止於至善

# Grid Current Control

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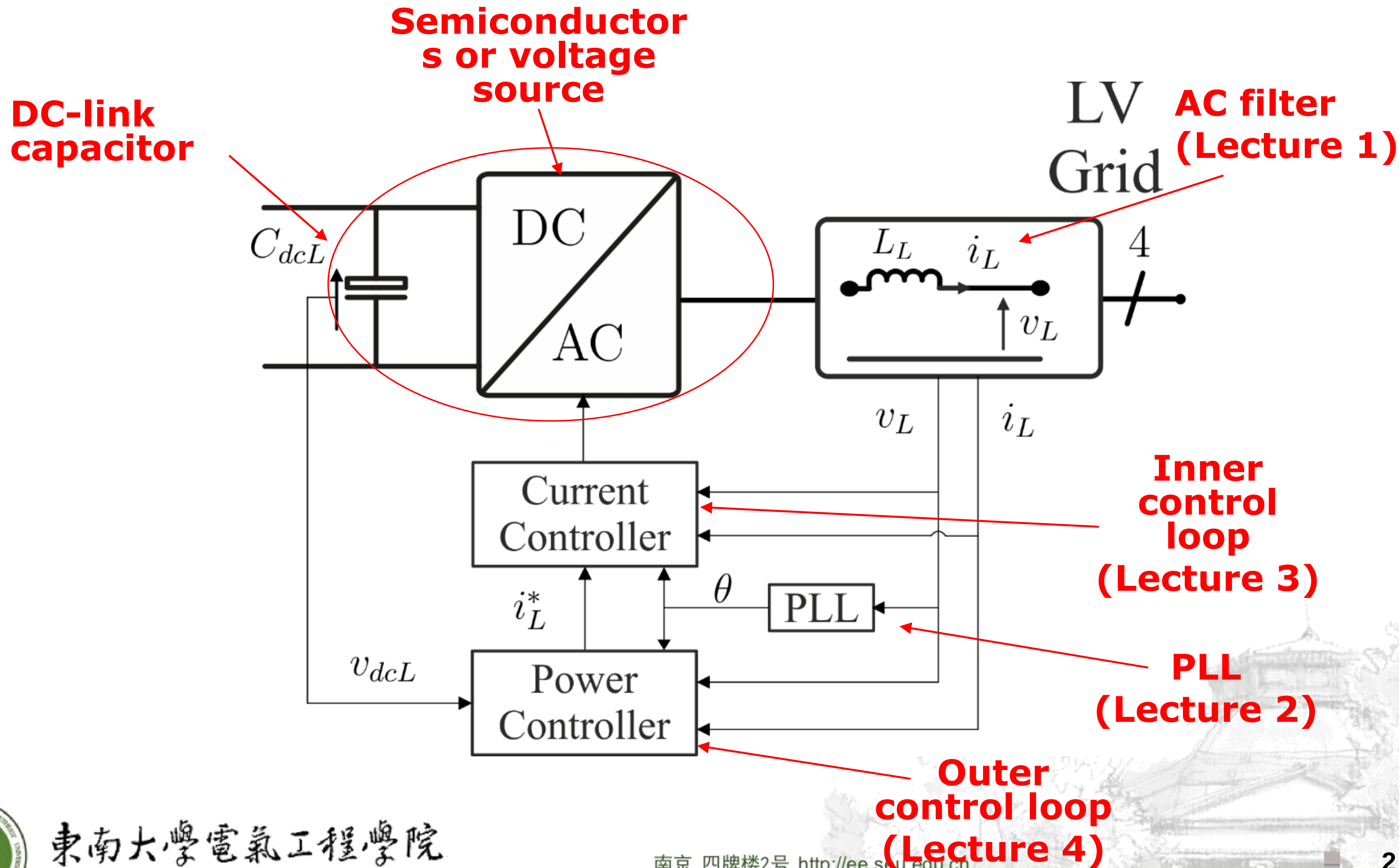
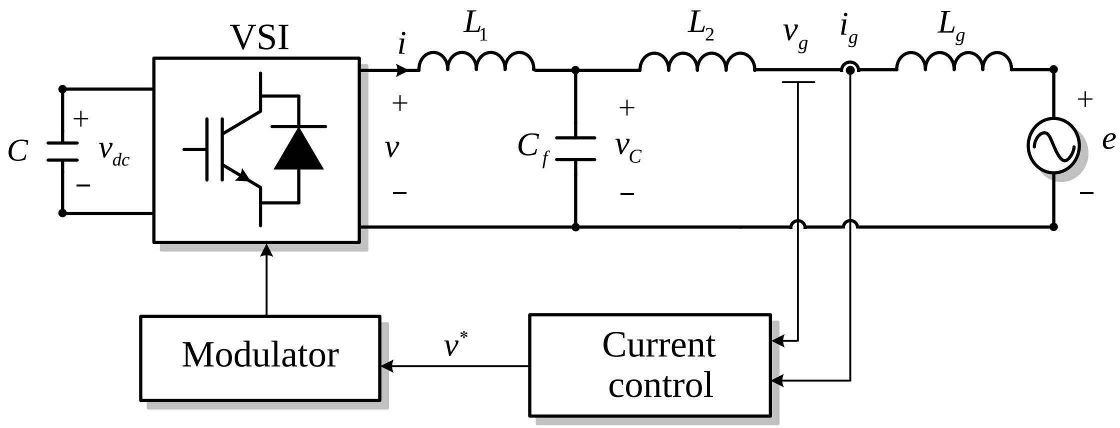
# Key Components of Grid Converters

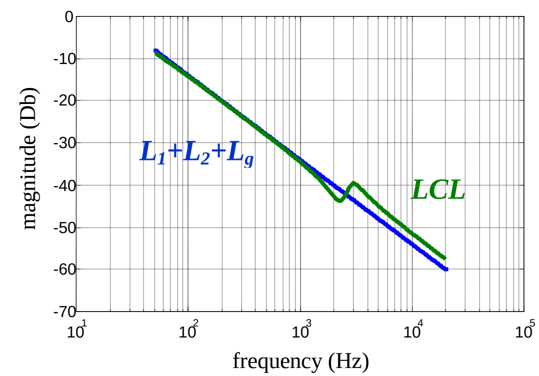


# Outline

- Harmonic requirements
- Current control overview
- Harmonic compensation

# Introduction of grid current control




- The influence of the capacitor of the filter will be neglected since it is only dealing with the switching ripple frequencies. In fact at frequencies lower than half of the resonance frequency the LCL-filter inverter model and the L-filter inverter models have the same frequency characteristic
- PI-based current control implemented in a synchronous frame is commonly used in three-phase converters
- In single-phase converters the PI controller capability to track a sinusoidal reference is limited and Proportional Resonant (PR) can offer better performances
- Modulation has an influence on the design of the converter (dc voltage value), losses and EMC problems including leakage current

# Harmonic requirements: PV-systems

- **In Europe there is the standard IEC 61727**
- **In US there is the recommendation IEEE 929**
- **The recommendation IEEE 1547 is valid for all distributed resources technologies with aggregate capacity of 10 MVA or less at the point of common coupling interconnected with electrical power systems at typical primary and/or secondary distribution voltages**
- **All of them impose the following conditions regarding grid current harmonic content**

| ODD HARMONICS | DISTORTION LIMIT |
|---|---|
| $3^{rd}$ through $9^{th}$ | less than 4.0% |
| $11^{th}$ through $15^{th}$ | less than 2.0% |
| $17^{th}$ through $21^{st}$ | less than 1.5% |
| $23^{rd}$ through $33^{rd}$ | less than 0.6% |
| | |

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

# Harmonic requirements: WT-systems

- **In Europe the standard 61400-21 recommends to apply the standard 61000-3-6 valid for polluting loads requiring the current THD smaller than 6-8% depending on the type of network**

| harmonic | limit |
|---|---|
| $5^{th}$ | 5-6 % |
| $7^{th}$ | 3-4 % |
| $11^{th}$ | 1.5-3 % |
| $13^{th}$ | 1-2.5 % |

