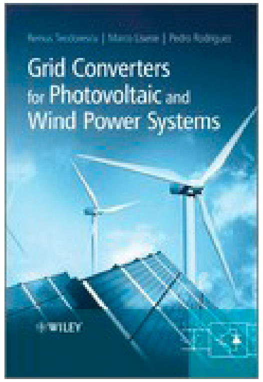


Grid Converters for Photovoltaic and Wind Power Systems

by R. Teodorescu, M. Liserre and P. Rodriguez

ISBN: 978-0-470-05751-3

Chapter 9

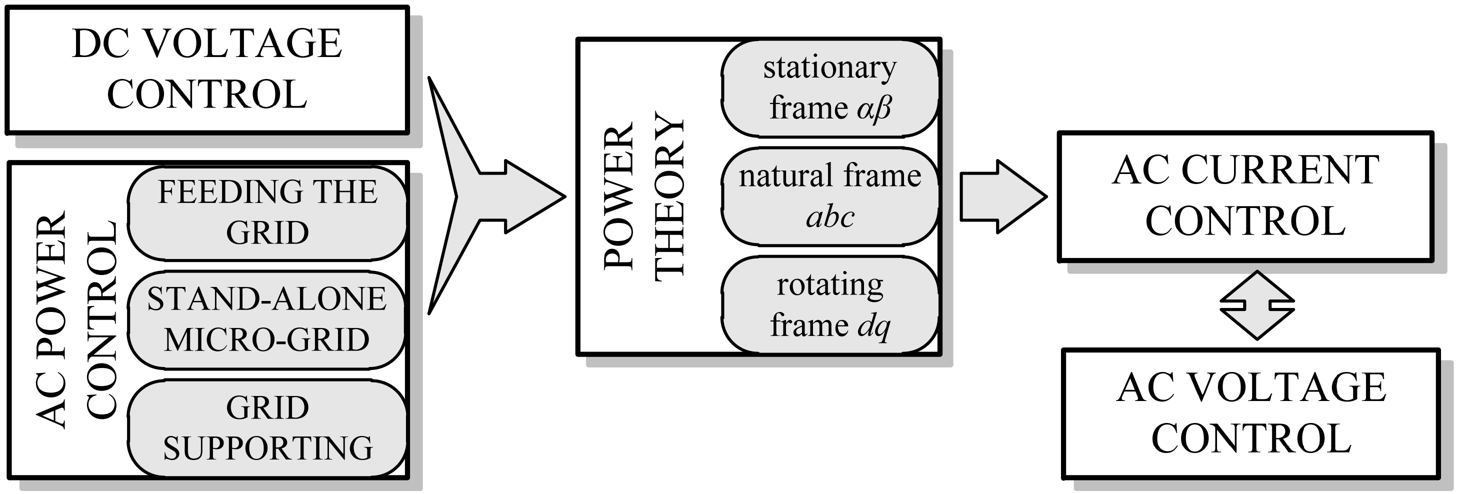
Grid Converter Control for WTS

A glance at the lecture content

- Introduction
- Model of the converter
- Ac-voltage and Dc-voltage control
- VOC and DPC
- Stand-alone, micro-grid, droop control and grid supporting

Introduction

- The grid converter can operate as grid-feeding or grid-forming device
- Main control tasks
  - Manage the dc-link voltage
  - Inject ac power (active/reactive)
- A third option is the operation as grid-supporting device (voltage, frequency, power quality)



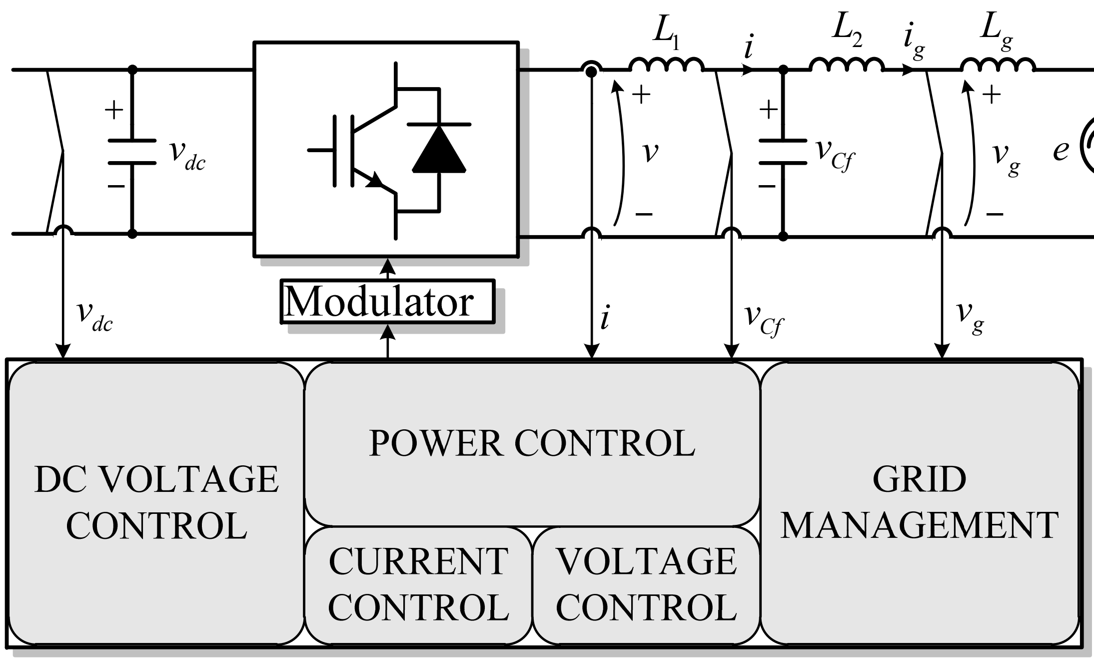
Introduction

- The grid converter of a distributed generation system operates as a controlled power source
- The power control can be performed using:
  - Voltage Oriented Control in analogy with the Field Oriented Control
  - Direct Power Control in analogy with the Direct Torque Control
- The power control can be synchronized on the grid voltage or on the virtual flux that is the integral of the grid voltage (from another point of view it is a filtered grid voltage)
- The power control can be performed in view of controlling voltage and frequency at PCC and/or improving power quality and ride-through capability

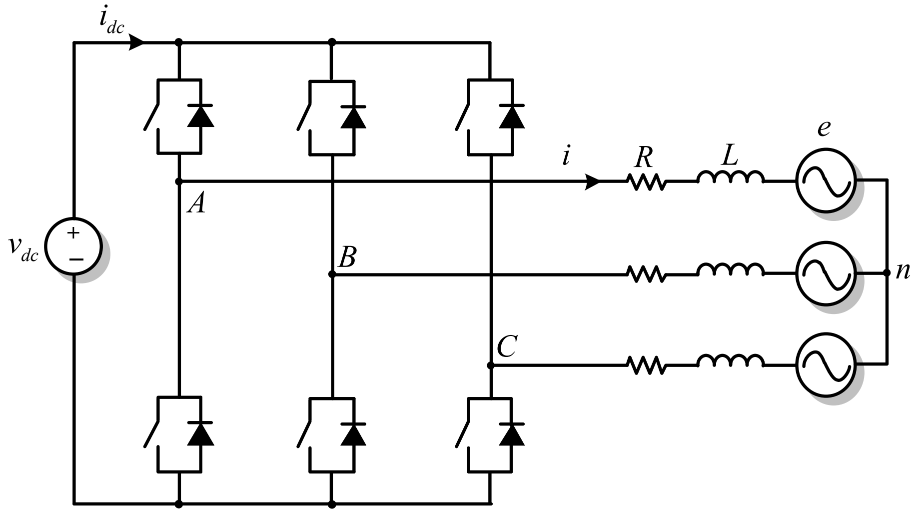
Introduction

- Another major difference is that the grid converter could be requested to operate on the grid side as:
  - A controlled current source
  - A controller voltage source

With the LCL-filter both the options can be integrated within a multiloop structure



