High performance controllers for grid-connected PWM voltage source converters

António Pina Martins
IEEE Member, University of Porto

Summary

- Introduction
- System modelling
  - Delayed converter actuation
  - Cross coupling
  - Complex domain modelling
- Complex pole placement
  - Observer
- Results
- Conclusions

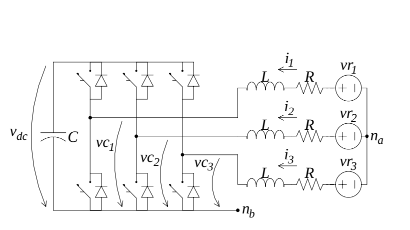
Introduction

- The design of high performance controllers for the grid connected VSC use the *dq* reference frame to model the system
  - MIMO system with cross coupling
- The usual approach is to design the two compensation controllers for the direct path and use a feed forward component to compensate for the coupling
  - Parameters are unknown and/or can change over time
- A controller that can directly handle with this coupling terms is the best approach to maintain the performance at high levels

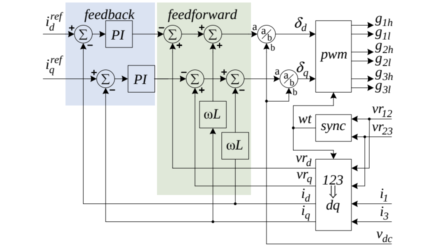
Introduction

- Design approaches include:
  - Voltage and current sensorless methods
  - Variable structure and sliding mode control
  - Dead beat
  - Direct power control
  - Lyapunov-based control design
  - Pole placement and
  - Input-output linearization
- System modelling in the complex domain and controller design based on pole placement is a powerful approach

Modelling the system with *L* filter (I)



Three phase grid-connected voltage source converter with a L filter



Conventional controller operating in *dq* synchronous coordinates with decoupling

- Parameter changing: *L*
- Delay between signal acquisition and PWM actuation

Modelling the system with *L* filter (II)

$$\begin{cases} L\dfrac{d}{dt}i_d = -R\,i_d + \omega L\,i_q + vr_d - vc_d \\ L\dfrac{d}{dt}i_q = -R\,i_q - \omega L\,i_d + vr_q - vc_q \end{cases}$$

- Zero-order-hold discretization

$$\begin{bmatrix} i_d[n+1] \\ i_q[n+1] \end{bmatrix} = \begin{bmatrix} c_{d1} & -c_{q1} & c_{d2} & -c_{q2} & c_{d3} & -c_{q3} \\ c_{q1} & c_{d1} & c_{q2} & c_{d2} & c_{q3} & c_{d3} \end{bmatrix} \mathbf{E}^T$$

$$\mathbf{E} = \begin{bmatrix} i_d[n] & i_q[n] & vc_d[n] & vc_q[n] & vr_d[n] & vr_q[n] \end{bmatrix}$$

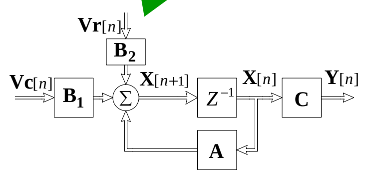
Modelling the system with *L* filter (III)

- New vector **E** and state-vector **X**

$$\mathbf{E} = \begin{bmatrix} i_d[n] & i_q[n] & vc_d[n-1] & vc_q[n-1] & vr_d[n] & vr_q[n] \end{bmatrix}$$

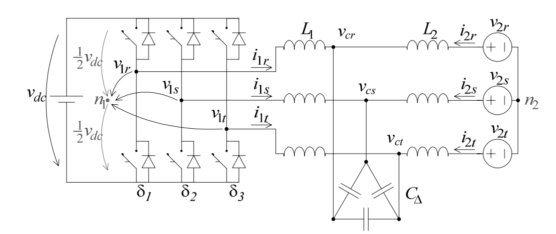
- New state-space representation

$$\mathbf{X}[n+1] = \mathbf{A}\,\mathbf{X}[n] + \mathbf{B}_1\mathbf{Vc}[n] + \mathbf{B}_2\mathbf{Vr}[n]$$
$$\mathbf{Y}[n] = \mathbf{C}\,\mathbf{X}[n]$$



Discrete time state-space representation of the VSC connected to the grid

Modelling the system with *LCL* filter (I)