- **In case of several WT systems**

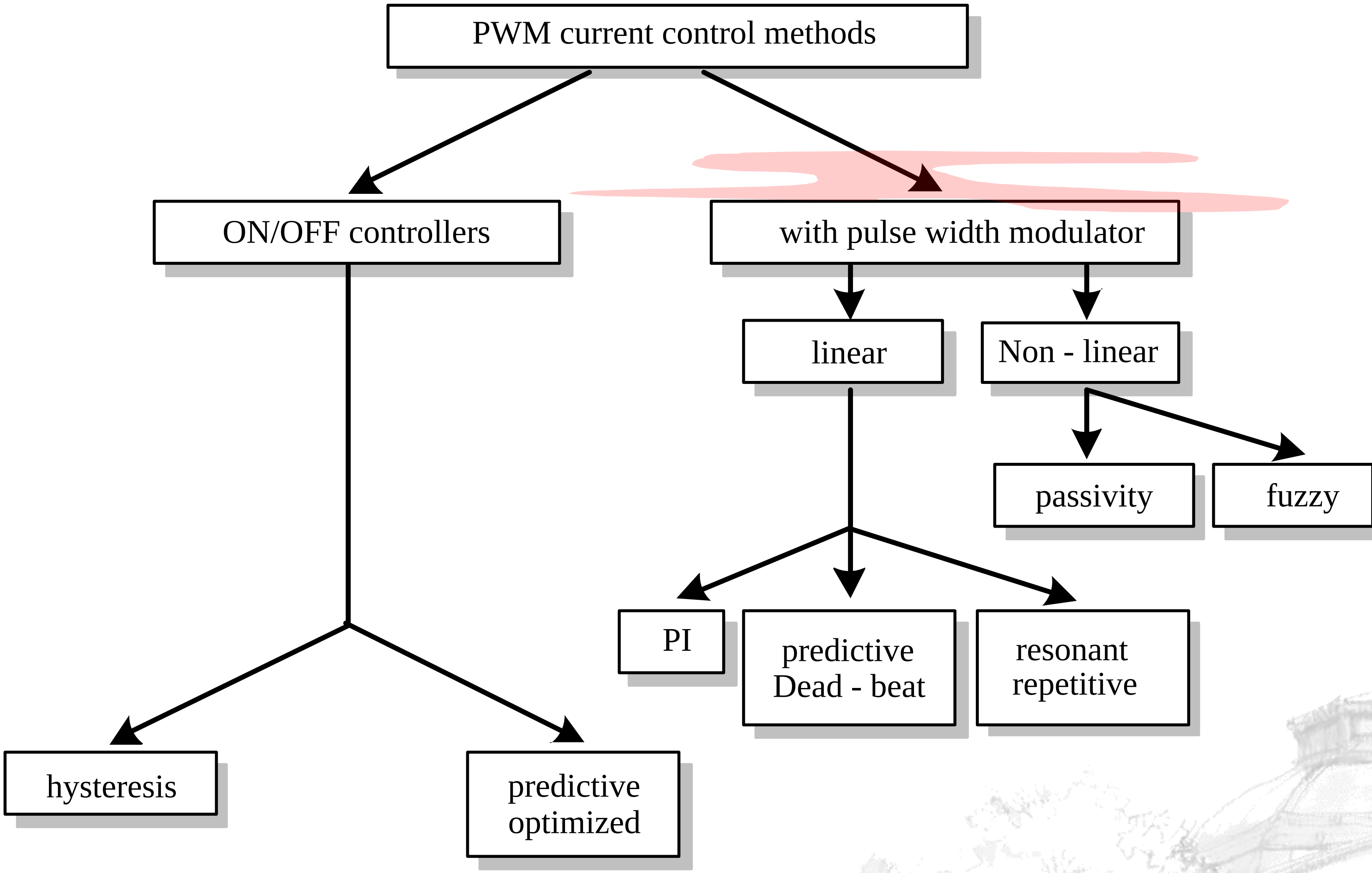
$$I_{h\Sigma} = \sqrt[\beta]{\sum_{i=1}^{N} \left( \frac{I_{hi}}{\upsilon_i} \right)^{\beta}}$$

$\upsilon_i$ – ratio of the transformer at the $i$th wind turbine

| Harmonic order | Exponent $\beta$ |
|---|---|
| $h < 5$ | 1.0 |
| $5 \leq h \leq 10$ | 1.4 |
| $h > 10$ | 2.0 |

- **In WT systems asynchronous and synchronous g the grid have no limitations respect to current h**

# Current Control overview



# Linear current control with separated modulation: use of averaging

- **Continuous switching vector which components are the duty cycle of each converter leg**

- **Average model**

$$\bar{d}(t)=\frac{2}{3}\left(d_a(t)+\alpha d_b(t)+\alpha^2 d_c(t)\right)$$

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

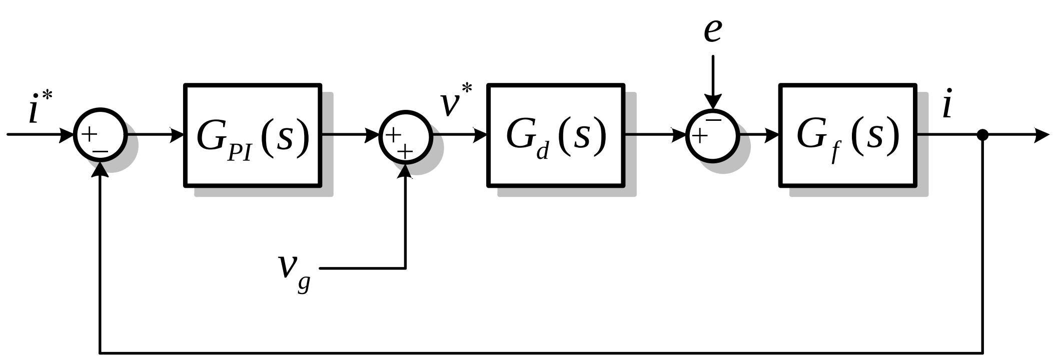
- **Linearized model $v_{dc}(t)=V_{dc}$**

$$\begin{cases}v_d(t)=d_d(t)v_{dc}(t)\\ v_q(t)=d_q(t)v_{dc}(t)\end{cases}$$

$$\frac{d}{dt}\begin{bmatrix}i_d(t)\\ i_q(t)\end{bmatrix}=\begin{bmatrix}-\dfrac{R}{L} & \omega\\ -\omega & -\dfrac{R}{L}\end{bmatrix}\begin{bmatrix}i_d(t)\\ i_q(t)\end{bmatrix}+\begin{bmatrix}\dfrac{V_{dc}}{L} & 0\\ 0 & \dfrac{V_{dc}}{L}\end{bmatrix}\begin{bmatrix}d_d(t)\\ d_q(t)\end{bmatrix}+\begin{bmatrix}-\dfrac{1}{L} & 0\\ 0 & -\dfrac{1}{L}\end{bmatrix}\begin{bmatrix}e_d(t)\\ e_q(t)\end{bmatrix}$$

# PI current control

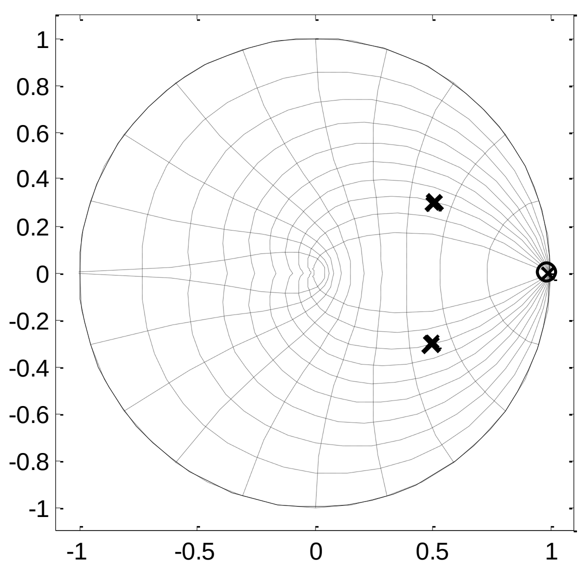
- **Typically PI controllers are used for the current loop in grid inverters**
- **Technical optimum design (damping 0.707 overshoot 5%)**