Model of the L-filter converter



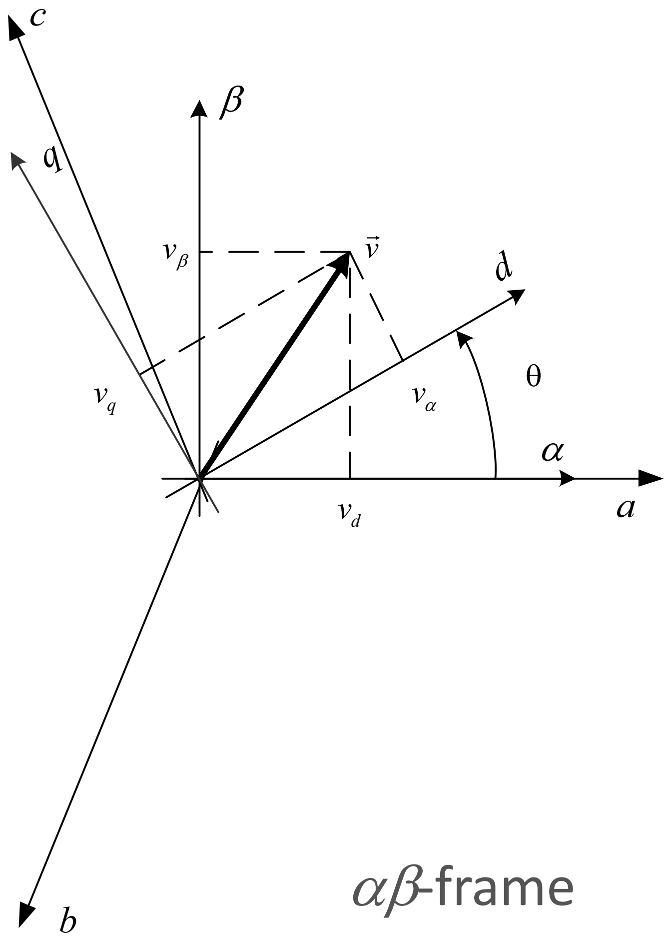
- Converter switching function

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

- AC voltage equation

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

Model of the L-filter converter



Use of a synchronous frame

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

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

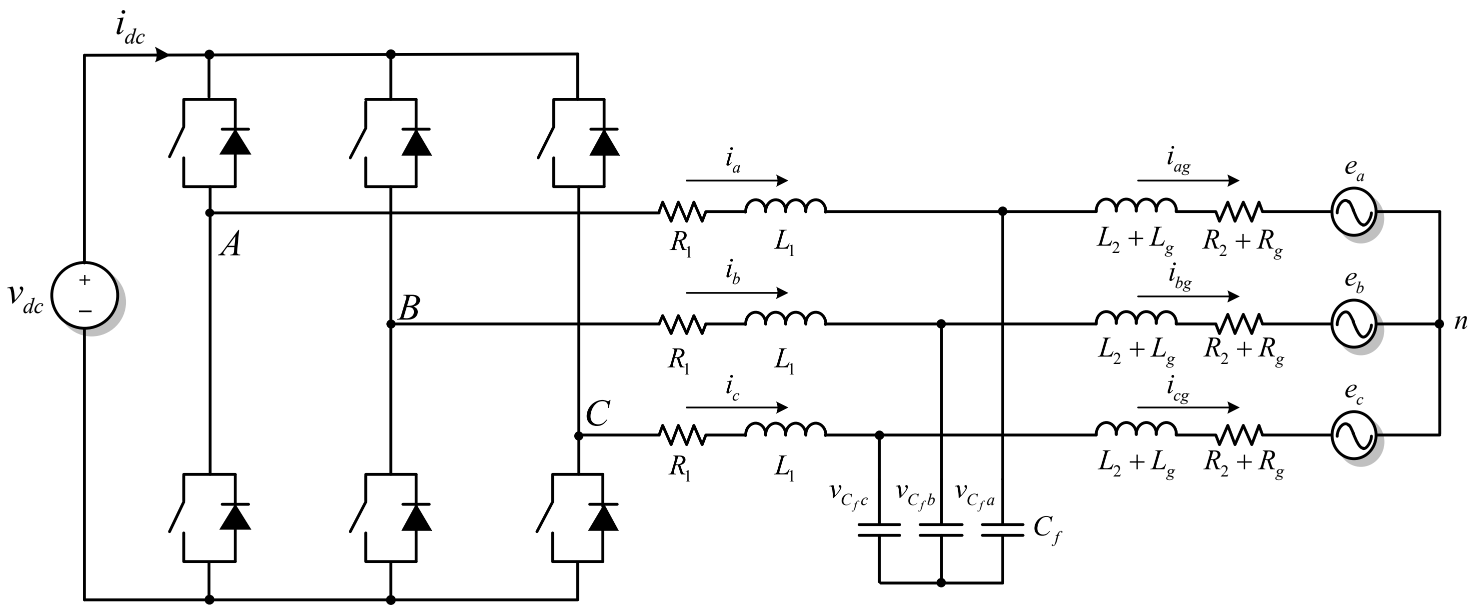
αβ-frame

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

dq-frame

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

Model of the LCL-filter converter



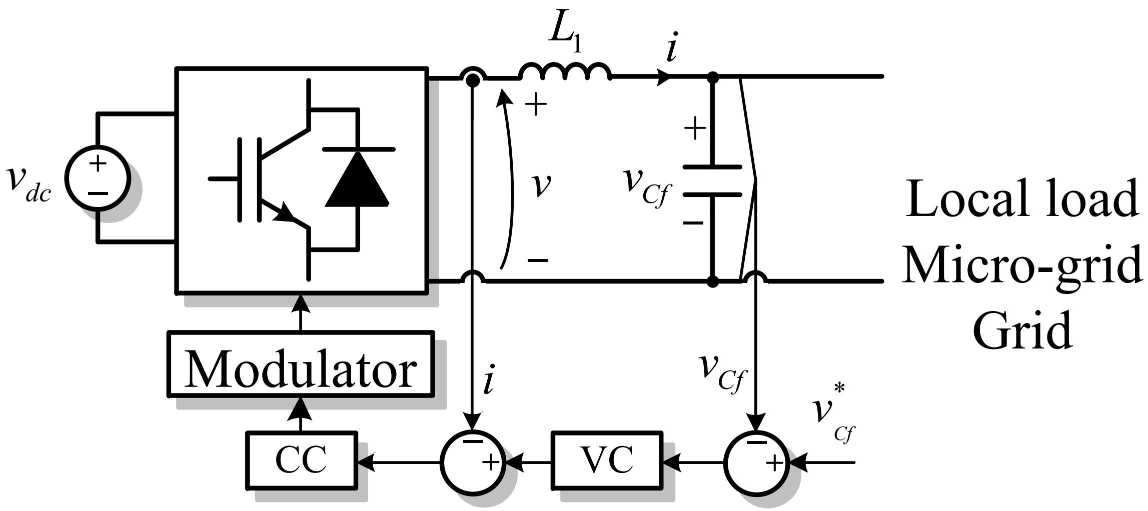
$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ v_{C_f d} \\ v_{C_f q} \\ i_{gd} \\ i_{gq} \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & \omega & -\frac{1}{L_1} & 0 & 0 & 0 \\ -\omega & -\frac{R_1}{L_1} & 0 & -\frac{1}{L_1} & 0 & 0 \\ \frac{1}{C_f} & 0 & 0 & \omega & -\frac{1}{C_f} & 0 \\ 0 & \frac{1}{C_f} & -\omega & 0 & 0 & -\frac{1}{C_f} \\ 0 & 0 & \frac{1}{(L_2+L_g)} & 0 & -\frac{(R_2+R_g)}{(L_2+L_g)} & \omega \\ 0 & 0 & 0 & \frac{1}{(L_2+L_g)} & -\omega & -\frac{(R_2+R_g)}{(L_2+L_g)} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{C_f d} \\ v_{C_f q} \\ i_{gd} \\ i_{gq} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -\frac{1}{L_1} & 0 \\ 0 & -\frac{1}{L_1} \end{bmatrix} \begin{bmatrix} e_d \\ e_q \end{bmatrix} + \begin{bmatrix} \frac{v_{dc}}{(L_2+L_g)} & 0 \\ 0 & \frac{v_{dc}}{(L_2+L_g)} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} p_d \\ p_q \end{bmatrix}$$

AC voltage control

AC voltage control:

- Stand-alone mode or micro-grid
- Supporting local loads, the local electrical power system or even the power grid

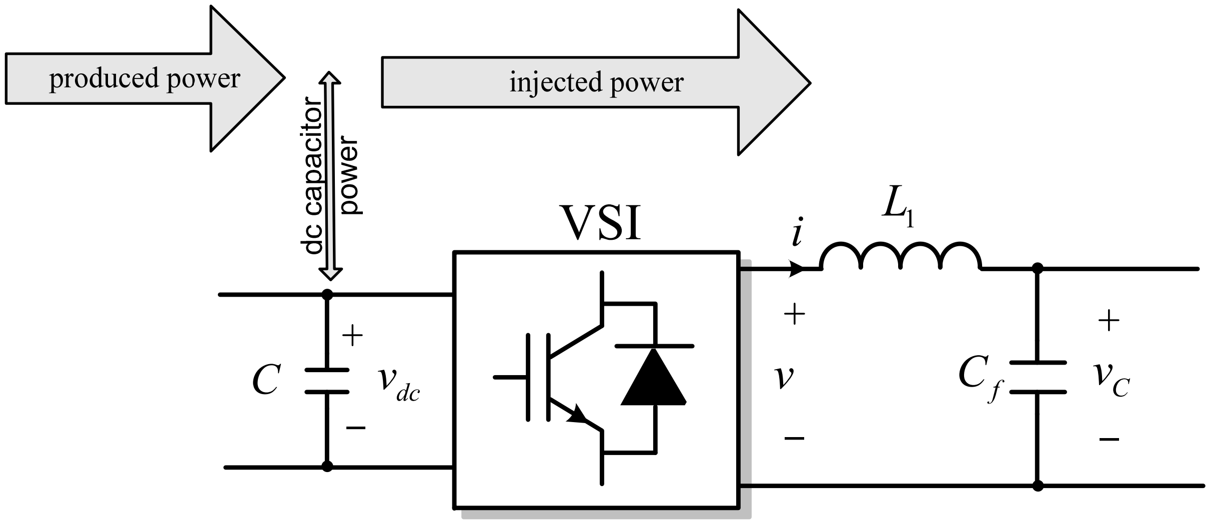
A multiloop control should be adopted: the AC capacitor voltage is controlled through the AC converter current. In fact, the current-controlled converter is operated as a current source used to charge/discharge the capacitor.



Poh Chiang Loh and Donald Grahame Holmes, “Analysis of Multiloop Control Strategies for LC/CL/LCL-Filtered Voltage-Source and Current-Source Inverters” IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 41, NO. 2, MARCH/APRIL 2005, 644-654

DC voltage control

- In the grid connected converter a change of the produced power causes transient conditions hence charge or discharge processes of the dc capacitor
- The increase of the produced power results in voltage overshoot while its decrease results in voltage undershoot
- So, from the point of view of the dc voltage control, power changes result in voltage variations that should be compensated by charge or discharge processes



DC voltage control

Voltage error as a result of power change

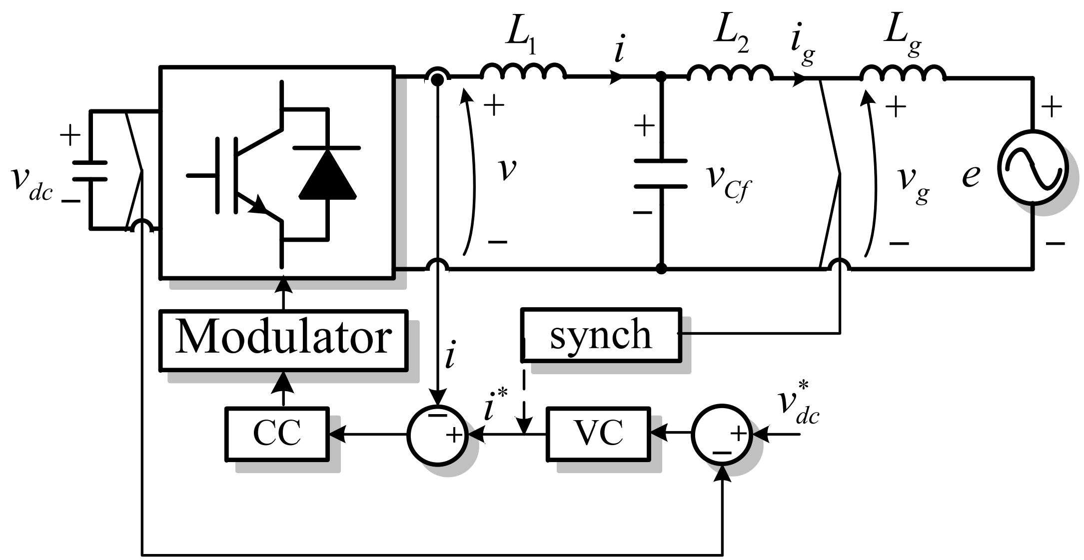
$$\Delta v_{dc} = \frac{\Delta P(3+n)T_s}{2 \cdot C \cdot v_{dc}^*}$$