Three phase grid-connected voltage source converter with a LCL filter

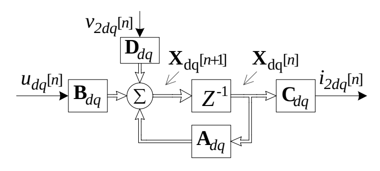
- Parameter changing: L_1, C and L_2
- Resonant frequency
  - Variable with L_2

Modelling the system with *LCL* filter (II)

- Using the zero-order-hold discretization and considering the delay between signal acquisition and PWM actuation

$$\mathbf{X}_{dq}[n+1] = \mathbf{A}_{dq}\mathbf{X}_{dq}[n] + \mathbf{B}_{dq}u_{dq}[n] + \mathbf{D}_{dq}v_{2dq}[n]$$
$$i_{2dq}[n] = \mathbf{C}_{dq}\mathbf{X}_{dq}[n]$$

$$\mathbf{X}_{dq} = \begin{bmatrix} i_{2dq}[n] \\ v_{cdq}[n] \\ i_{1dq}[n] \\ v_{1dq}[n] \end{bmatrix}$$



Discrete time state-space representation of the VSC connected to the grid

Complex pole placement (I)

- Complex variables are used to model the system
  - Examples:

$$c_{dq1} = c_{d1} + j\,c_{q1};\quad c_{dq2} = c_{d2} + j\,c_{q2}$$

- Current behavior using complex notation

$$i_{dq}[n+1] = c_{dq1}\,i_{dq}[n] + c_{dq2}\,vc_{d}[n-1] + c_{dq3}\,vr_{dq}[n]$$

- The following state-space formulation is obtained

$$\mathbf{X}_{dq}[n+1] = \mathbf{A}_{dq}\mathbf{X}_{dq}[n] + \mathbf{B}_{1dq}vc_{dq}[n] + \mathbf{B}_{2dq}vr_{dq}[n]$$
$$i_{dq}[n] = \mathbf{C}_{dq}\mathbf{X}_{dq}[n]$$

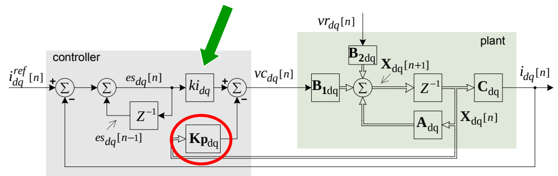
Complex pole placement (II)

- The complex state vector

$$\mathbf{X}_{dq}[n] = \begin{bmatrix} i_{dq}[n] \\ vc_{n1dq}[n] \end{bmatrix}$$

- The system is represented by a SISO state-space model, with complex variables
- The controllability matrix has rank 2
  - The system is controllable

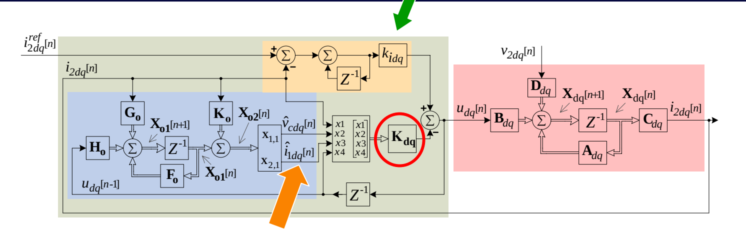
Complex pole placement (III)



Controller schematics using state feedback

- The controller design consists in the determination of the gains Ki_{dq} and $\mathbf{Kp}_{dq}$
  - The closed-loop pole placement technique is used to determine the gains

Complex pole placement: *LCL* filter (I)

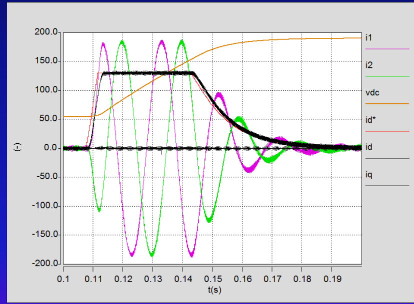


Controller schematics with observer-based state feedback

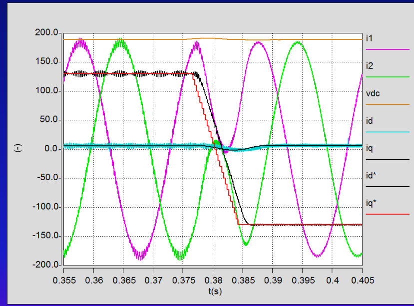
- The controller design consists in the determination of the gains Ki_{dq} and $\mathbf{Kp}_{dq}$
  - Closed-loop pole placement
- The observer estimates the capacitor voltage and the converter current