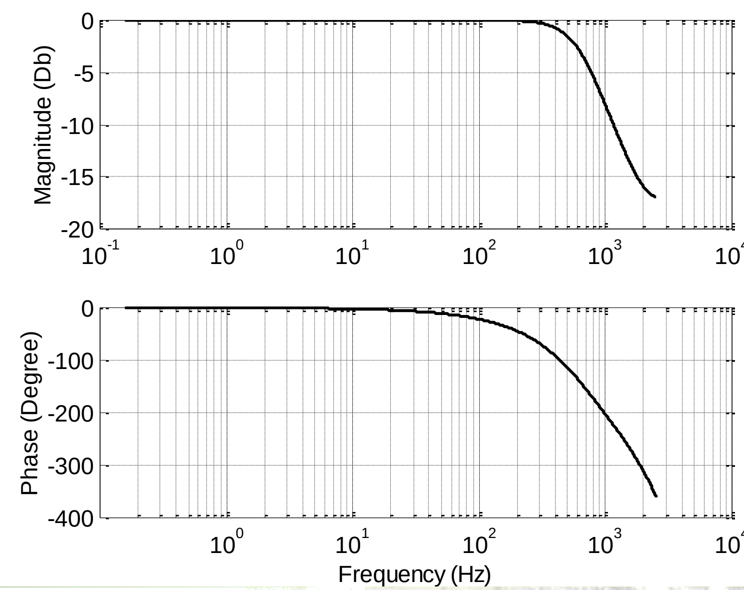



$$G_{PI}(s) = k_P + \frac{k_I}{s}$$

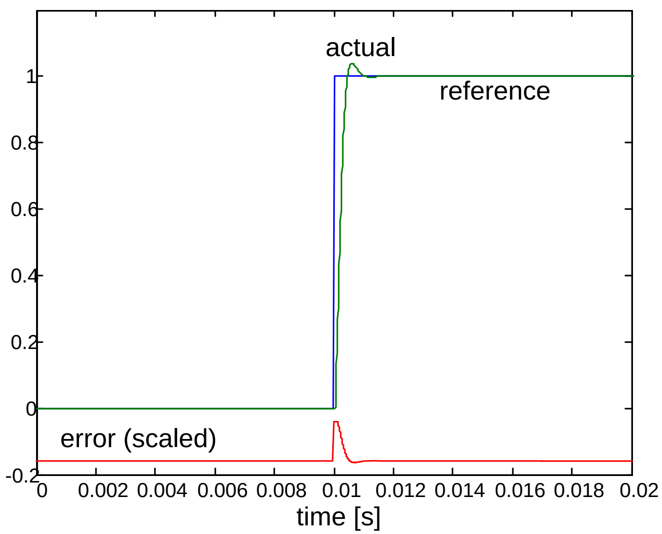
$$G_d(s) = \frac{1}{1+1.5T_s s}$$

$$G_f(s) = \frac{i(s)}{v(s)} = \frac{1}{R+Ls}$$



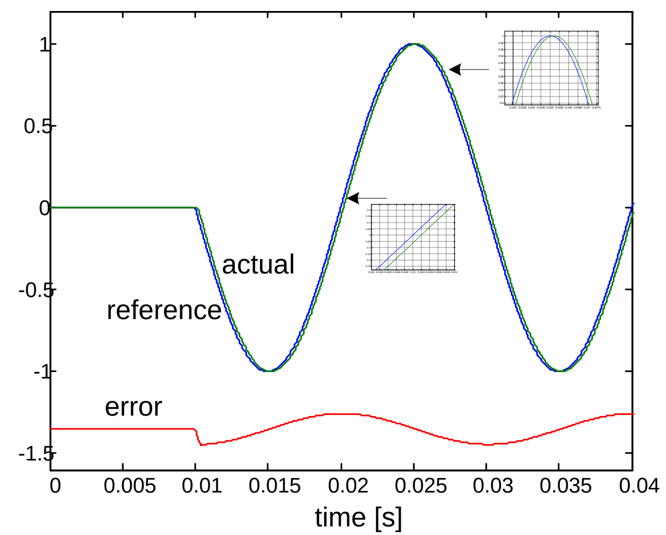



# Shortcomings of PI controller



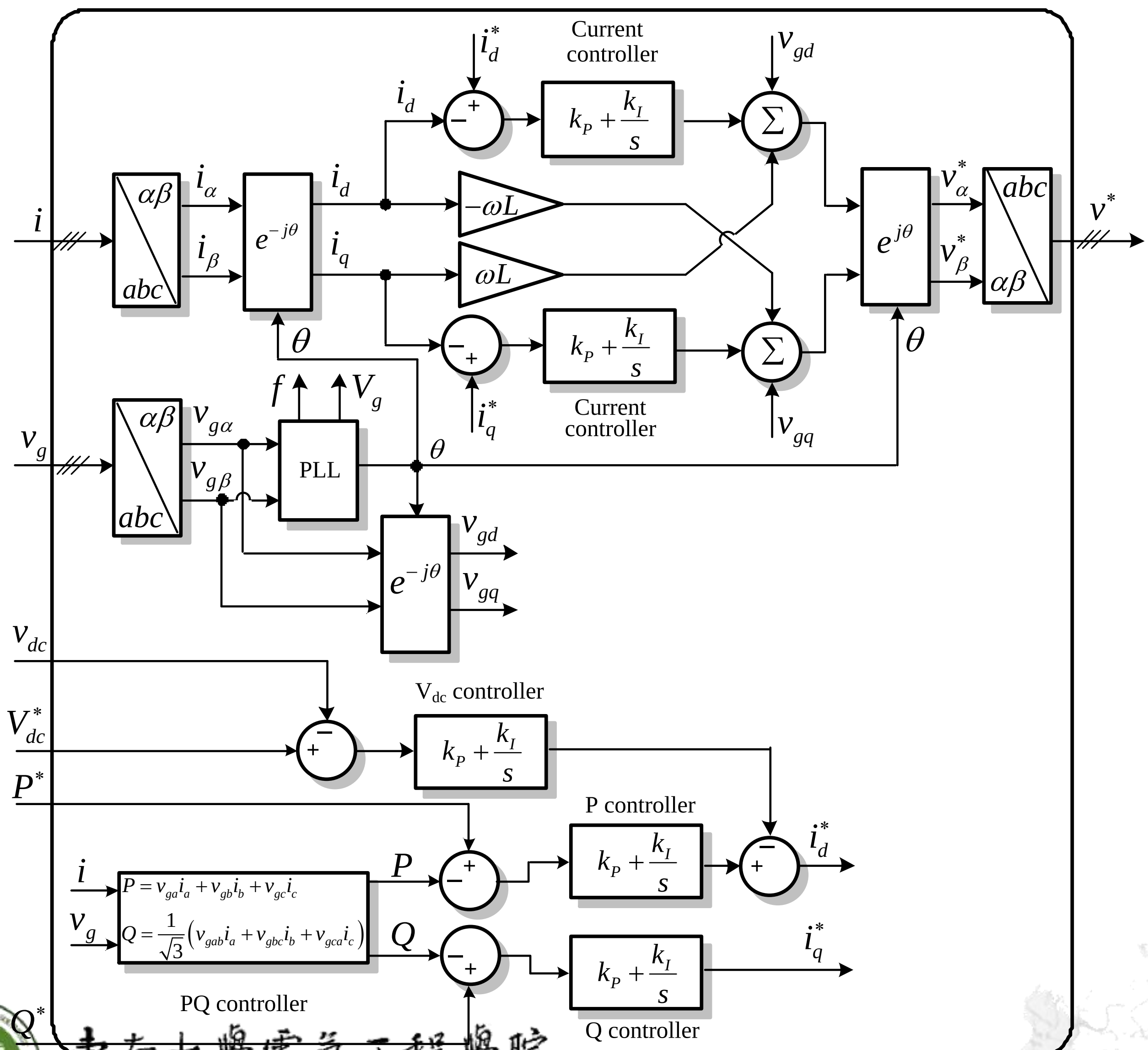

**steady-state magnitude and phase error**

**limited disturbance rejection capability**

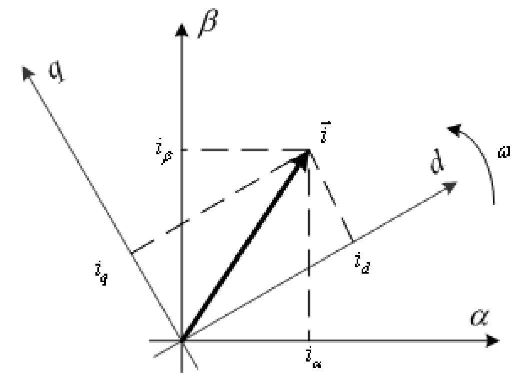



- **When the current controlled inverter is connected to the grid, the phase error results in a power factor decrement and the limited disturbance rejection capability leads to the need of grid feed-forward compensation**
- **However the imperfect compensation action of the feed-forward control due to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

# Use of a PI controller in a rotating frame



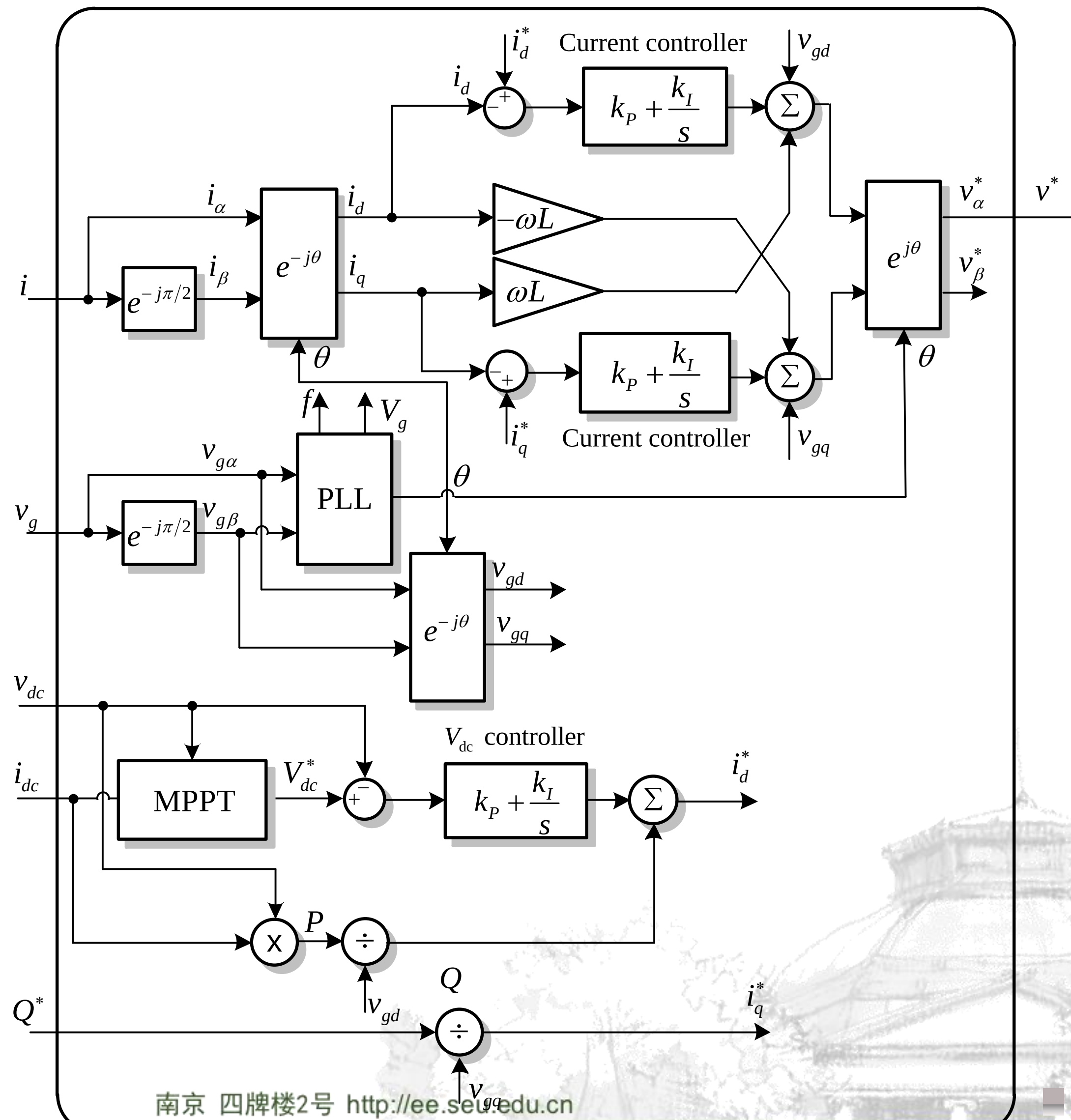

**In order to overcome the limit of the PI in dealing with sinusoidal reference and harmonic disturbances, the PI control is implemented in a rotating frame**



$$G_{PI}(s)_{dq} = \begin{bmatrix} k_P + \frac{k_I}{s} & 0 \\ 0 & k_P + \frac{k_I}{s} \end{bmatrix}$$