- The dc voltage control is achieved through the control of the power exchanged by the converter with the grid or through the control of a dc/dc converter
  - In the first case the decrease or increase of the dc voltage level is obtained injecting more or less power to the grid respect to that one produced by the WTS
  - In the second case the grid converter does not play a role in the management of the dc-link

L. Malesani, L. Rossetto, P. Tenti and P. Tomasin, “AC/DC/AC PWM converter with reduced energy storage in the dc link”, IEEE Transactions on Industry Applications, 1995, 287-292

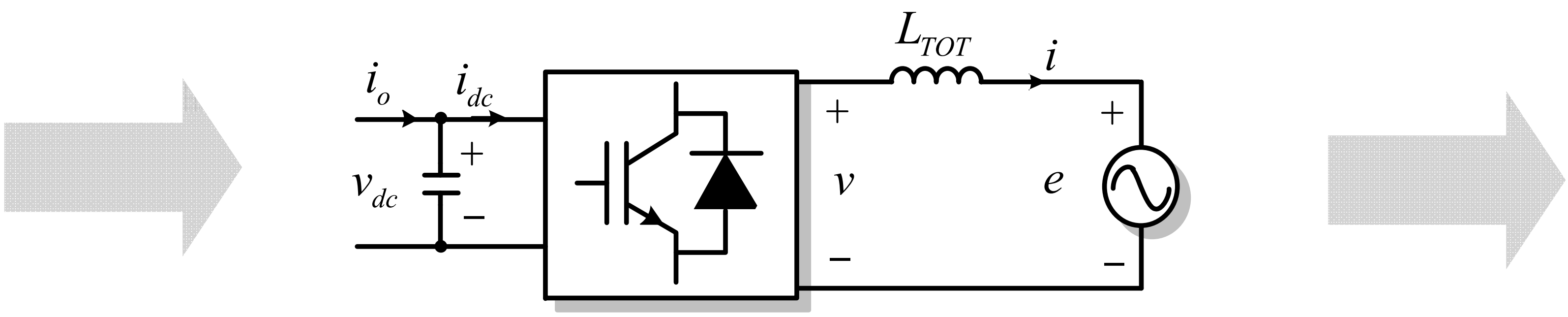
DC voltage control

- The control of the dc voltage through the ac current can result in the identification of two loops, an outer dc voltage loop and an internal current loop
- The internal loop is designed to achieve short settling times
- On the other hand, the outer loop main goals are optimum regulation and stability thus the voltage loop could be designed to be some what slower
- Therefore, the internal and the external loops can be considered decoupled



J.R. Espinoza, G. Joos, M. Perez, T.L.A Moran, "Stability issues in three-phase PWM current/voltage source rectifiers in the regeneration mode", Proc. of ISIE'00, Vol. 2, pp. 453-458, 2000

Linear control: small signal analysis



$$\left(V_{dc}+\hat{v}_{dc}\right)\left(I_o+\hat{i}_o\right)+\left(V_{dc}+\hat{v}_{dc}\right)C\frac{\mathrm{d}\left(V_{dc}+\hat{v}_{dc}\right)}{\mathrm{d}t}=\frac{3}{2}\left\{\left(E_d+\hat{e}_d\right)\left(I_d+\hat{i}_d\right)+\left(E_q+\hat{e}_q\right)\left(I_q+\hat{i}_q\right)\right\}$$

$$\frac{\hat{v}_{dc}}{\hat{i}_d}=\frac{\sqrt{3}}{2}\cdot\frac{R_o}{\left(1-R_oCs\right)}$$

Plant

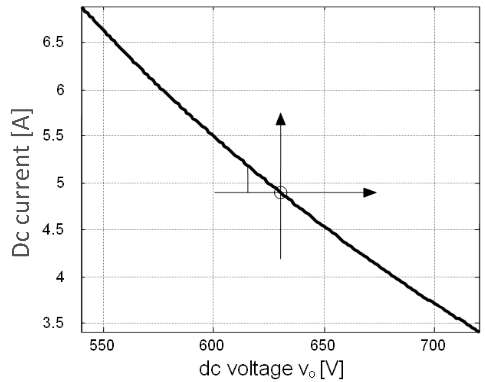
$$\frac{\hat{v}_{dc}}{\hat{i}_o}=\frac{-R_o}{\left(1-R_oCs\right)}$$

Generator disturbance

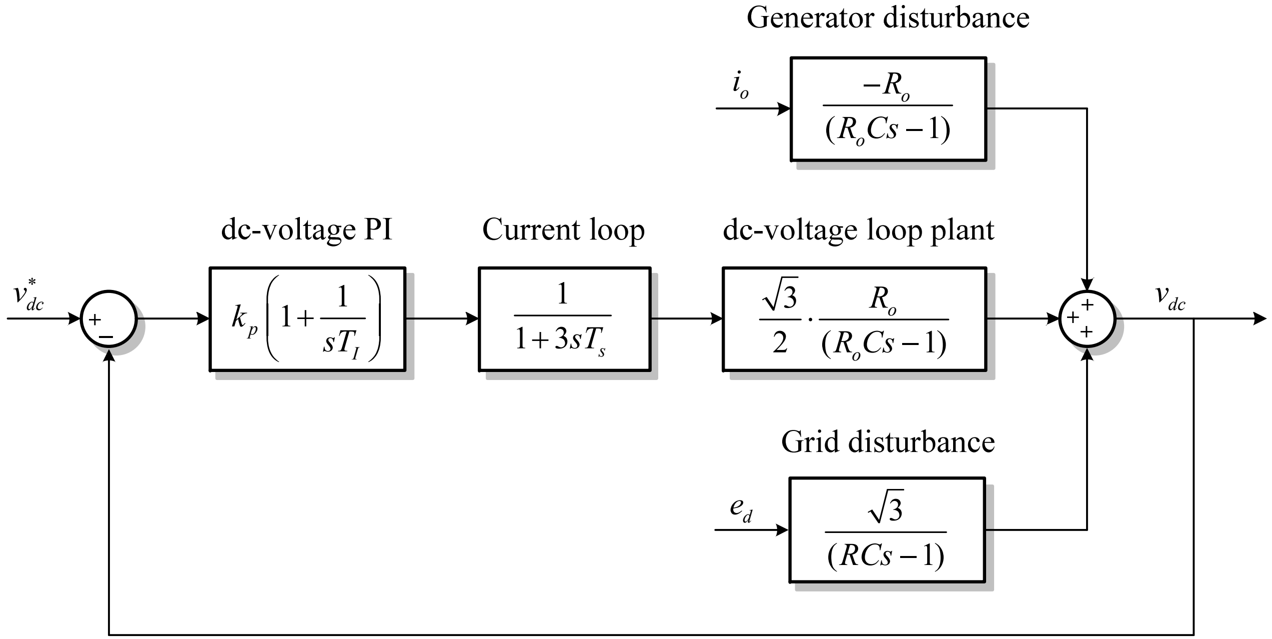
$$\frac{\hat{v}_{dc}}{\hat{e}_d}=\frac{\sqrt{3}}{\left(1-R_oCs\right)}$$

Grid disturbance

Constant power case



Linear control: PI tuning procedure



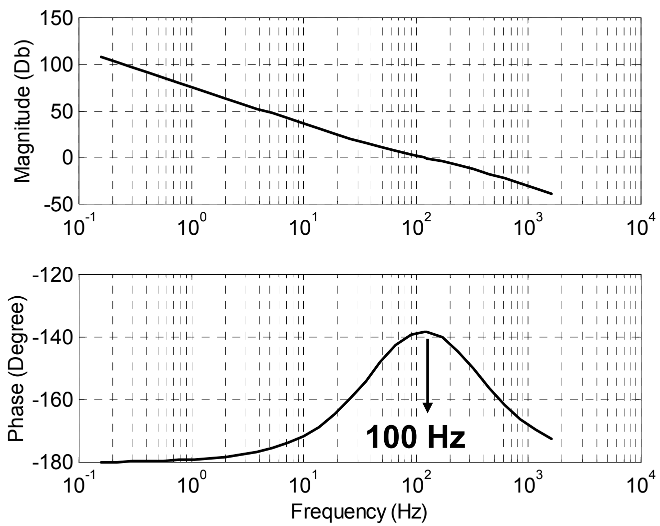
$$H_{ov}(s)=\frac{\sqrt{3}k_P(1+T_Is)}{2T_Is(1+3T_ss)(Cs)}$$