Simulation results: *L* filter (I)

- Parameters: V_s=139/240 V, 50 Hz, 200 kW, R_s=0.01 Ω, L_s=1 mH; F_s=3.3 kHz

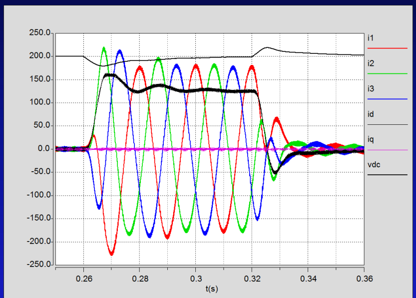


DC capacitor charging [from 500 V to 750 V] under current control (the *id* current reference is the output of the DC voltage controller)



Reactive power inversion, showing the DC voltage [100 V/div], two AC currents, the *id* and *iq* references (*id** and *iq**) and their actual values

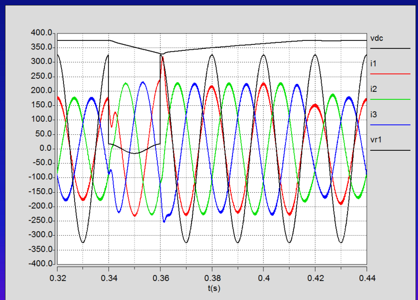
Simulation results: *L* filter (II)



Active power variation, showing the DC voltage [50 V/div], the AC currents, and the *id* and *iq* components

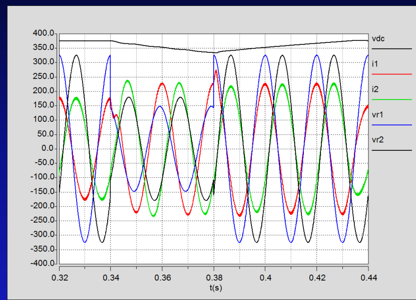
P=K*

AC → DC



Fault ride-through capability under symmetric voltage sag: DC voltage [100 V/div], phase 1 voltage, and AC currents

Simulation results: *L* filter (III)



P=K*

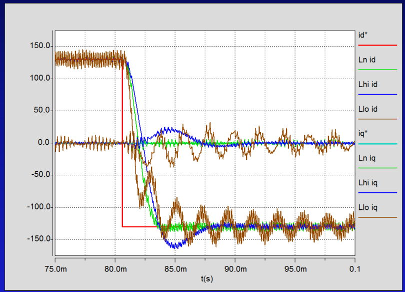
AC → DC

Fault ride-through capability under asymmetric voltage sag: DC voltage [100 V/div], two AC voltages, two and AC currents

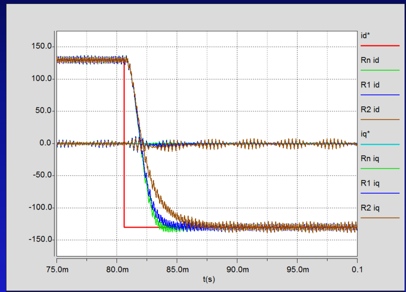
- In all the simulations
  - Fast current controller response
  - Small variation in the DC voltage

Simulation results: *L* filter (IV)

- Robustness



Active power flow inversion with different grid inductances

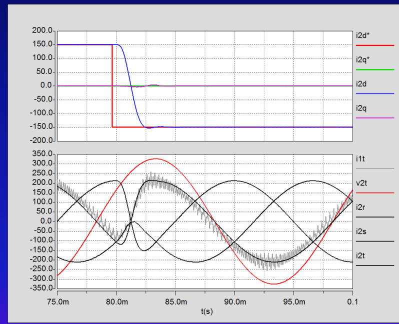


Active power flow inversion with different equivalent resistances

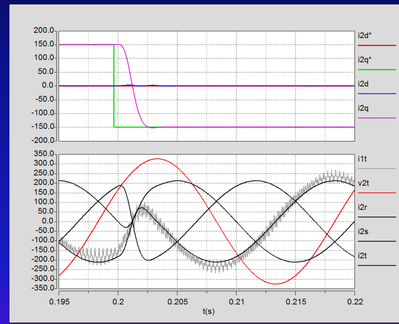
- Lower inductance deteriorates the response
  - The resistance value has no influence

