High performance controllers for grid-connected PWM voltage source converters

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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

System modelling

- Delayed converter actuation
- Cross coupling
- Complex domain modelling

Complex pole placement
- Observer

Results

Conclusions

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)

- Zero-order-hold discretization

\[
\begin{align*}
L \frac{di_d}{dt} &= -Ri_d + \omega Li_q + vr_d - vc_d \\
L \frac{di_q}{dt} &= -Ri_q - \omega Li_d + vr_q - vc_q
\end{align*}
\]

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

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

New state-space representation

\[
X[n+1] = A X[n] + B_1 Y[n] + B_2 Vr[n]
\]

\[
Y[n] = C X[n]
\]

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

Modelling the system with *LCL* filter (I)

- 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

\[
\begin{align*}
X_{dq}[n+1] &= A_{dq} X_{dq}[n] + B_{dq} u_{dq}[n] + D_{dq} v_{2dq}[n] \\
i_{2dq}[n] &= C_{dq} X_{dq}[n]
\end{align*}
\]

\[
X_{dq} = \begin{bmatrix} i_{2dq}[n] \\ v_{cdq}[n] \\ i_{1dq}[n] \\ v_{1dq}[n] \end{bmatrix}
\]

Discrete time-state 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
  \[
  i_{dq}[n+1] = c_{dq1} i_{dq}[n] + c_{dq2} v_{cdq}[n-1] + c_{dq3} v_{r dq}[n]
  \]

- The following state-space formulation is obtained
  \[
  \begin{align*}
  X_{dq}[n+1] &= A_{dq} X_{dq}[n] + B_{1dq} v_{cdq}[n] + B_{2dq} v_{r dq}[n] \\
i_{dq}[n] &= C_{dq} X_{dq}[n]
  \end{align*}
  \]

Complex pole placement (II)

- The complex state vector
  \[
  X_{dq}[n] = \begin{bmatrix} i_{dq}[n] \\ v_{c1dq}[n] \end{bmatrix}
  \]

- 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)

- The controller design consists in the determination of the gains \( K_{i_{dq}} \) and \( K_{p_{dq}} \)
  - The closed-loop pole placement technique is used to determine the gains
Complex pole placement: LCL filter (I)

The controller design consists in the determination of the gains $K_{idq}$ and $K_{pdq}$ – Closed-loop pole placement

The observer estimates the capacitor voltage and the converter current

Controller schematics with observer-based state feedback

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

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

Simulation results: L filter (III)

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

Fault ride-through capability under asymmetric voltage sag: DC voltage [100 V/div], two AC voltages, two and AC currents
Simulation results: **L filter (IV)**

- **Robustness**

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

  ![Graphs showing active power flow inversion with different grid inductances and equivalent resistances.]

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; $C=250 \mu$F, $F_s=3$ kHz

  - Active power inversion: $i_d$ and $i_q$ references ($i_d^*$ and $i_q^*$) and actual values;
  - grid currents ($i_1r$, $i_1s$, and $i_1t$), grid phase $V_2$ voltage ($v_2t$) and converter phase $I_1$ current.

  ![Graphs showing active and reactive power inversions with different grid inductances and equivalent resistances.]

Simulation results: **LCL filter (II)**

- **LCL filtering**
  - Better grid interface

  ![Graphs showing converter output current spectrum, $i_1r$, and grid current spectrum, $i_2r$, in nominal conditions.]

- **Robustness**
  - Unknown grid inductance

  ![Graphs showing response to an active power flow inversion with different grid inductances.]

Simulation results: **LCL filter (III)**

- **Ride-through capability**
  - Demanding grid codes

  ![Graphs showing fault ride-through capability under symmetric voltage sag: grid voltage and current, grid currents and phase $I_1$ converter current.]

High performance controllers for grid connected PWM voltage source converters
Experimental results: $L$ filter

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

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.