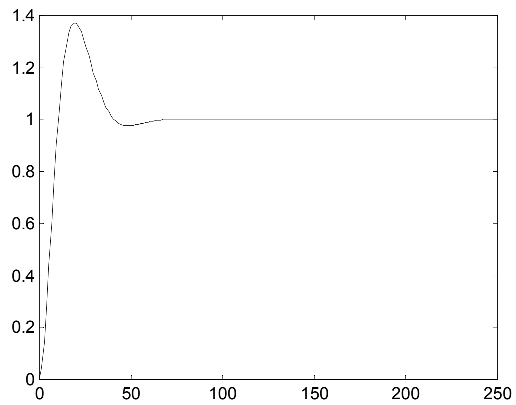
$$\omega_c=\frac{1}{3aT_s}$$

$$a=\frac{1+\cos\psi}{\sin\psi}$$

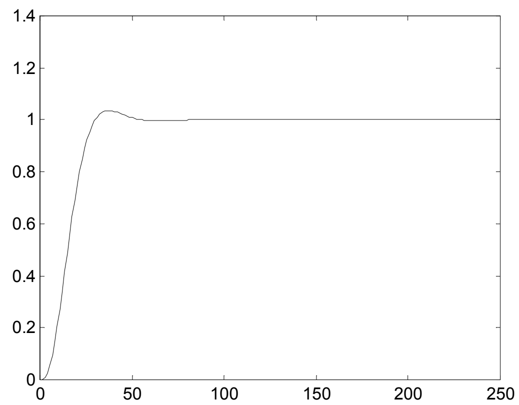
$$a=\sqrt{\frac{T_I}{3T_s}}$$

$$k_P=\frac{C}{2\sqrt{3}aT_s}$$





Without pre-filter

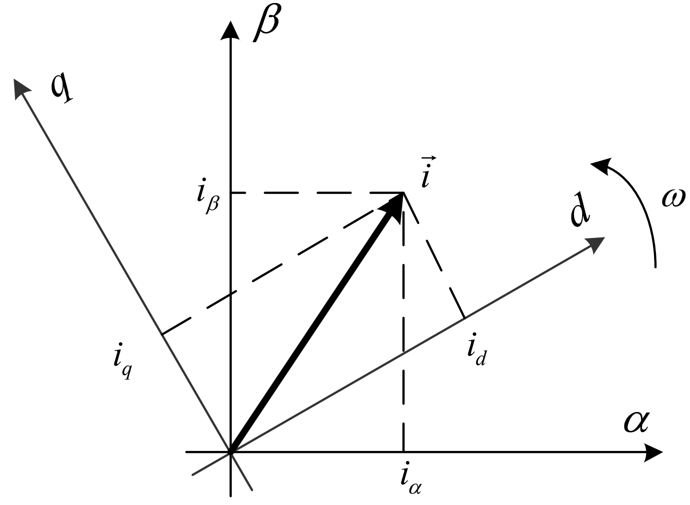


With pre-filter

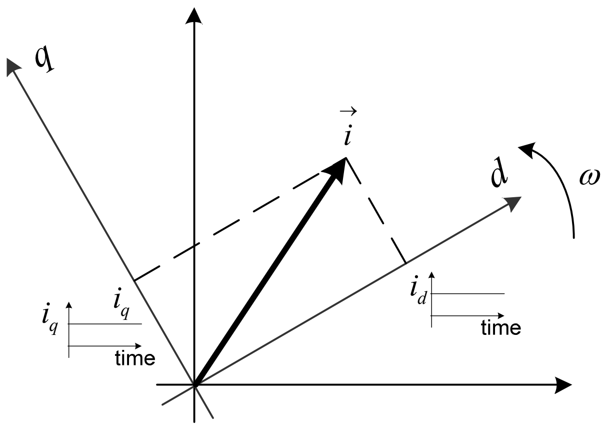
Voltage-oriented control

- The Voltage Oriented Control (VOC) of the grid converter is based on the use of a *dq*-frame rotating at ω speed and oriented such as the *d*-axis is aligned on the grid voltage vector

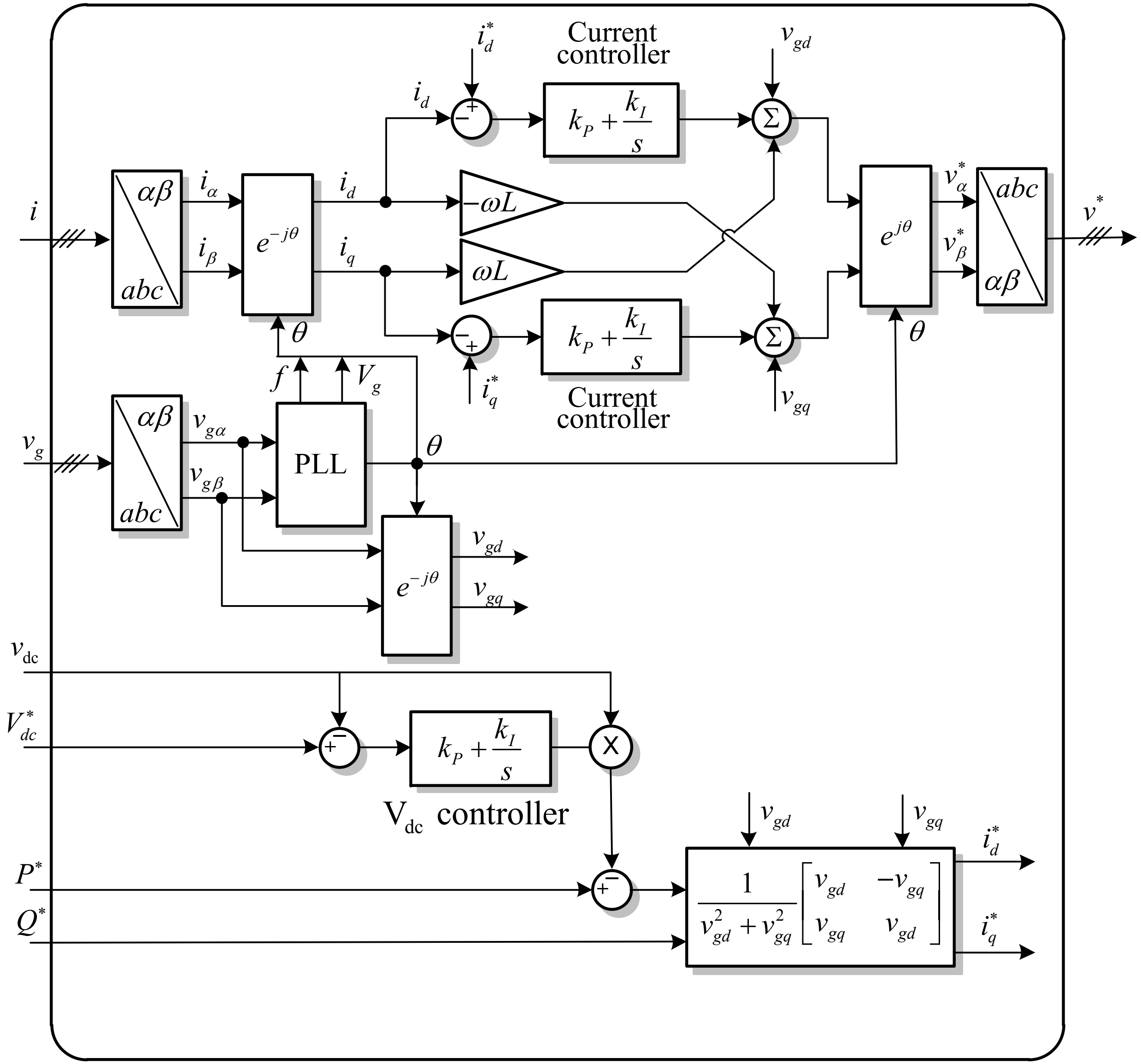
- The reference current *d*-component i^*_d is controlled to perform the active power regulation while the reference current *q*-component i^*_q is controlled to obtain reactive power regulation
- Similar results can be achieved in a stationary *ab*-frame



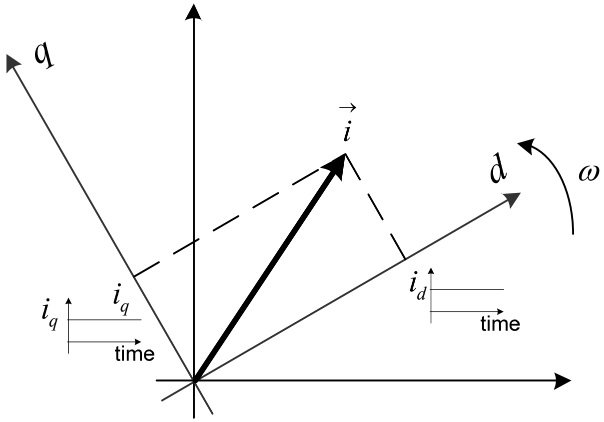
Synchronous frame VOC: PQ open loop control

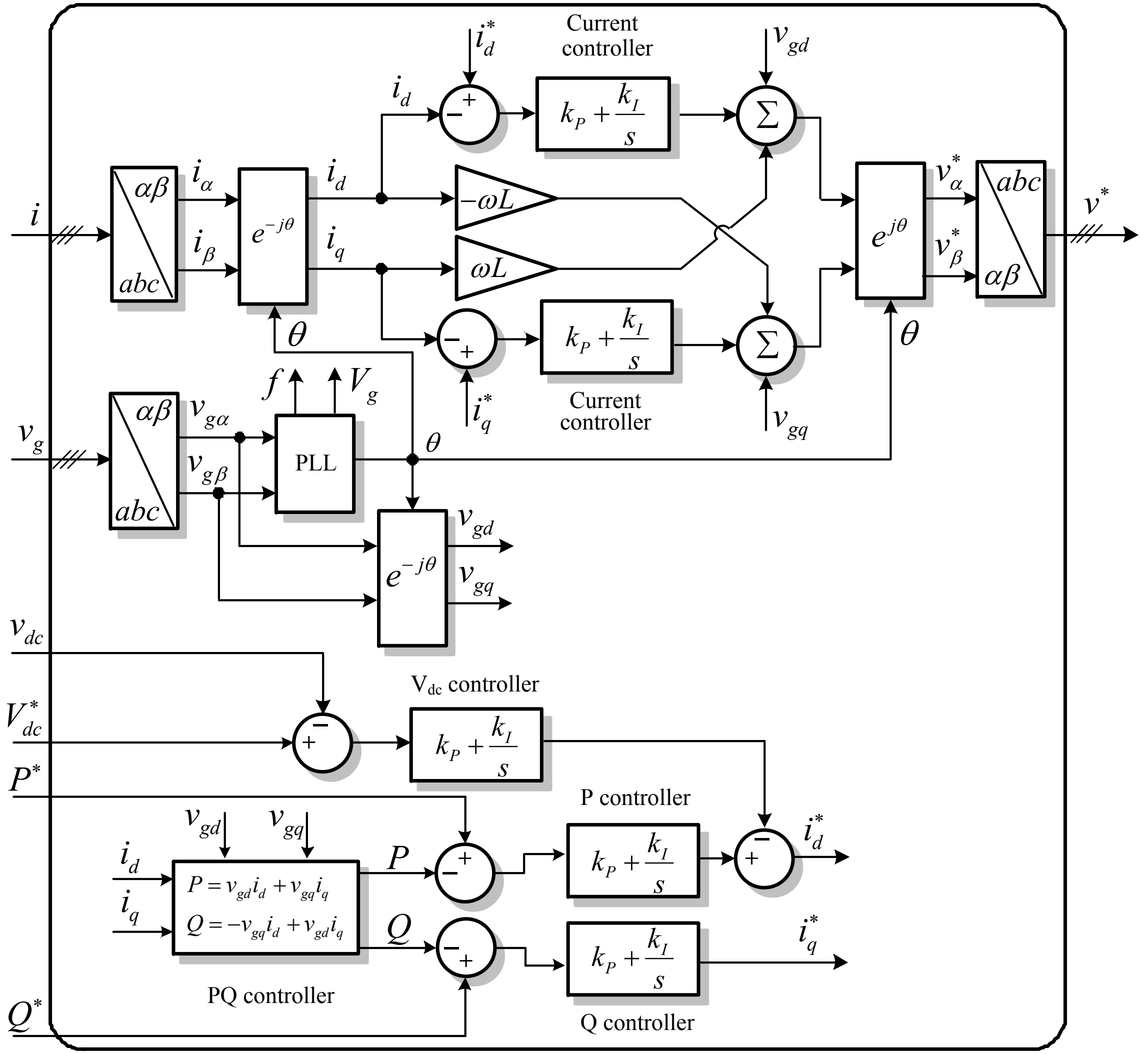


- Active and reactive power feed-forward control
- V_{dc} control acts on the power reference