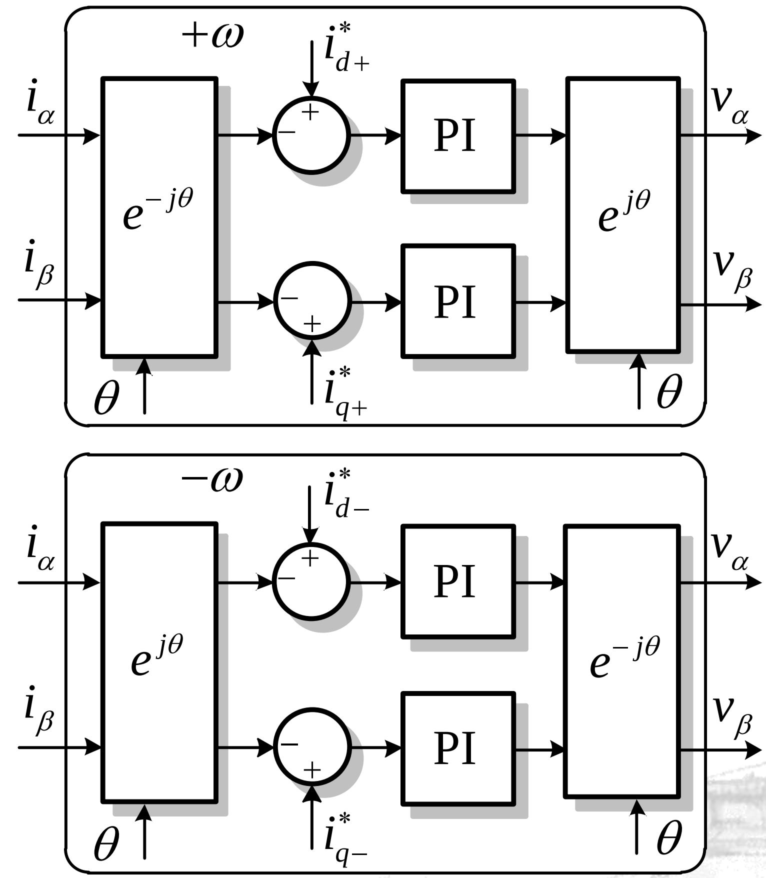
# phase systems

- An independent Q control is achieved
- A phase delay block create the virtual quadrature component that allows to emulate a two-phase system
- The $v_\beta$ component of the command voltage is ignored for the calculation of the duty-cycle



# Use of a PI controllers in two rotating frames

- **Under unbalanced conditions in order to compensate the harmonics generated by the inverse sequence present in the grid voltage both the positive- and negative-sequence reference frames are required**
- **Obviously using this approach, double computational effort must be devoted**

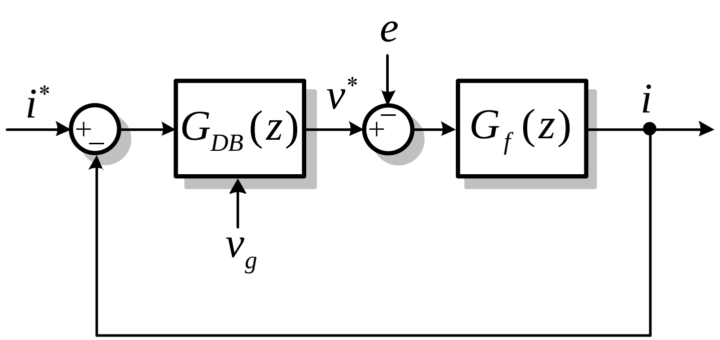


# Linear current control with separated modulation: Dead-beat controller

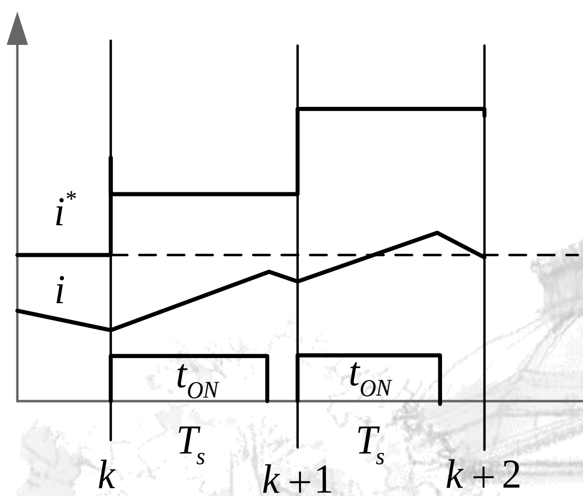
- The dead-beat controller belongs to the family of the predictive controllers
- They are based on a common principle: to foresee the evolution of the controlled quantity (the current) and on the basis of this prediction:
  - To choose the state of the converter (ON-OFF predictive) or
  - The average voltage produced by the converter (predictive with pulse width modulator)
- The starting point is to calculate its derivative to predict the effect of the control action
- The controller is developed on the basis of the model of the filter and of the grid, which is used to predict the system dynamic behavior: the controller is inherently sensitive to model and parameter mismatches

# Dead-beat controller

- **The information on the model is used to decide the switching state of the converter with the aim to minimize the possible commutations (ON-OFF predictive) or the average voltage that the converter has to produce in order to null it**




- **In case it is imposed that the error at the end of the next sampling period is zero the controller is defined as "dead-beat". It can be demonstrated that it is the fastest current controller allowing nulling the error after two sampling periods**

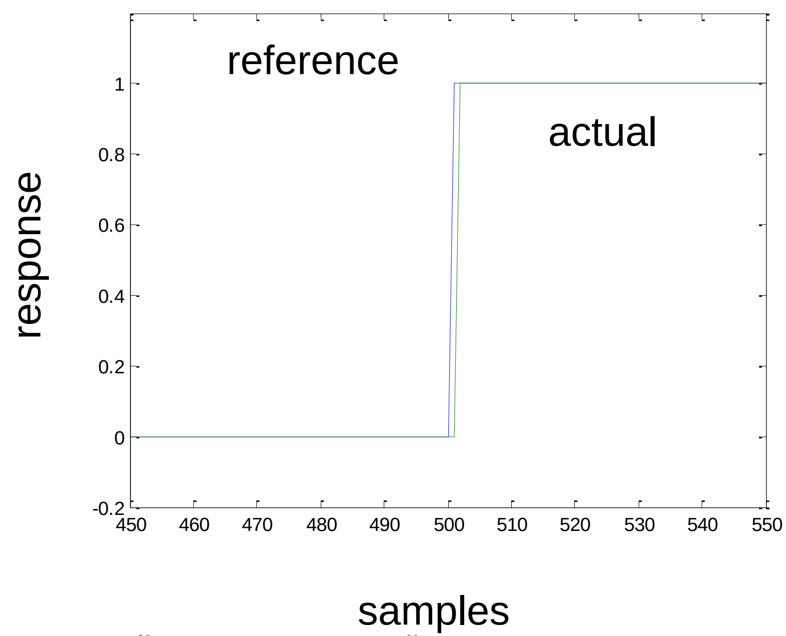


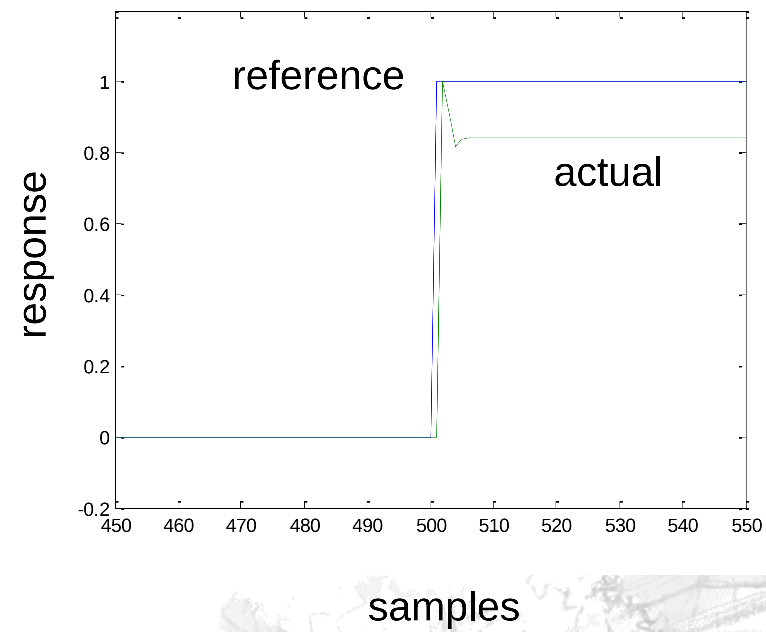
# Dead-beat controller

$$v(k+1) = v(k-1) + \frac{1}{b}\Delta i(k) - \frac{a}{b}\Delta i(k-1) + e(k+1) - e(k-1)$$

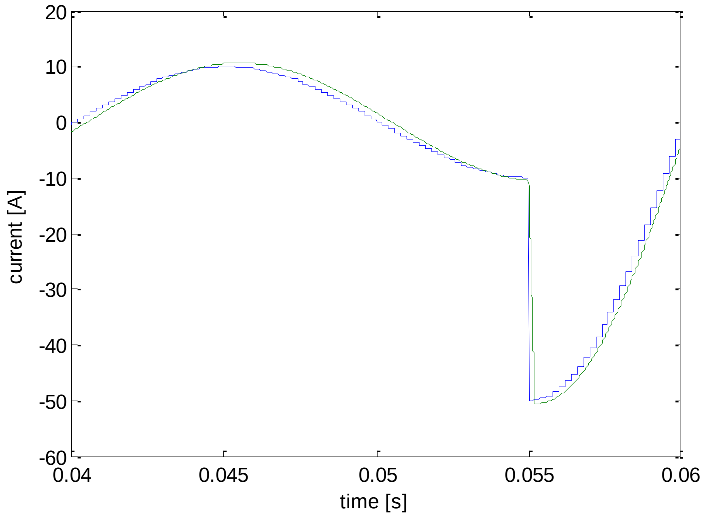
$$v(k+1) = -v(k) + \frac{1}{b}\Delta i(k) + e(k+1) + e(k)$$