Simulation results: *LCL* filter (I)

- Parameters: V_s=230/400 V, 50 Hz, 100 kVA, L_1=0.4 mH, L_2=0.4 mH; C=250 µF F_s=3 kHz



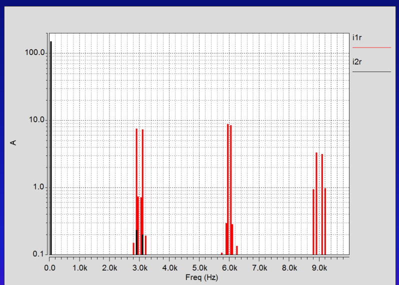
Active power inversion:
- *i2d* and *i2q* references (*i2d** and *i2q**) and actual values;
- grid currents (*i1r*, *i1s*, and *i1t*), grid phase *t* voltage (*v2t*) and converter phase *t* current, *i1t*



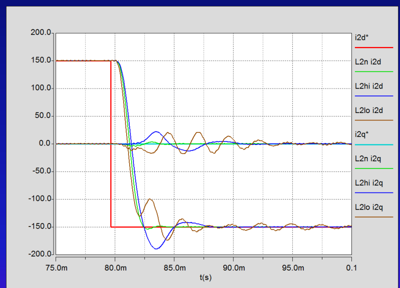
Reactive power inversion:
- *i2d* and *i2q* references (*i2d** and *i2q**) and actual values:
- grid currents (*i1r*, *i1s*, and *i1t*), grid phase *t* voltage (*v2t*) and converter phase *t* current, *i1t*

Simulation results: *LCL* filter (II)

- LCL filtering
  - Better grid interface
- Robustness
  - Unknown grid inductance



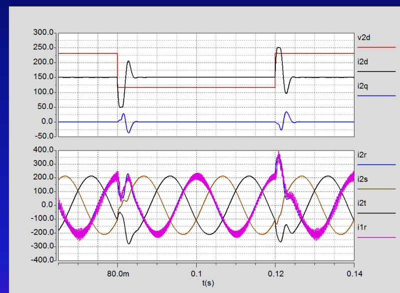
Converter output current spectrum, i1r, and grid current spectrum, i2r, in nominal conditions



Response to an active power flow inversion with different grid inductances

Simulation results: *LCL* filter (III)

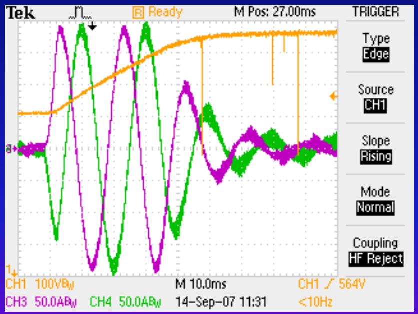
- Ride-through capability
  - Demanding grid codes



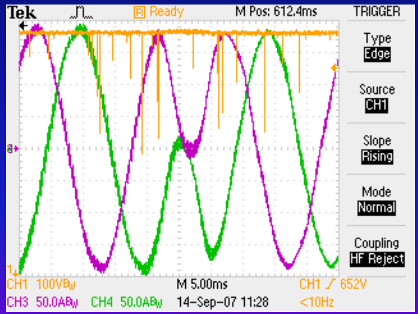
Fault ride-through capability under symmetric voltage sag:
- grid voltage and current;
- grid currents and phase r converter current

Experimental results: *L* filter

- Control platform based on a TMS320C6713 DSP
  - Daughterboard with a Xilinx Virtex FPGA and A/D converters



DC capacitor voltage charging (orange) under current control (the *id* current reference is the output of the DC voltage controller)



Reactive power inversion (DC voltage and two AC currents)

Conclusions (I)

- Accurate process and controller modelling is essential to obtain high levels of performance
- An integrated approach to design current controllers for grid-connected VSCs is important
  - *L* and *LCL* filter connections
- Complex domain modelling and pole placement based design allows the complete processing of the *d* and *q* variables and its coupling components
  - No need of the feed forward compensation terms
  - Easy inclusion of additional dynamics

Conclusions (II)

- The (complex domain) observer allows the use of less sensors
- Results show that the approach to the controller design is a very effective one
  - Power flow control
  - Current tracking and regulation
  - Parameter variation

Thank you for your attention.