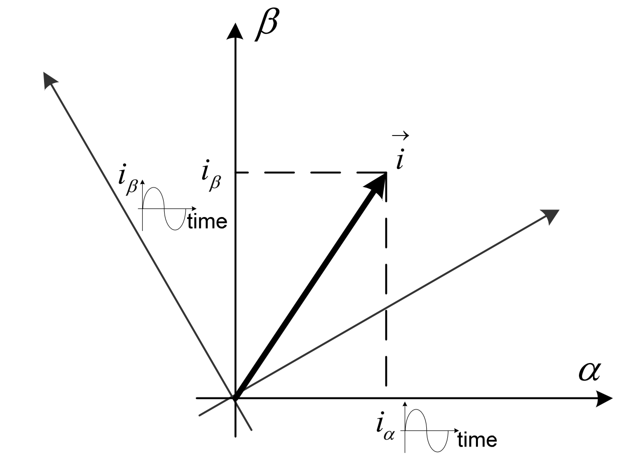
Synchronous frame VOC: PQ closed loop control



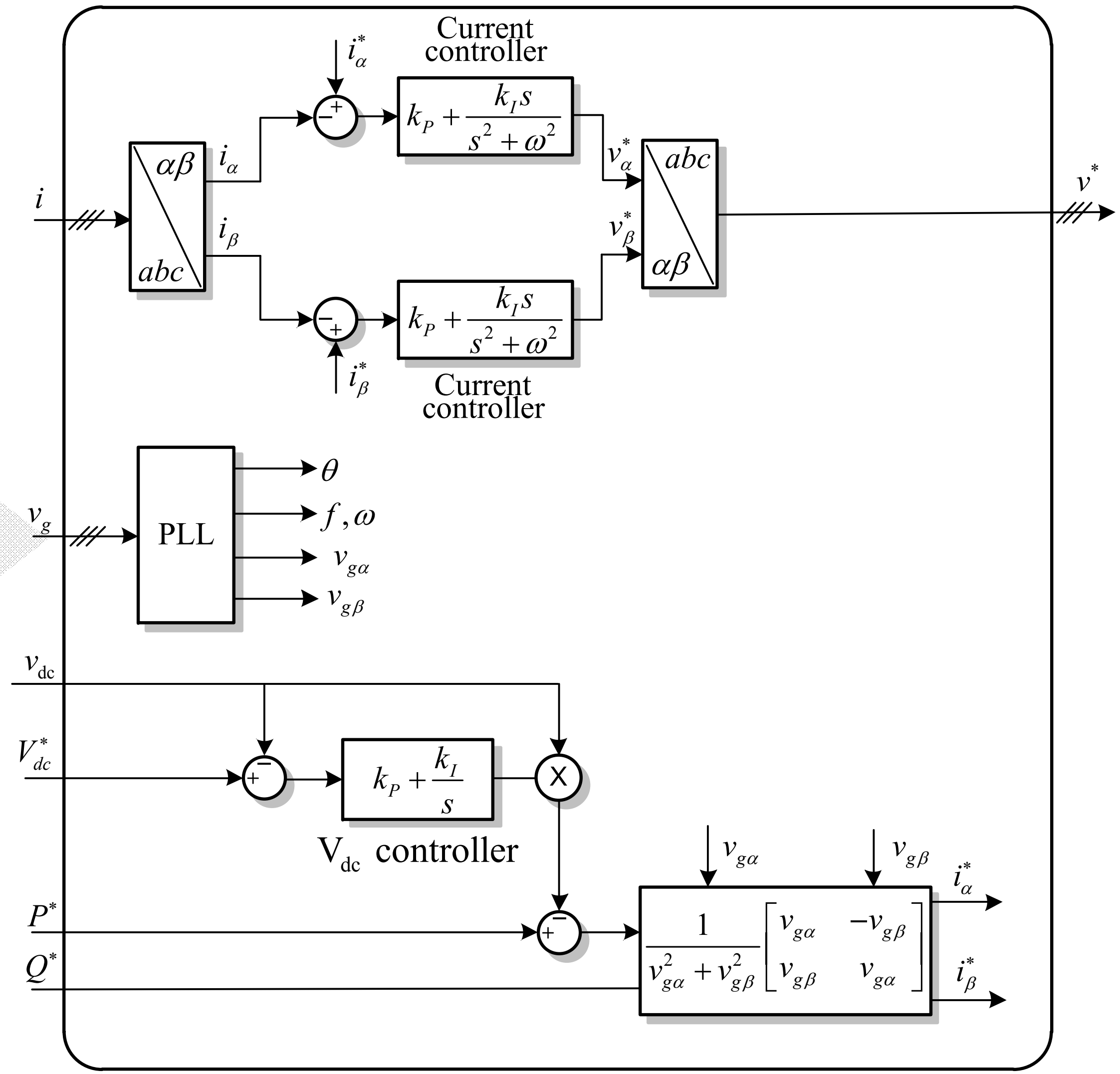


- Active and reactive power PI-based control
- V_{dc} control acts on i^*_d

Stationary frame VOC: PQ open loop control

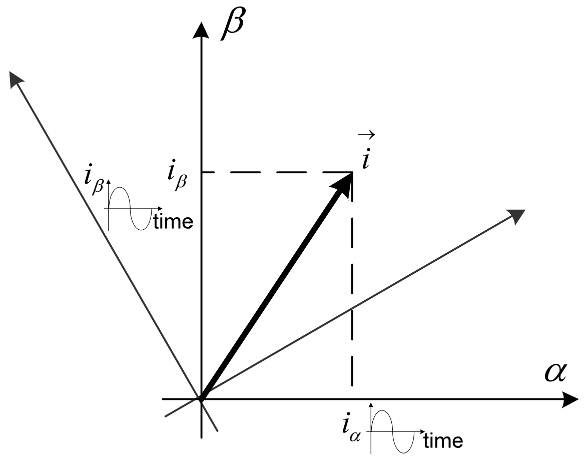


- PLL may be avoided but it is used for making the control freq. adaptive and compute the first harmonic

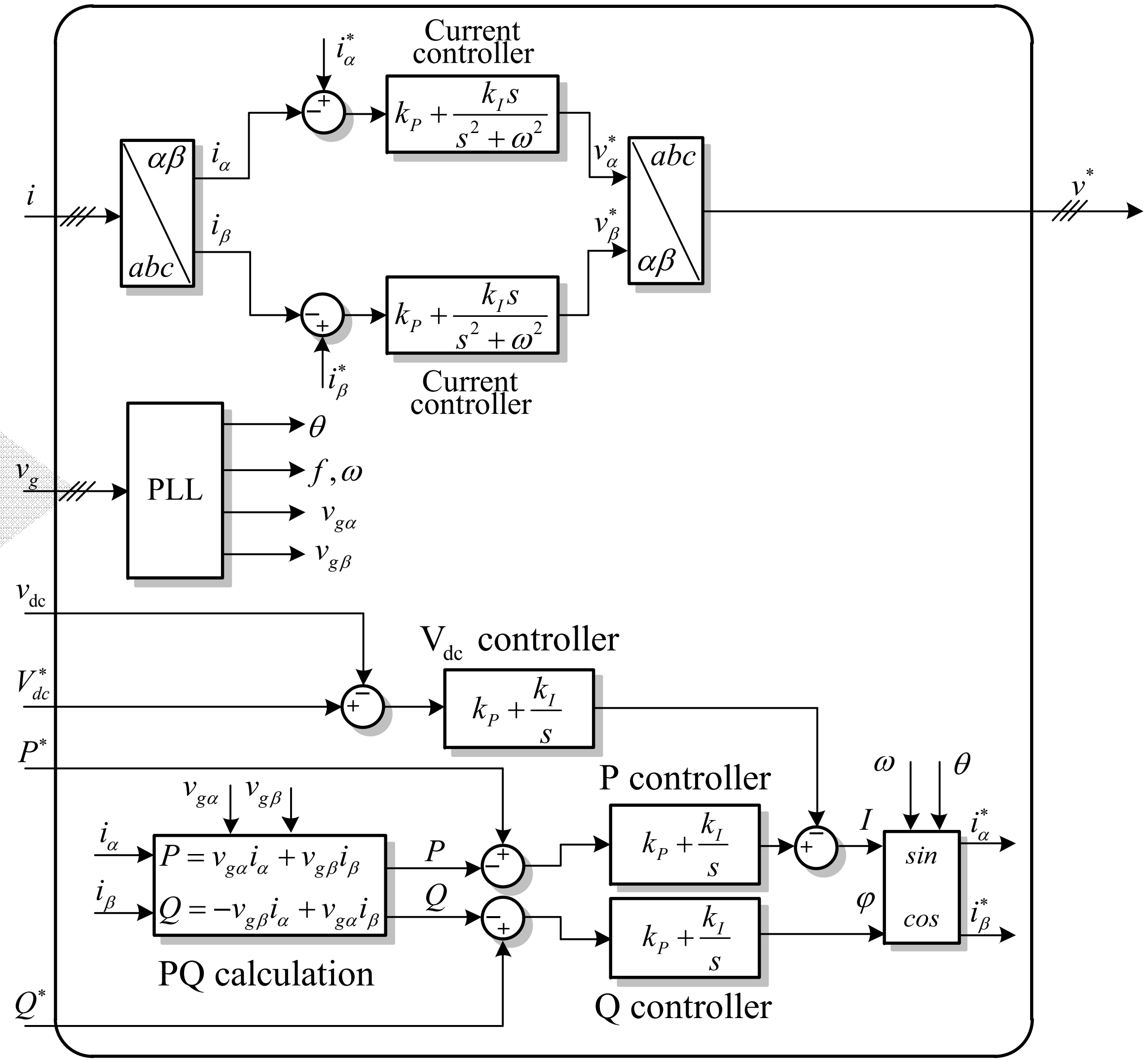


- Active and reactive power feed-forward control
- V_{dc} control acts on the power reference