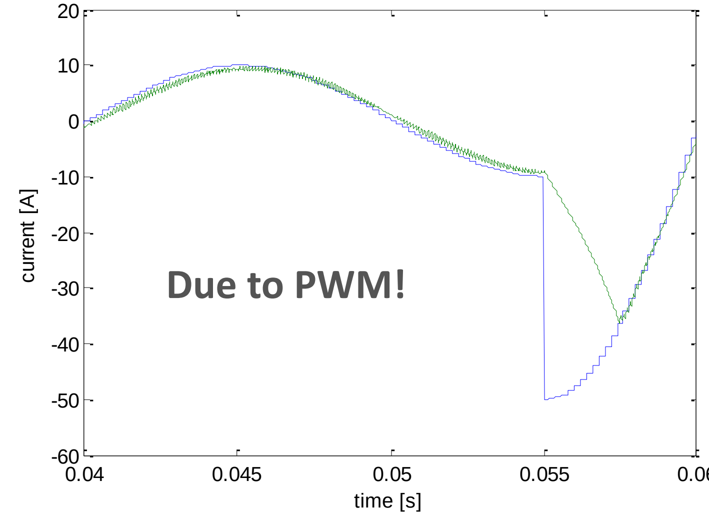
**Neglecting R!**

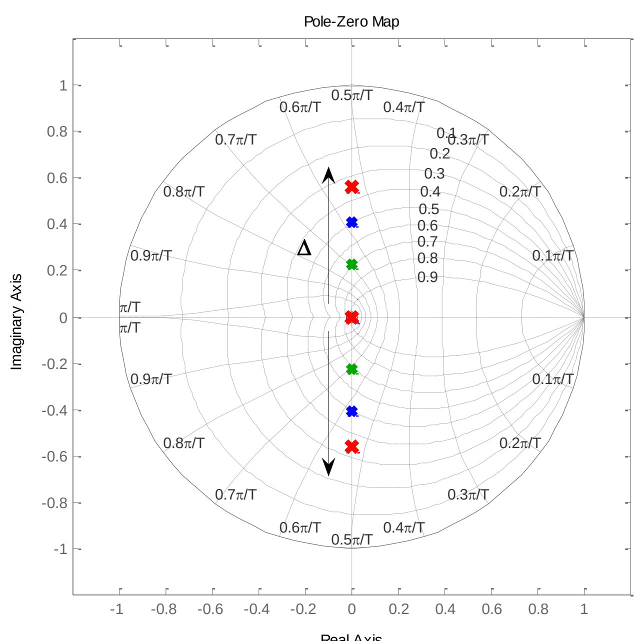


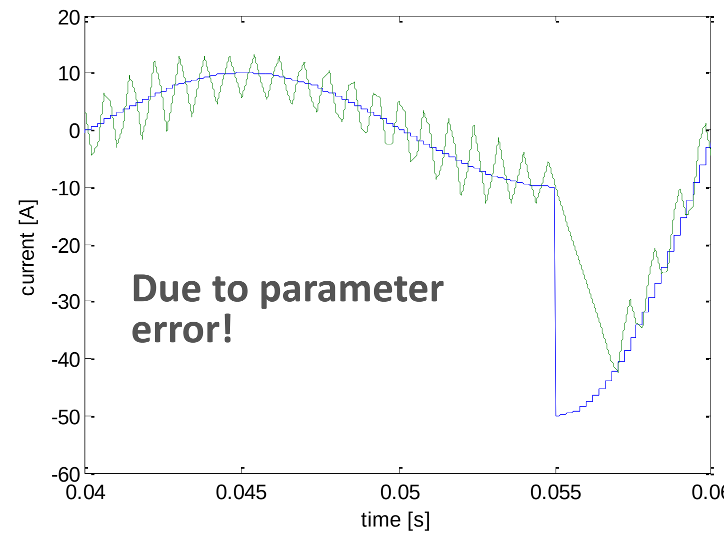



# Dead-beat controller: limits



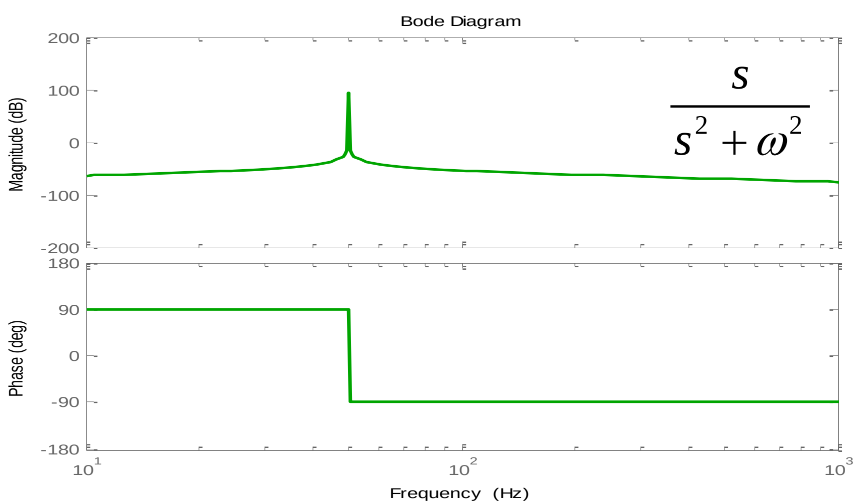



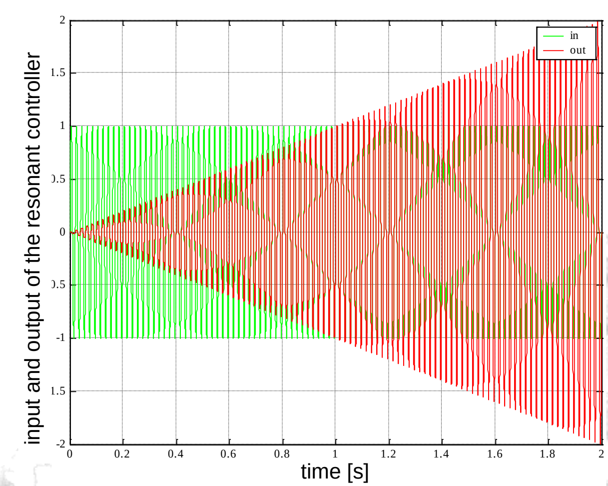
# Linear current control with separated modulation: Resonant controller

- **Resonant control is based on the use of Generalized Integrator (GI)**
- **A double integrator achieves infinite gain at a certain frequency, called resonance frequency, and almost no attenuation outside this frequency**

$$\textbf{GI} \qquad \frac{s}{s^2+\omega^2}$$

- **The GI will lead to zero stationary error and improved and selective disturbance rejection as compared with PI controller**



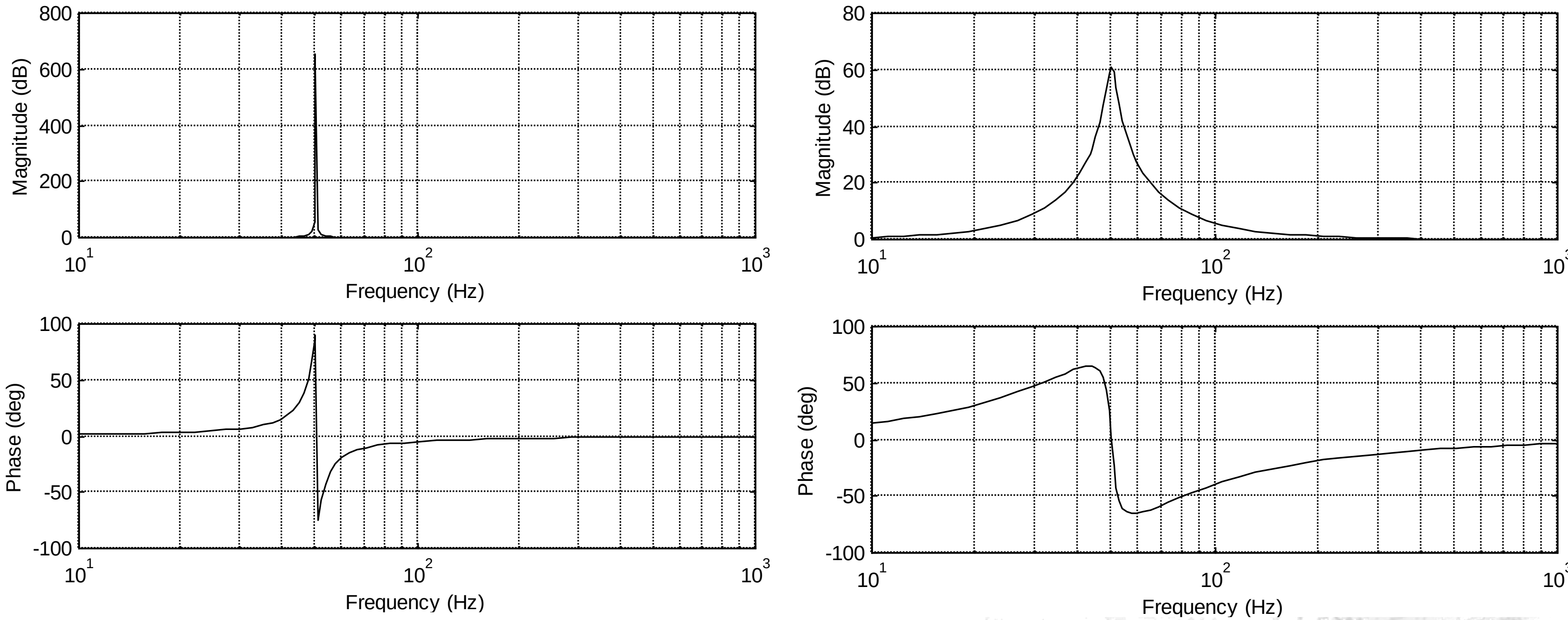
# Resonant control

- **The resonant controller can be obtained via a frequency shift**

$$G_{AC}(s) = G_{DC}(s - j\omega) + G_{DC}(s + j\omega)$$

$$G_{DC}(s) = \frac{k_I}{s} \longrightarrow G_{AC}(s) = \frac{2k_I s}{s^2 + \omega^2}$$

