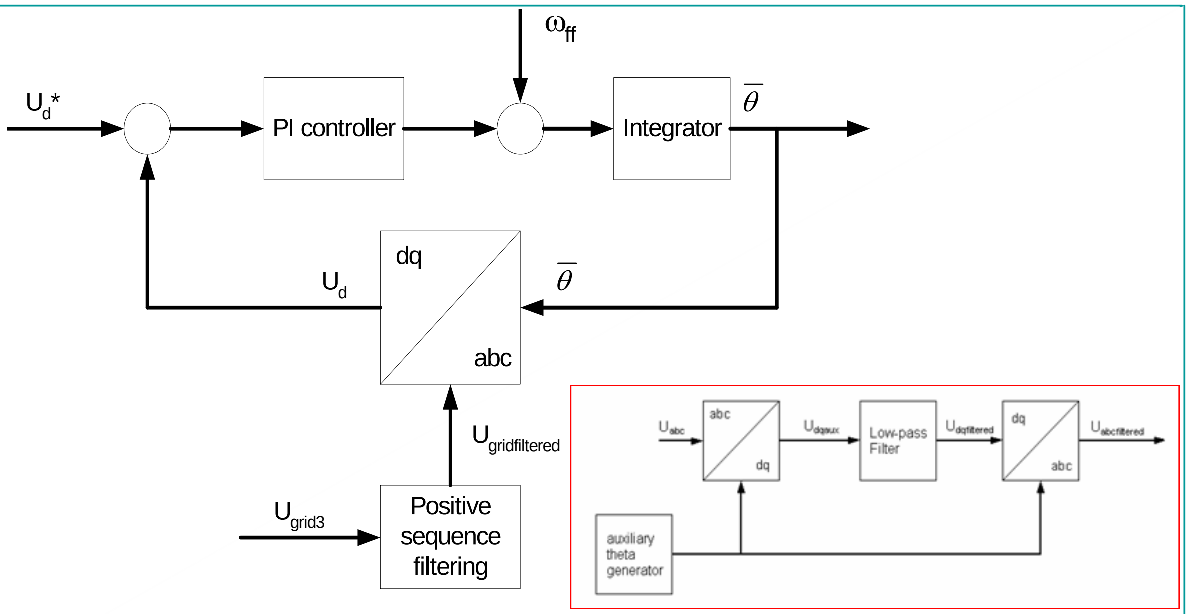


Phase-Looked Loop (PLL) method



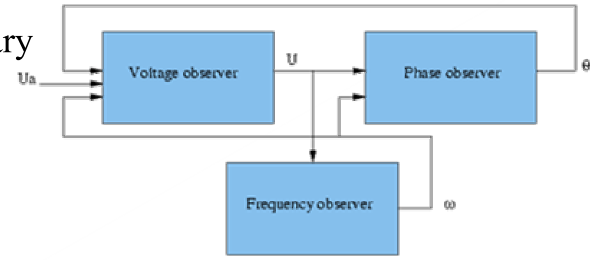
- ✓ Method widely used in radio communication
- ✓ Looking by setting Vd*=0
- ✓ Needs transformation into synchronous reference frame
- ✓ Uses a controller to track the phase angle

Phase-Looked Loop (PLL) method based on positive seq.



Adaptive PLL

- ✓ Structure for single phase
  - ✓ three algorithms necessary
- ✓ One observer for each grid parameter:
  - ✓ voltage
  - ✓ frequency
  - ✓ phase



- Output of one controller is input in the other
  - adaptive regulation
- Can detect all grid parameters
- Difficult to tune due to interaction of the controllers

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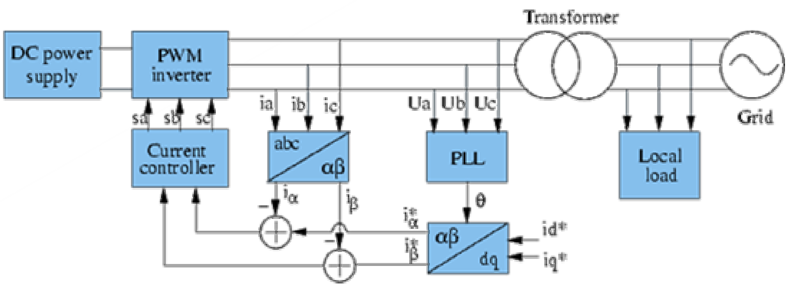
Grid synchronization – Evaluation of Algorithms

- ✓ **Experimental setup**
- ✓ Laboratory implementation
  - ✓ Control strategy in stationary reference frame
  - ✓ All synchronization algorithms implemented
  - ✓ Grid simulator used to create grid faults



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Experimental setup

- ✓ DC power supplies to charge the dc-link
- ✓ Danfoss VLT 5000 inverter
- ✓ Hardware LCL filter
- ✓ Isolation transformer
- ✓ Voltec power analyzer
- ✓ dSpace board for control implementation