Stationary frame VOC: PQ closed loop control



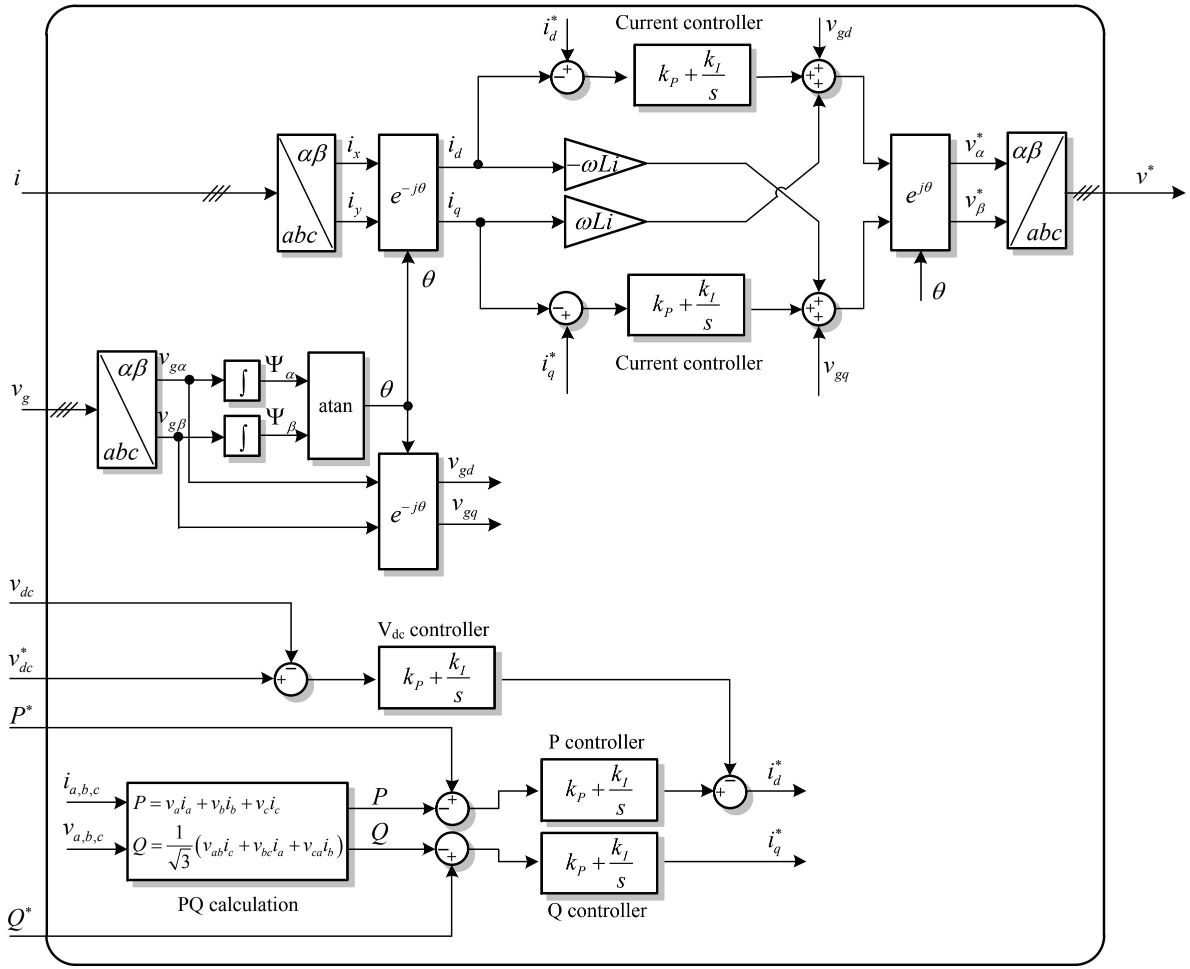
- PLL is still indispensable for reference generation



- Active and reactive power PI-based control
- V_{dc} control acts on I

Virtual flux

- The idea is to model the grid as a big electrical machine and estimate the equivalent air-gap flux for control purposes
- The estimation obtained integrating the measured grid voltage can be used for synchronization purposes and/or to estimate the power injected into the grid for controlling power fluxes

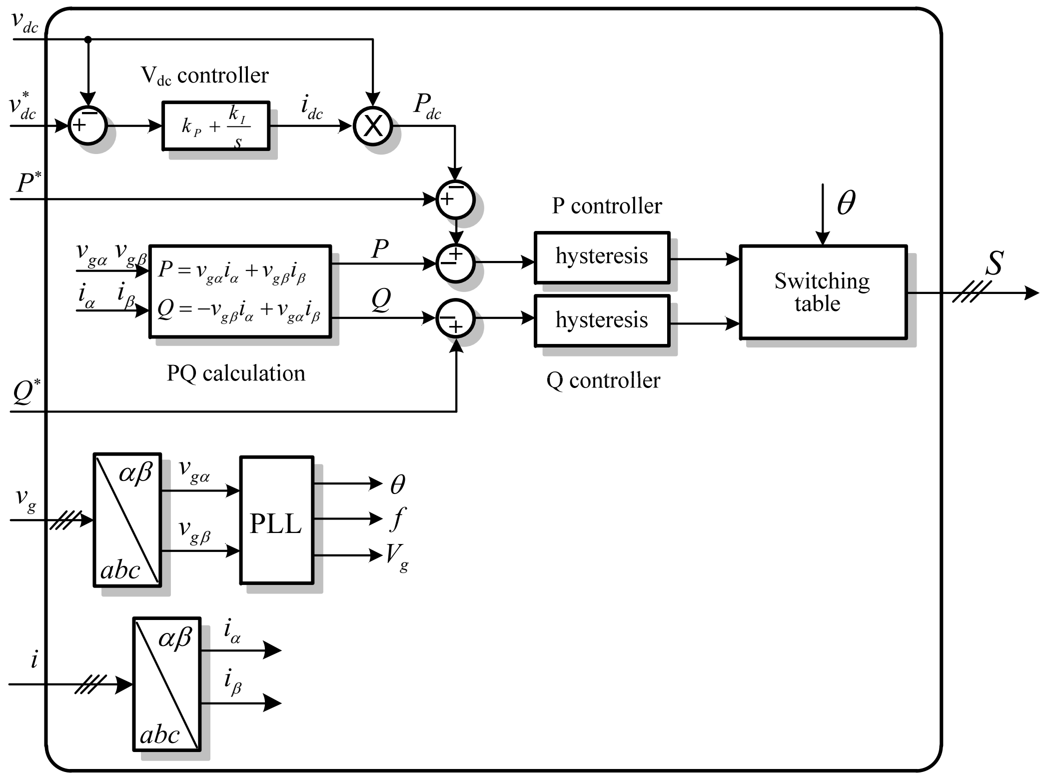


Malinowski, M.; Kazmierkowski, M.P.; Hansen, S.; Blaabjerg, F.; Marques, G.D., “Virtual-flux-based direct power control of three-phase PWM rectifiers”,, IEEE Transactions on Industry Applications, pp. 1019-1027, Volume: 37, Issue: 4, Jul/Aug 2001

Direct power control

- The direct power control developed in analogy to the well known direct torque control used for drives
- In DPC there are no internal current loops and no PWM modulator block because the converter switching states are appropriately selected

By a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power

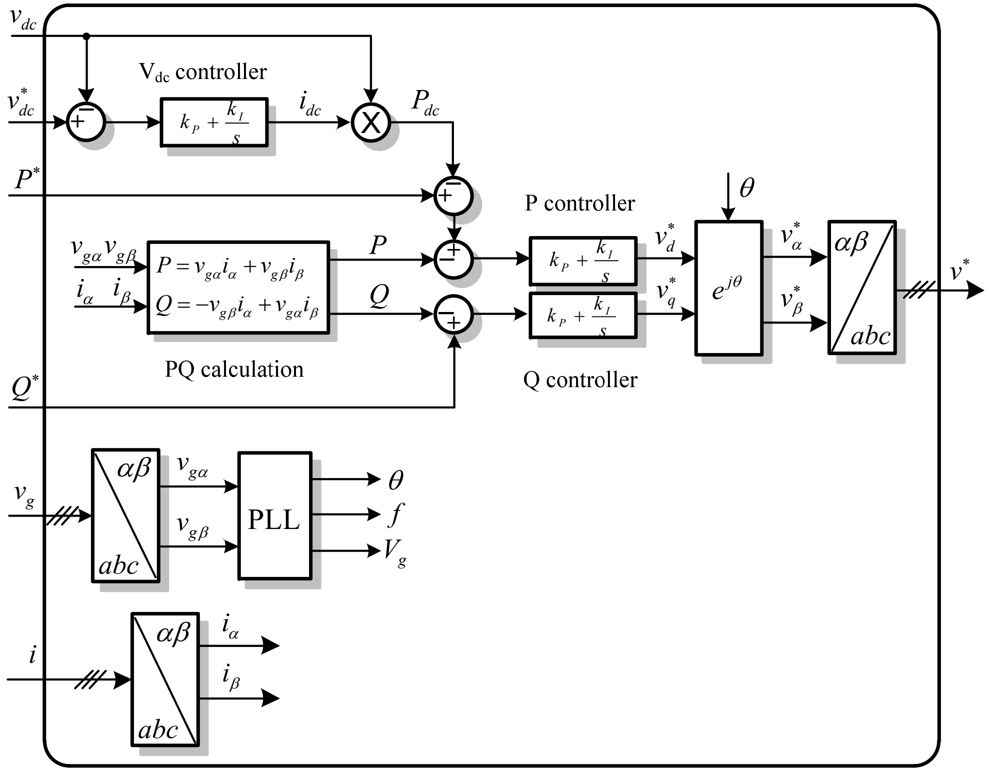


T. Ohnishi, "Three phase PWM converter/inverter by means of instantaneous active and reactive power control", Proc. of IECON 91, Vol. 2, 1991, pp. 819-824.T. Noguchi, H. Tomiki, S. Kondo, I. Takahashi, "Direct power control of PWM converter without power-source voltage sensors", IEEE Trans. on Ind. App., vol. 34, May/June 1998, pp. 473-479