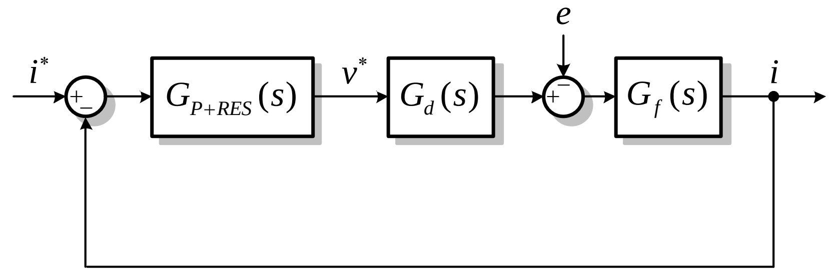
$$G_{DC}(s) = \frac{k_I}{\left(1 + \left(s/\omega_c\right)\right)} \longrightarrow G_{AC}(s) \approx \frac{2k_I \omega_c s}{s^2 + 2\omega_c s + \omega^2}$$




**Bode plots of ideal and non-ideal PR with** $k_P = 1$, $k_I = 20$, $\omega = 314$ rad/s, $\omega_c = 10$ rad/s

# Resonant control

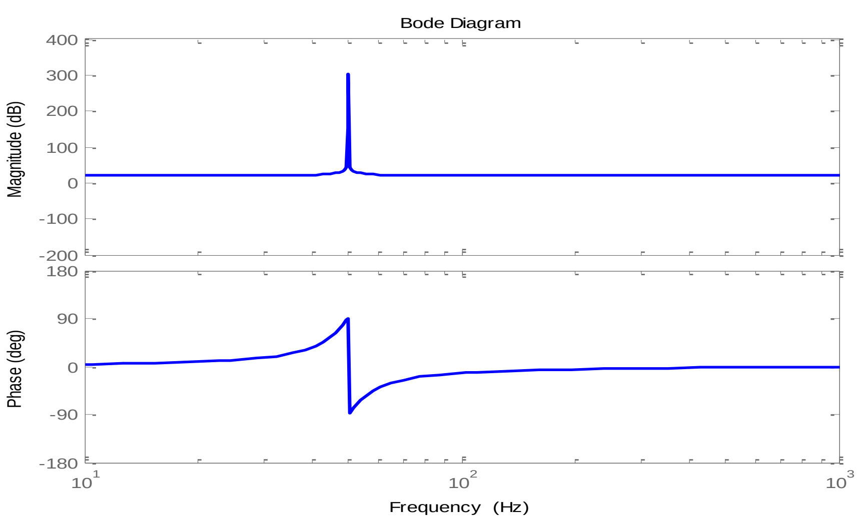
- **The stability of the system should be taken into consideration**

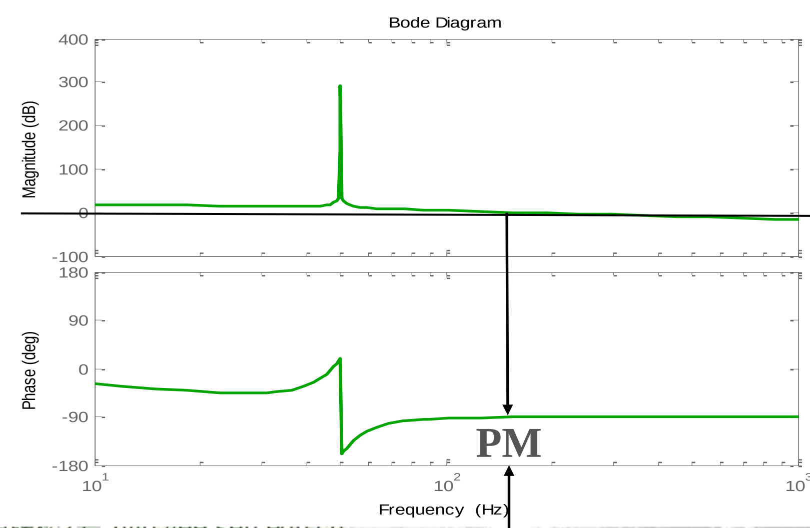



- **The phase margin (PM) decreases as the resonant frequency approach to the crossover frequency**

$$k_P + k_I \frac{s}{s^2+\omega^2}$$

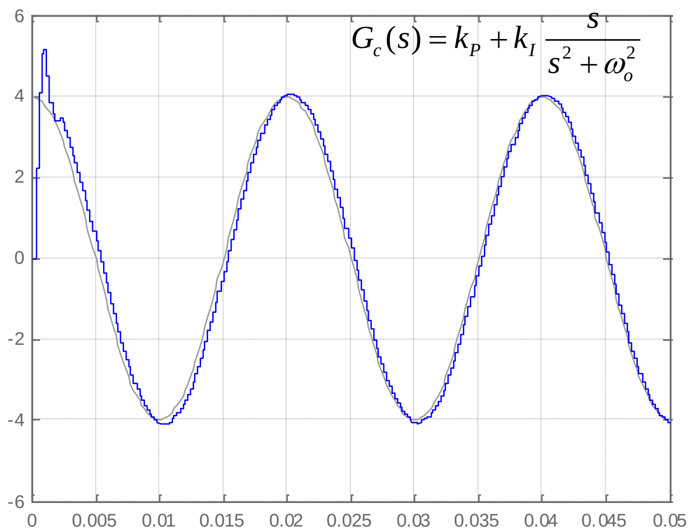
$$\left(k_P + k_I \frac{s}{s^2+\omega^2}\right)\left(\frac{1}{R+Ls}\right)$$



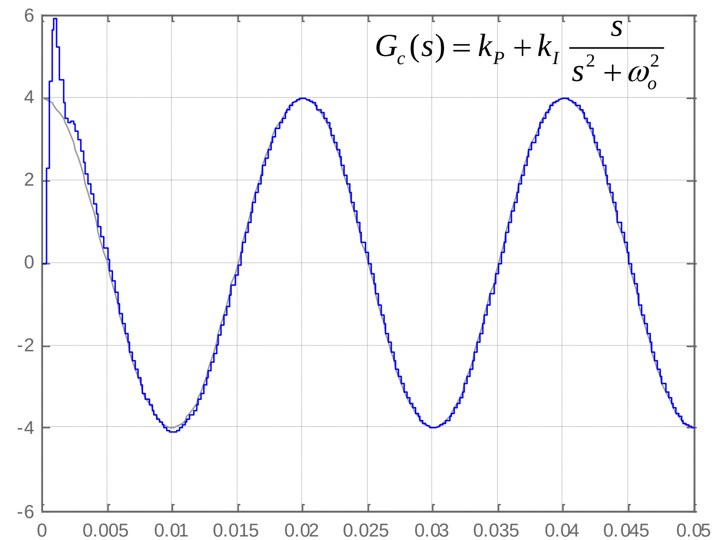



# Tuning of resonant control

- The gain $k_P$ is founded by ensuring the desired bandwidth using either rlocus Matlab function or SISOTOOL
- The integral constant $k_I$ acts to eliminate the steady-state phase error