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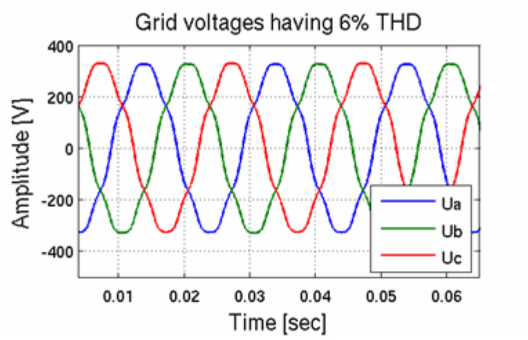
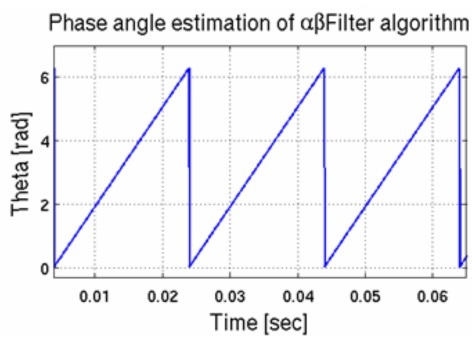
Test results

- ✓ Harmonics content of 6%





- ✓ appropriate gains or filter parameters necessary to filter out the harmonics
- ✓ all algorithms can overcome such distortion

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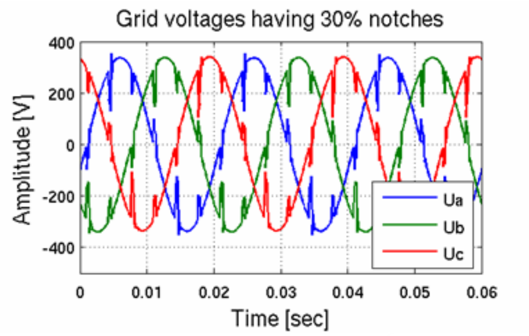
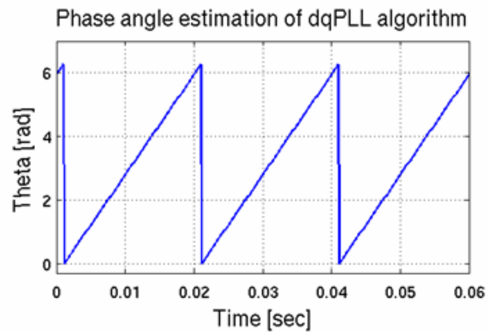
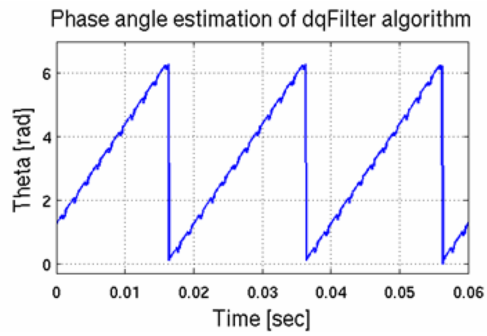
Test results

- ✓ Notches







- ✓ most algorithms overcome notches
- ✓ Delay Signal Cancellation is sensitive to grid frequency thus has problems when this is different than 50 Hz

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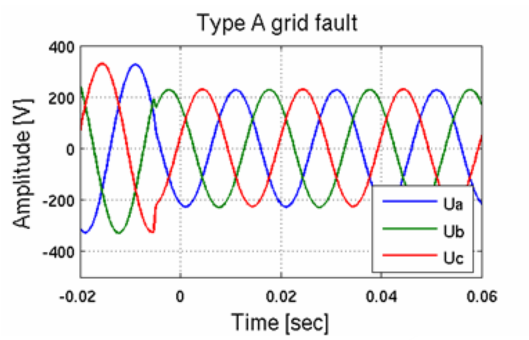
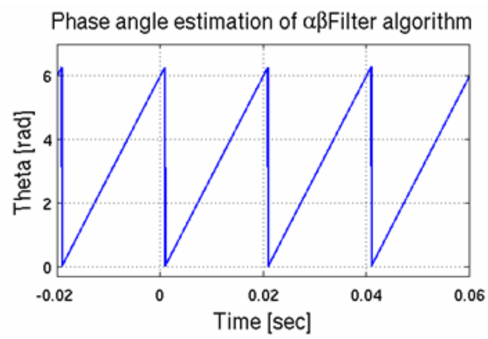
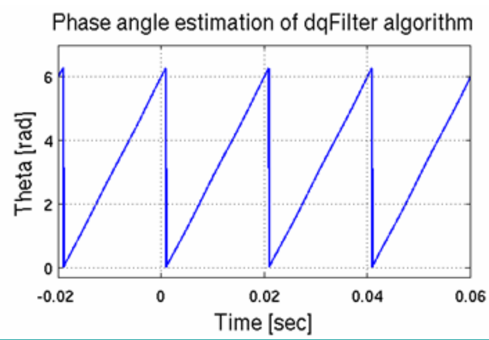
Test results