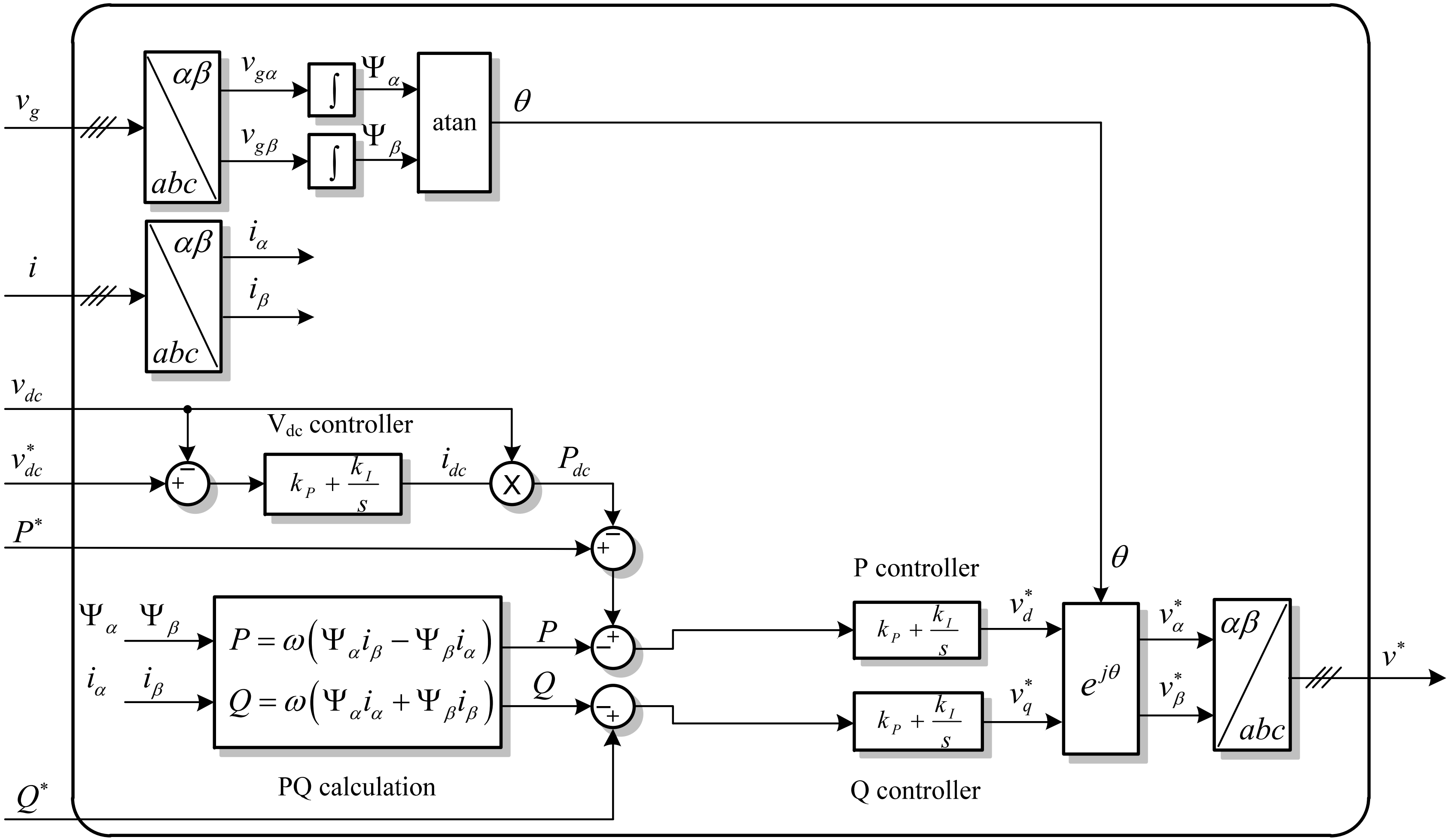
Direct power control with modulator

- Introduced to solve the problem related to the request of high sampling frequency of the previous scheme
- If the grid is stiff the active and reactive power loops behave like classical d and q current loops

- In case the grid voltage is weak substantial differences may arise

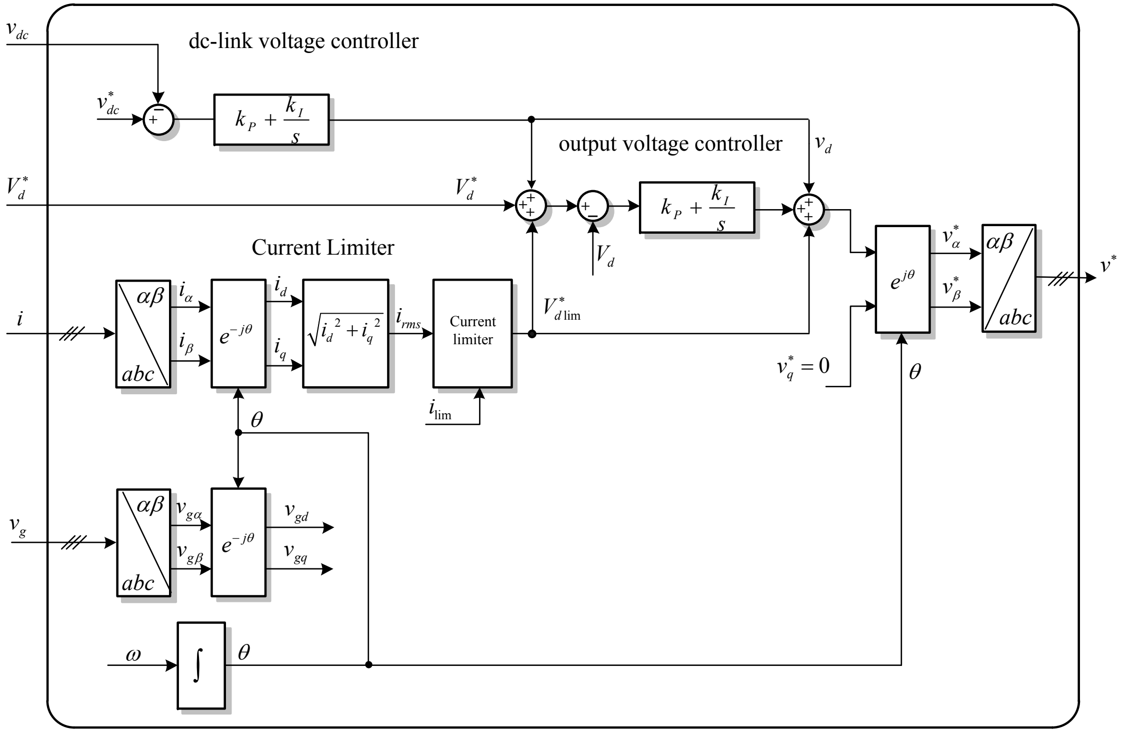


Direct power control with modulator and virtual flux



Islanding operation: Gaia project

- The converter voltage is controlled directly
- There is not a current control but a current limiter add a voltage contribution in order to limit the current if it is too high
- The dc voltage controller gives a contribution only if the dc voltage is below the natural dc-link voltage in order to avoid the PWM saturation, if the dc voltage is above the dc natural voltage the chopper dissipates the power in excess

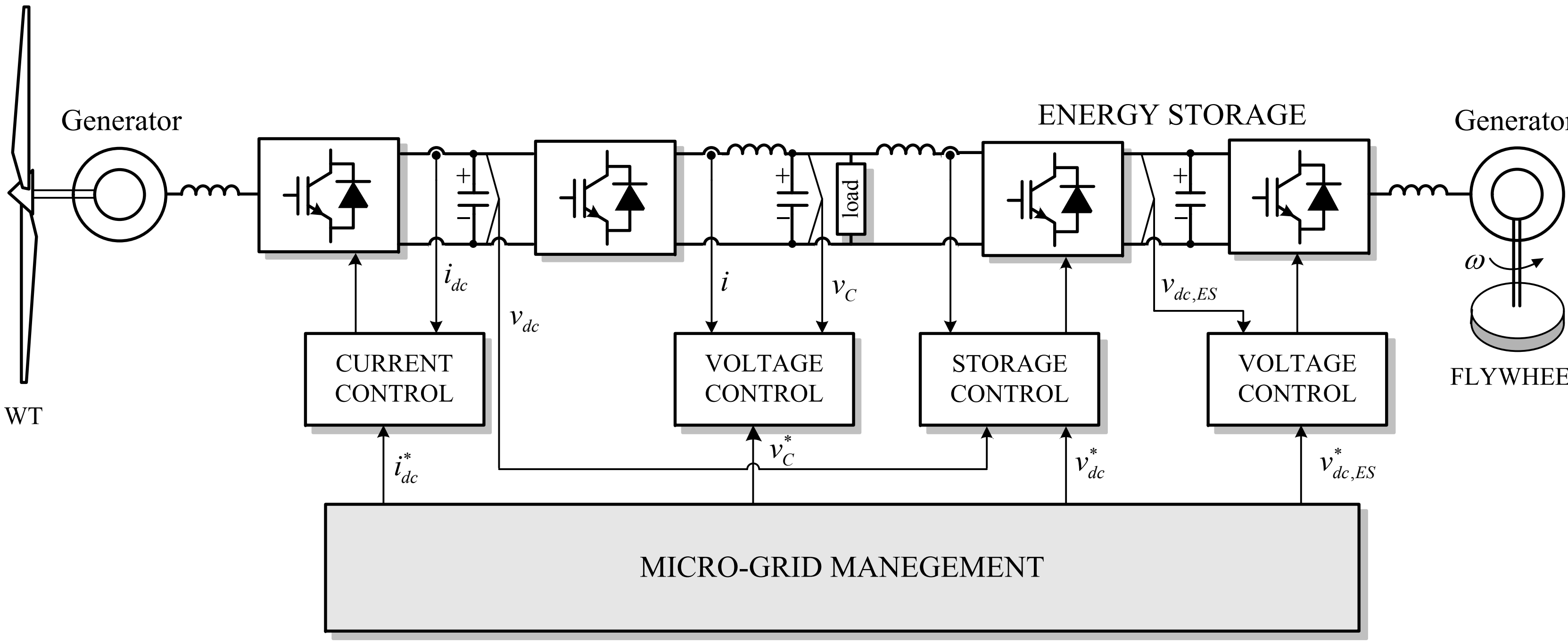


Gaia project: 11 kW IG for household and remote locations

R. Teodorescu, F. Blaabjerg, "Flexible Control of Small Wind Turbines with Grid Failure Detection Operating in Stand-Alone and Grid-Connected Mode", IEEE Trans. on Power Electronics, Vol. 19, No. 5, 2004, pp. 1323-1332

Microgrid operation with controlled storage

- Multiloop control for microgrid operation with WT system
- The management of the dc voltage is in charge of the controlled storage unit ESS
- A flyweel is used



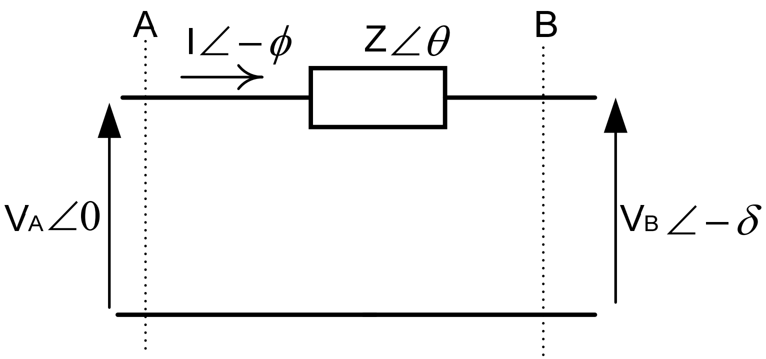
R. Cárdenas, R. Peña, M. Pérez, J. Clare, G. Asher, and F. Vargas, "Vector Control of Front-End Converters for Variable-Speed Wind–Diesel Systems" IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 53, NO. 4, AUGUST 2006 1127