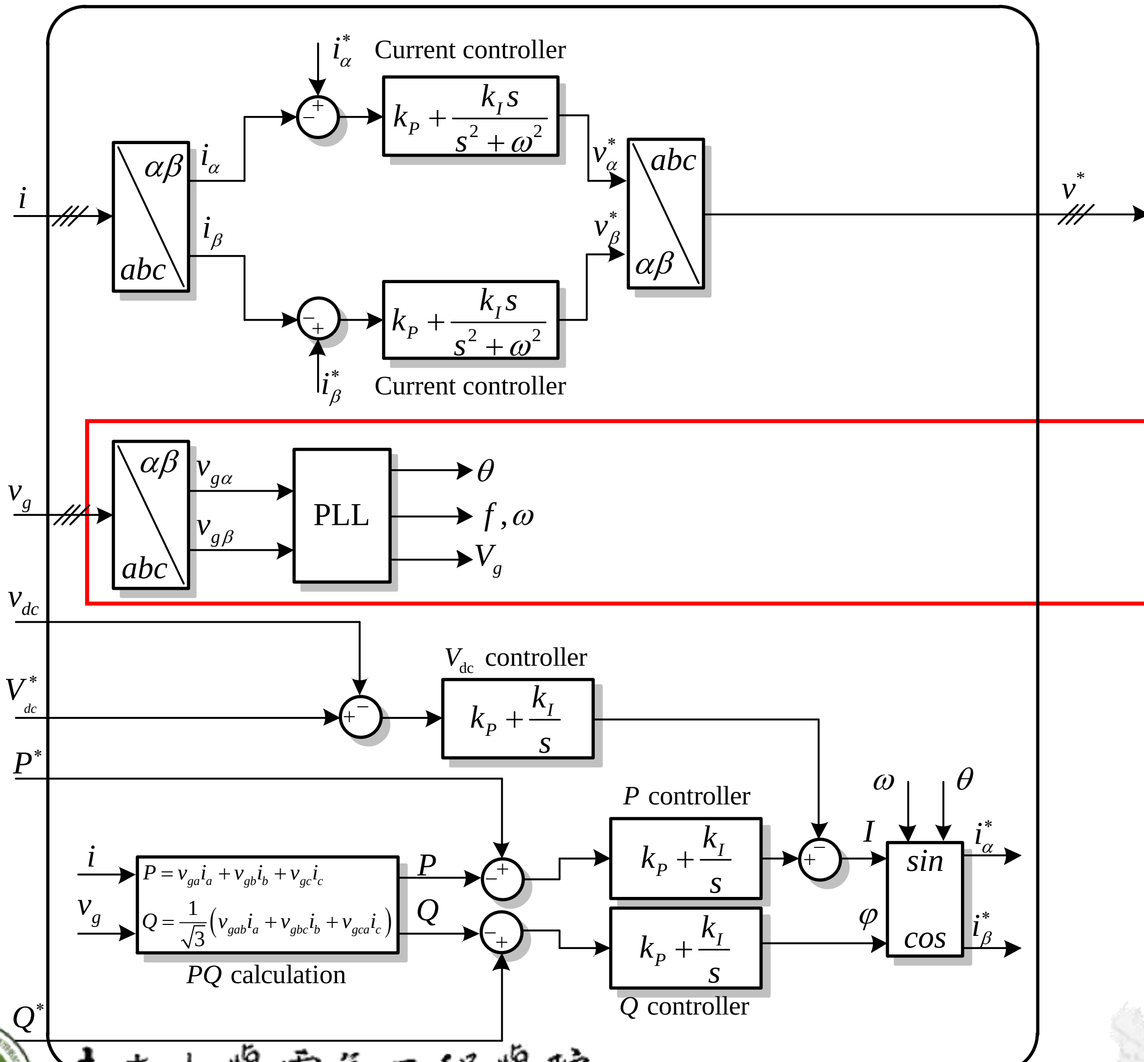

$k_I = 100$




$k_I = 500$

- A higher $k_I$ will "catch" the reference faster but with higher overshoot
- Another aspect is that $k_I$ determines the bandwidth centered 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%

# Use of P+resonant controller in stationary frame



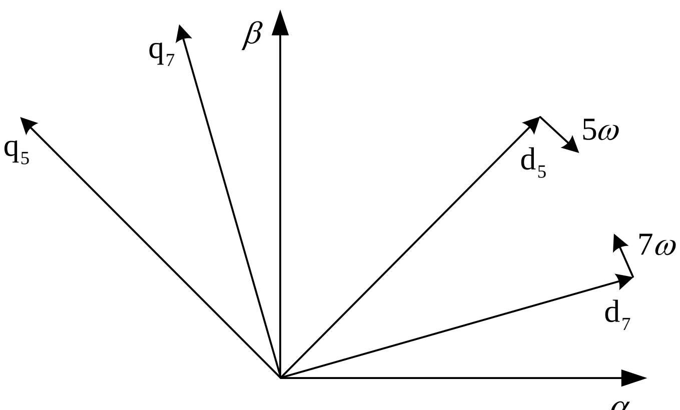

- **PLL is still indispensable for reference generation**

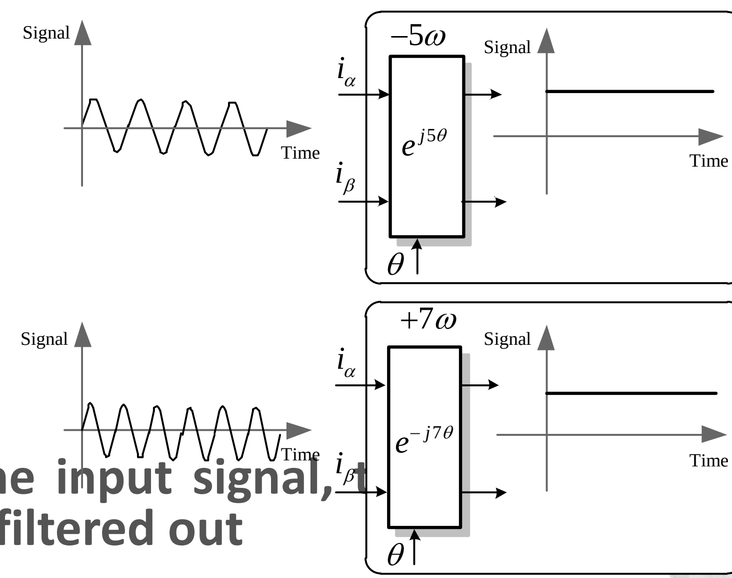
# Harmonic compensation

- The decomposition of signals into harmonics with the aim of monitor and control them is a matter of interest for various electric and electronic systems
- There have been many efforts to scientifically approach typical problems (e.g. faults, unbalance, low frequency EMI) in power systems (power generation, conversion and transmission) through the harmonic analysis
- The use of Multiple Synchronous Reference Frames (MSRFs), early proposed for the study of induction machines, allows compensating selected harmonic components in case of two-phase motors, unbalance machines or in grid connected systems

# Harmonic compensation

- **The harmonic components of power signals can be represented in stationary or synchronous frames using phasors**
- **In case of synchronous reference frames each harmonic component is transformed into a dc component (frequency shifting)**