- ✓ Symmetrical voltage dip (Type A)







- ✓ no problems for algorithms on symmetrical faults
- ✓ no negative sequence present
- ✓ grid amplitude does not influence the angle estimation

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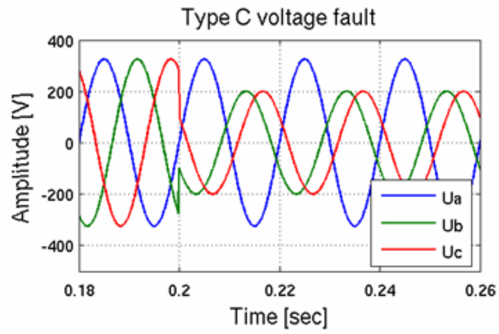
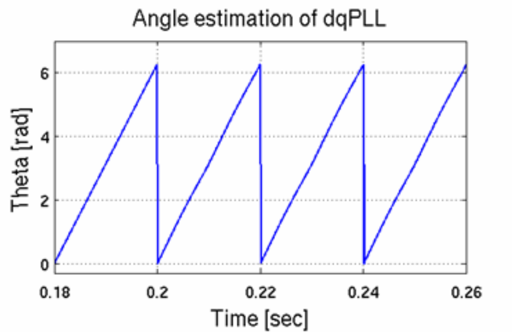
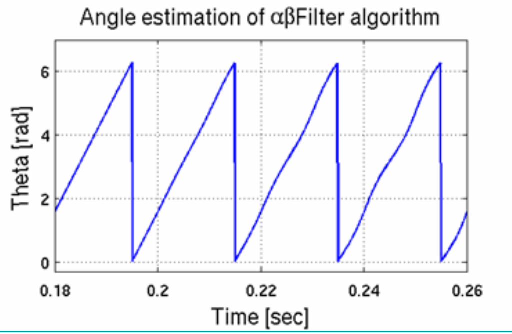
Test results

- ✓ Asymmetrical grid fault (Type C)







- ✓ negative sequence makes the ab components to not have the same amplitude ->100 Hz ripple present in the angle signal
- ✓ other algorithms perform well

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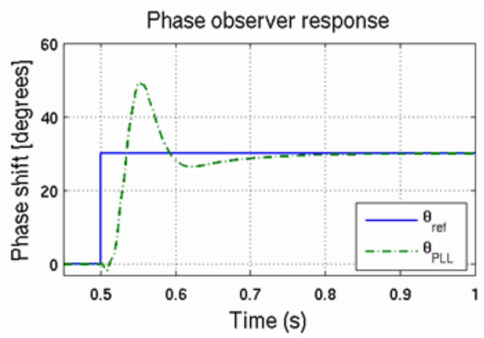
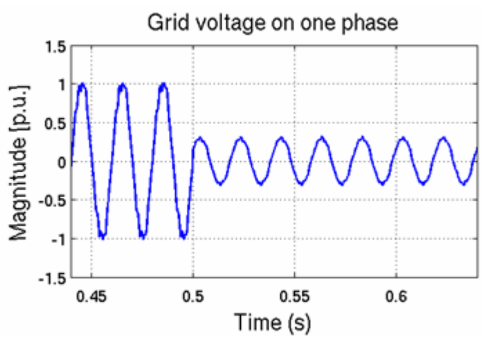
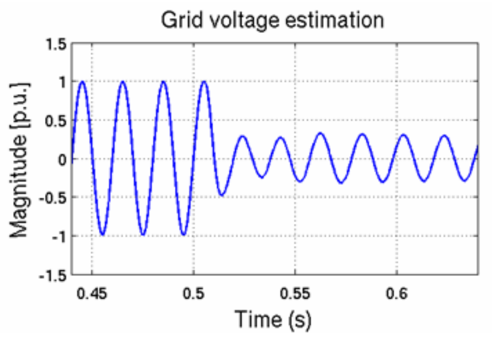
Test results

Adaptive PLL

- ✓ Single phase implementation
- ✓ Test on one phase
  - ✓ 70% voltage dip
  - ✓ 8% harmonics
  - ✓ 30 degrees phase jump







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Comparison of the synchronization algorithms

Algorithm	Strong points	Weak points
$dqFilter$ (with DSC)	simplicity	on frequency shift variations
$\alpha\beta Filter$	simplicity	on unbalanced grid
$dqPLL$	works on every grid type, provides ride through capability	slow dynamics
$adaptivePLL$	estimates amplitude, frequency and phase angle	complex structure

Conclusions

- ✓ Most of the algorithms can overcome grid problems when grid faults occur
- ✓ Appropriate settings are necessary in the controller or filters
- ✓ Can provide ride through capabilities from the synchronization point of view
  - ✓ Helping the DPGS to run over short disturbances
  - ✓ Contributing to grid stability
- ✓ Some can also be used in grid monitoring
  - ✓ Provide amplitude, frequency and phase angle
  - ✓ Detection time is less than grid codes specify

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