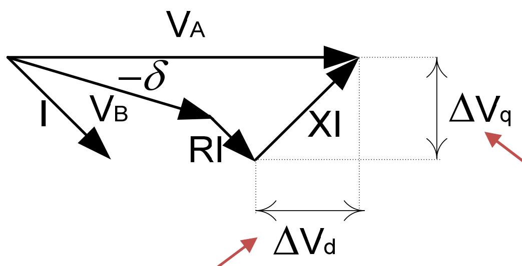
Droop control

- Using short-line model and complex phasors, the analysis below is valid for both single-phase and balanced three-phase systems

$$P_A = \frac{V_A}{Z}\cos\theta - \frac{V_A V_B}{Z}\cos(\theta+\delta) \qquad Q_A = \frac{V_A^2}{Z}\sin\theta - \frac{V_A V_B}{Z}\sin(\theta+\delta)$$

- At the section A





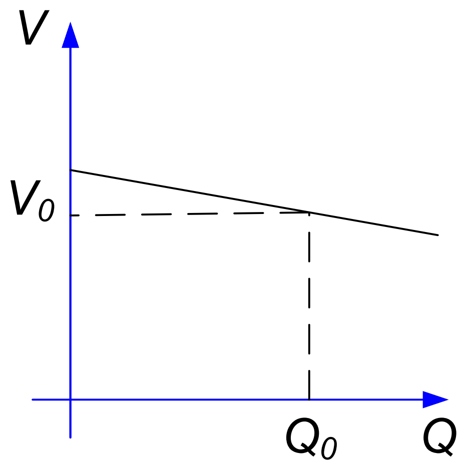
$$\boxed{\Delta V_d = V_A - V_B\cos\delta = \frac{RP_A + XQ_A}{V_A}} \qquad \boxed{\Delta V_q = V_B\sin\delta = \frac{XP_A - RQ_A}{V_A}}$$

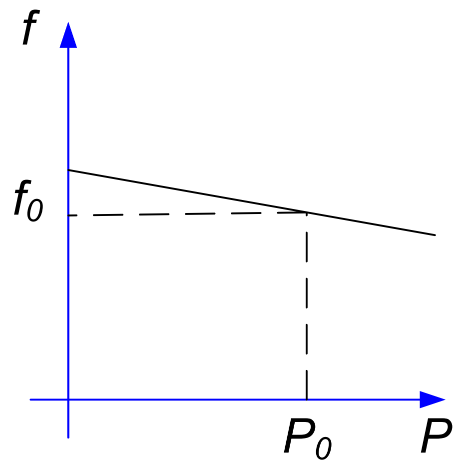
- For a mainly inductive line $\delta \cong \frac{XP_A}{V_A V_B}$ $\quad V_A - V_B \cong \frac{XQ_A}{V_A}$

Droop control

- The angle δ can be controlled regulating the active power P whereas the inverter voltage VA is controllable through the reactive power Q
- Control of the frequency dynamically controls the power angle and, thus, the real power flow
- Thus by adjusting P and Q independently, frequency and amplitude of the grid voltage are determined

$$V - V_0 = -k_q\left(Q - Q_0\right) \qquad f - f_0 = -k_p\left(P - P_0\right)$$



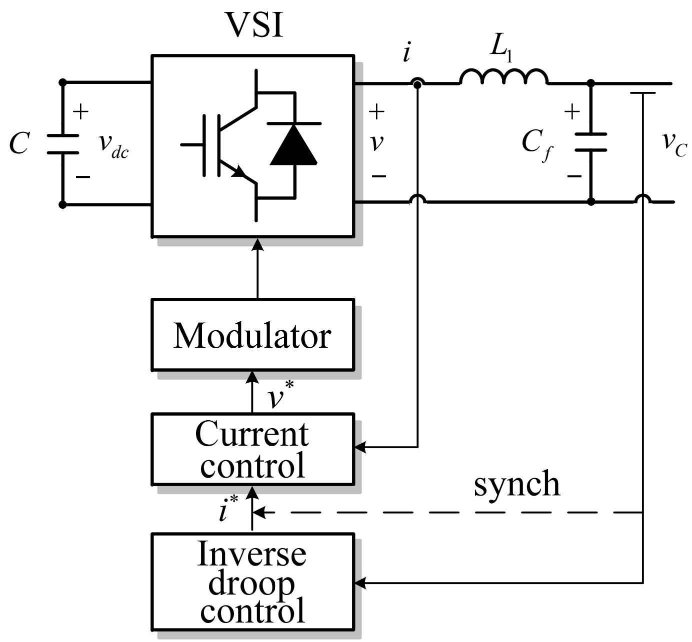


- However, low voltage distribution lines have a mainly resistive nature

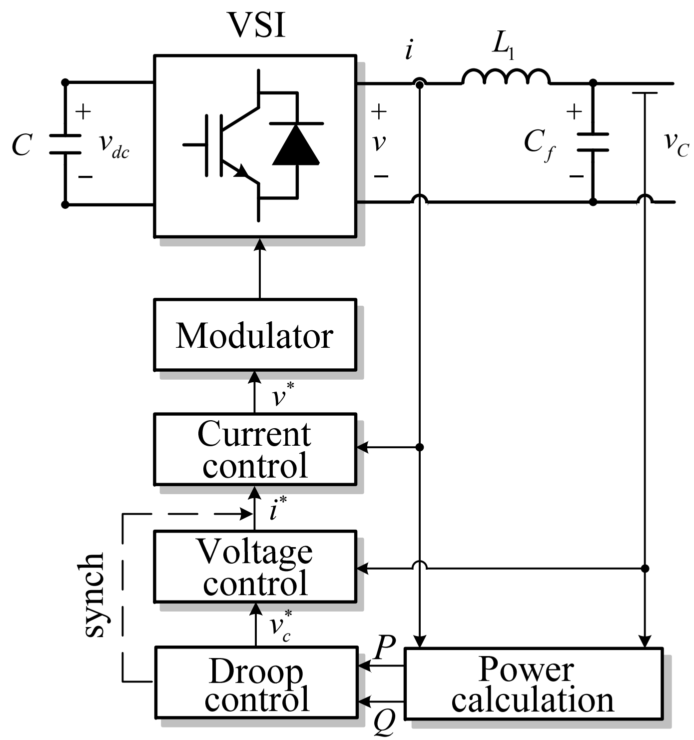
Droop control Implementation

- The droop control is not only used in island application when it is needed to a have a wireless load sharing but also in grid connection mode
- In this case grid-feeding and grid-forming schemes can be modified accordingly including droop control

Grid feeding



Grid forming

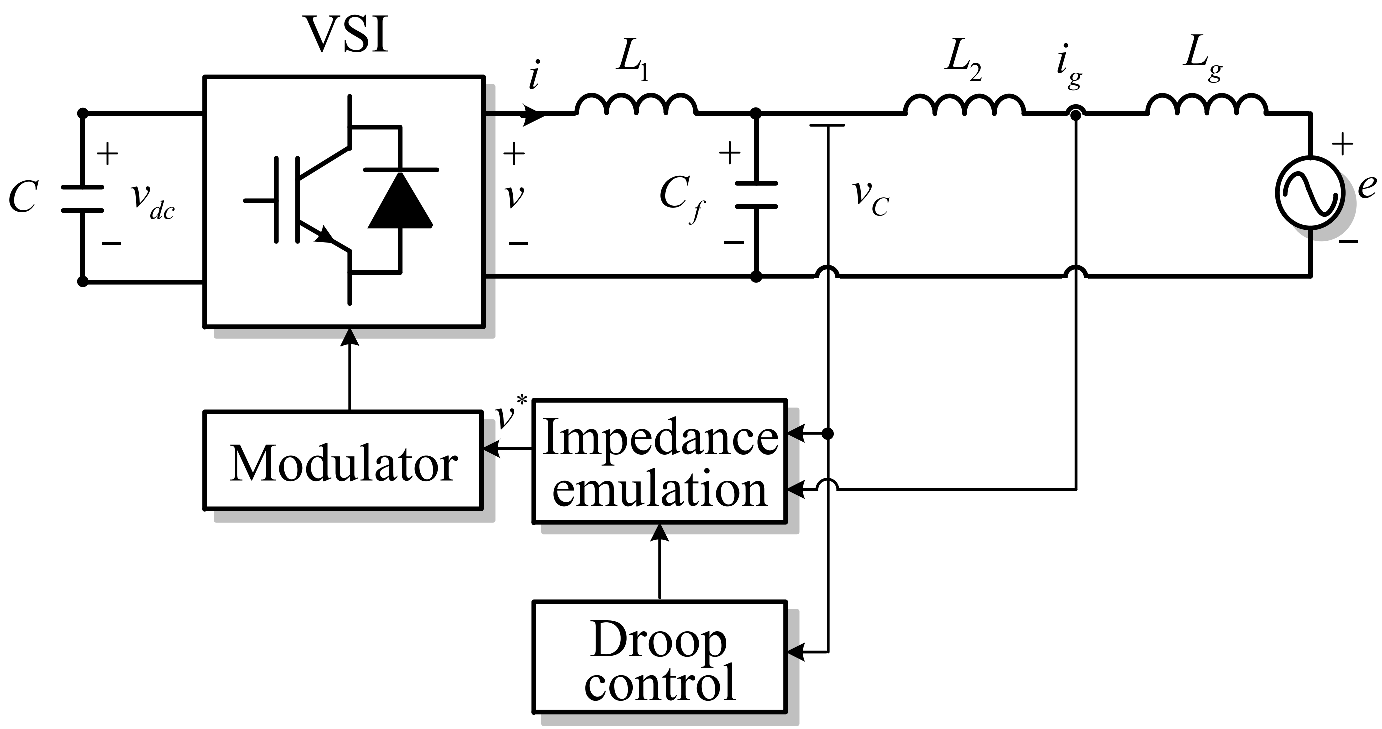


K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen and R. Belmans, “A voltage and frequency droop control method for parallel inverters” Proc. of Pesc 2004, Aachen 2004

J. M. Guerrero, L. García de Vicuña, J. Matas, M. Castilla, and J. Miret, “ A Wireless Controller to Enhance Dynamic Performance of Parallel Inverters in Distributed Generation Systems” IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 19, NO. 5, SEPTEMBER 2004, 1205-1213

Droop control Implementation: impedance emulation

- The multiloop approach can be modified into finite-output impedance emulation
- The aim is to control the virtual impedance on the grid side of the converter in order to optimize the power sharing of different units in parallel or to provide hot-swap capability



Conclusions

- Three operation modes: grid forming, grid feeding or grid supporting
- Ac voltage control is mandatory for higher power WTS
- Dc voltage control can be implemented using a cascade structure
- Power control through Voltage oriented control or direct power control (with or without virtual flux)
- Droop control for voltage amplitude and frequency control