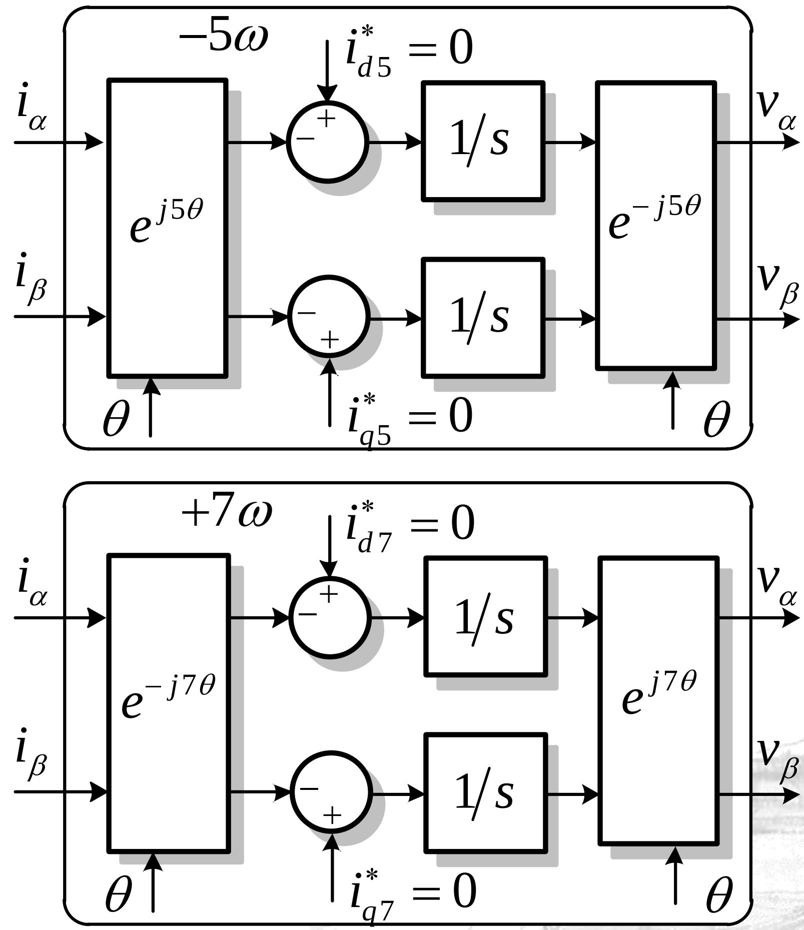


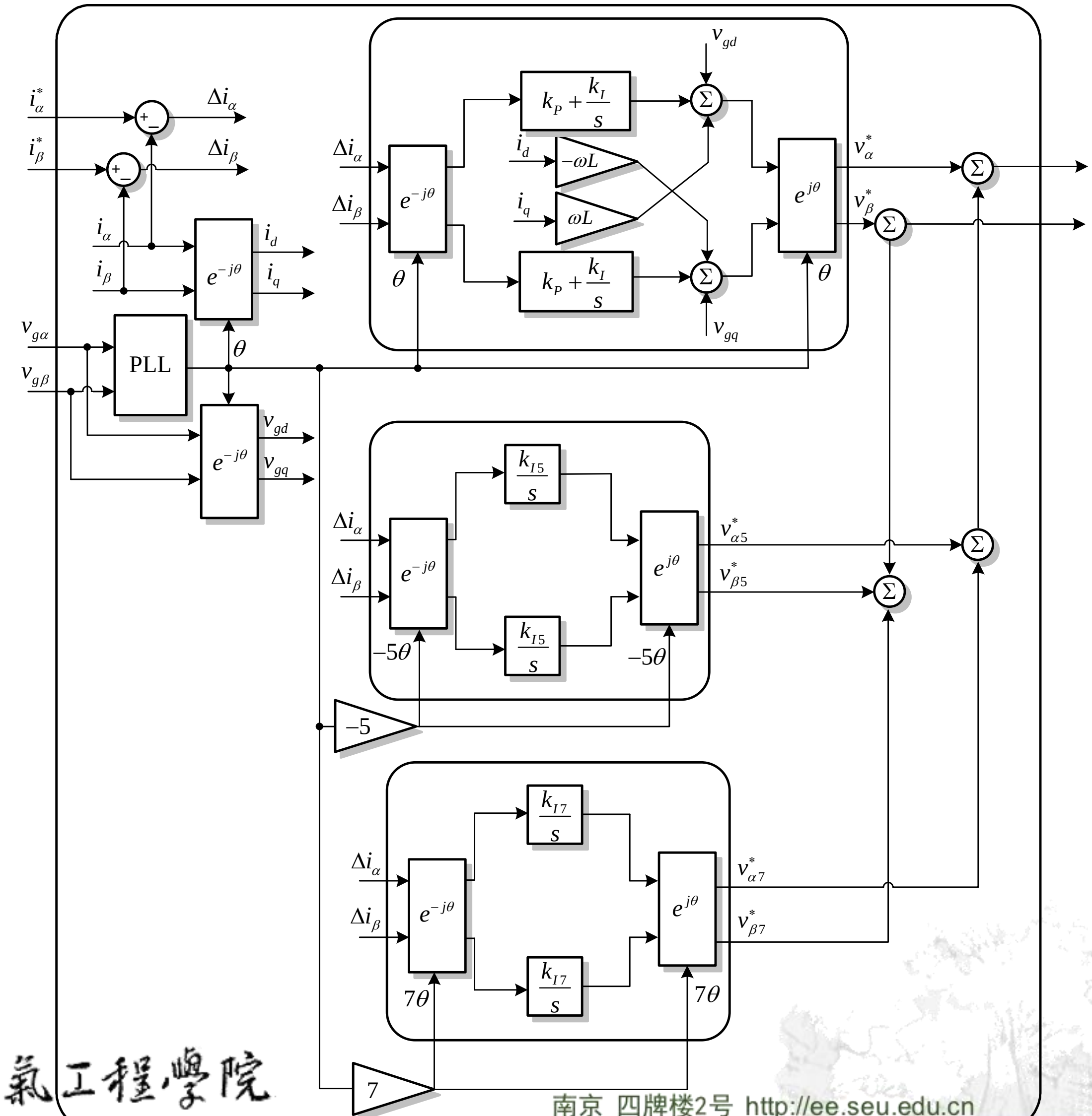

- **If other harmonics are contained in the input signal, t ll be disturbed by a ripple that can be easily filtered out**

# Harmonic compensation by means of synchronous *dq*-frames

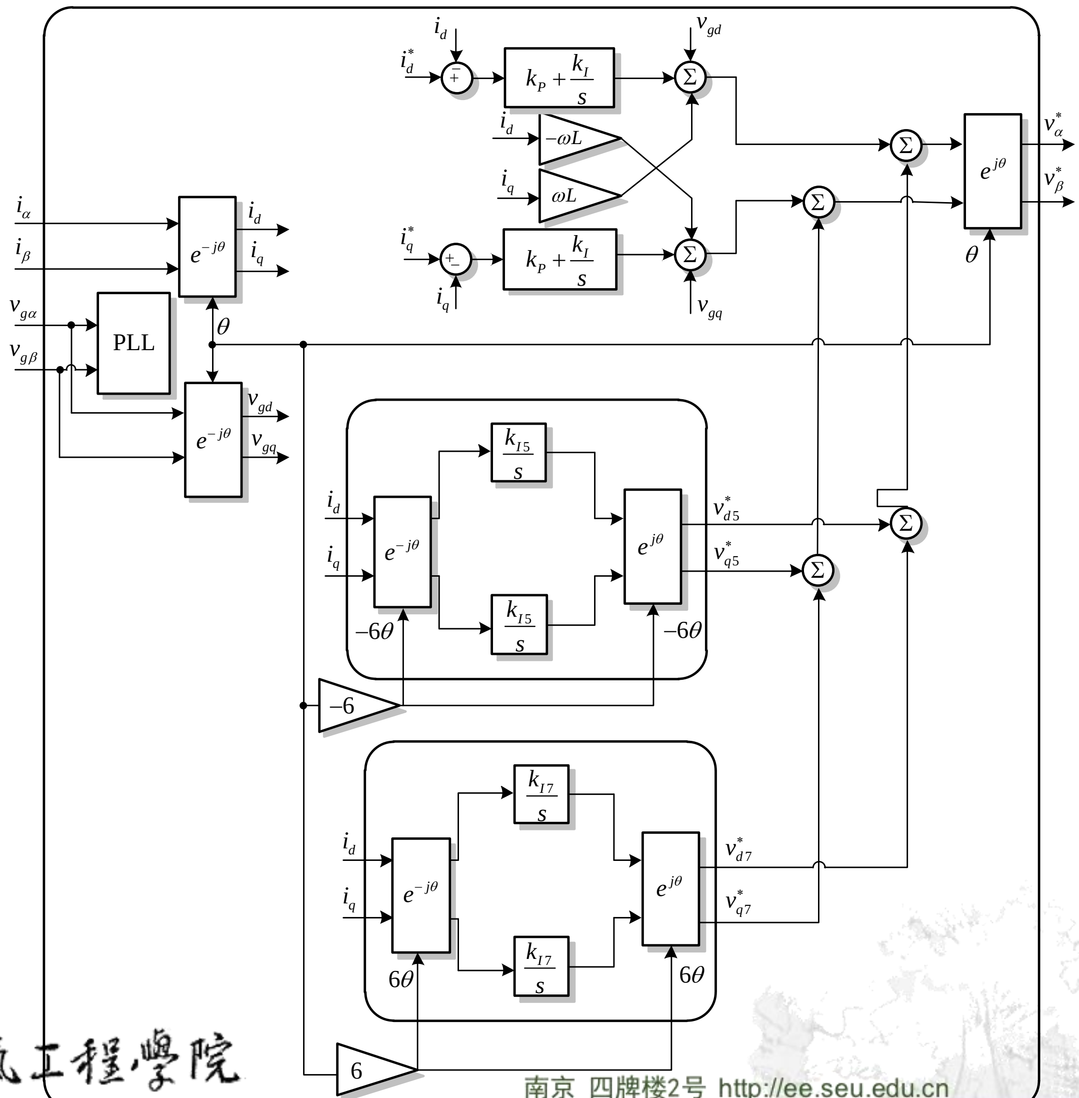
- **Two controllers should be implemented in two frames rotating at -5ω and 7ω**
- **Or nested frames can be used i.e. implementing in the main synchronous frame two controllers in two frames rotating at 6ω and -6ω**
- **Both solutions are equivalent also in terms of implementation burden because in both the cases two controllers are needed**



# Harmonic compensation by means of synchronous *dq*-frames



# Harmonic compensation by means of synchronous *dq*-frames

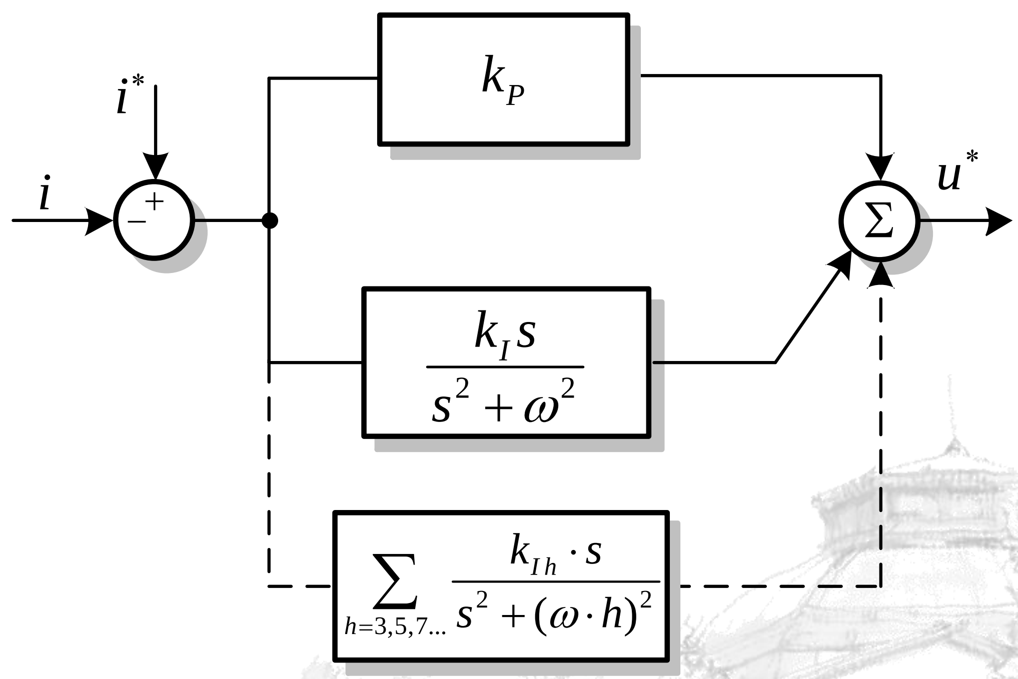


# Harmonic compensation by means of stationary $\alpha\beta$-frame

**Besides single frequency compensation (obtained with the generalized integrator tuned at the grid frequency), selective harmonic compensation can also be achieved by cascading several resonant blocks tuned to resonate at the desired low-order harmonic frequencies to be compensated.**

**As an example, the transfer functions of a non-ideal harmonic compensator (HC) designed to compensate for the 3rd, 5th and 7th harmonics is reported.**

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



# Conclusions of grid current control

- The PR uses Generalized Integrators (GI) that are double integrators achieving very high gain in a narrow frequency band centered 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
- PI adopted in a rotating frame achieves similar results, it is equivalent to the use of three PR's one for each phase
- Also single phase use of PI in a *dq* frame is feasible
- Dead-beat controller can compensate current error in two samples but it is affected by PWM limits and parameters mismatches
- Dead-beat controller is faster in limiting overcurrent during faults