Small-Signal Impedance Modeling of

Grid-Following Inverter

\\Oled\lea\Forschung\ogP\8316_BMWi_PV_Kraftwerk2025\Intern\Daten\zya\01_Data\01_Figure\01_Circuit\01_Three-Phase Grid-Tied Inverter\System_Single_Inv_LCL_Lg_ACC_PLL_DVC.emf

Established by

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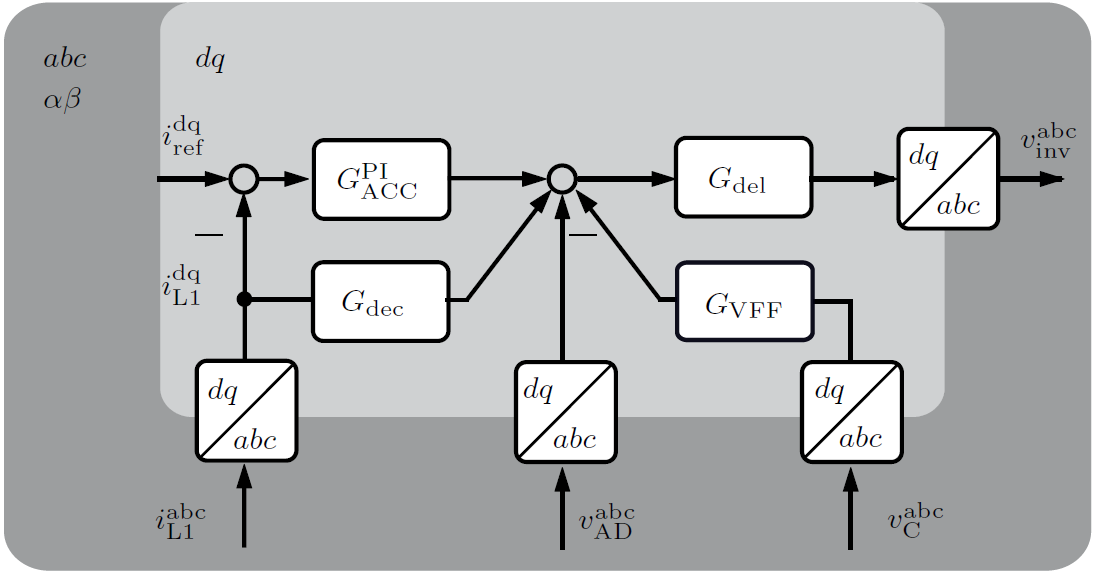
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# Alternating-Current Control (ACC)

## Proportional-integral (PI) control



Control transfer function

Control transfer matrix

Decoupling transfer matrix

Voltage feedforward filter (VFF) transfer matrix

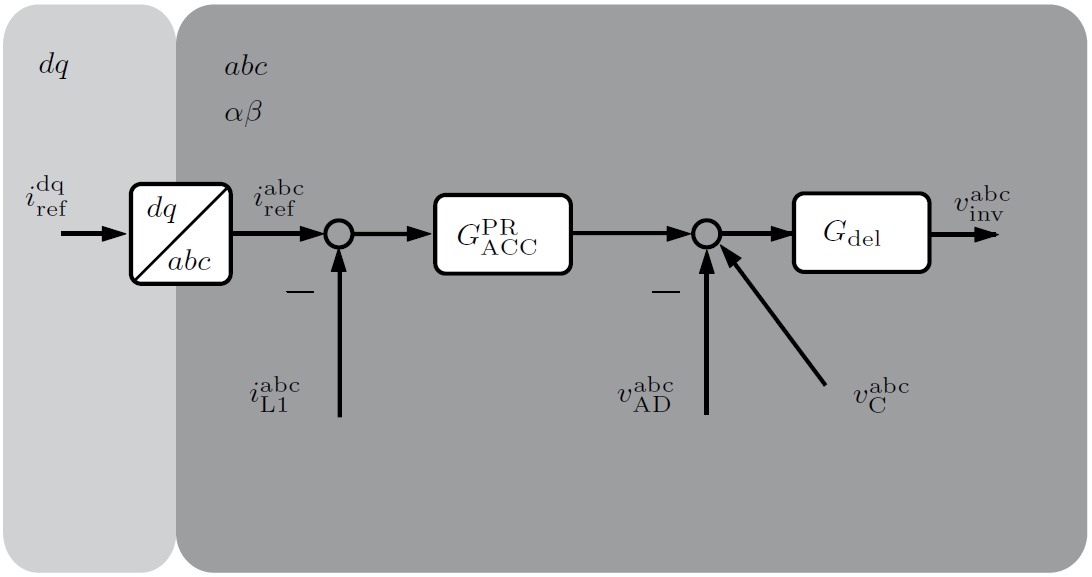
Active damping (AD) transfer matrix

Delay matrix in Padé approximation form

Frequency-domain relation

Linearization

## Proportional-resonant (PR) control



Control transfer function

Control transfer matrix

Active damping (AD) transfer matrix

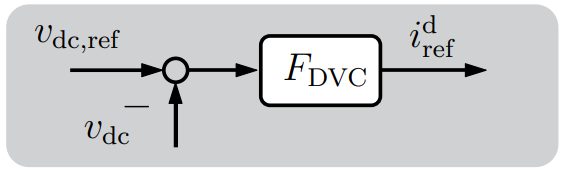
Delay matrix in Padé approximation form

Frequency-domain relation

Linearization

# LCL Filter

# Direct-Voltage Control (DVC)

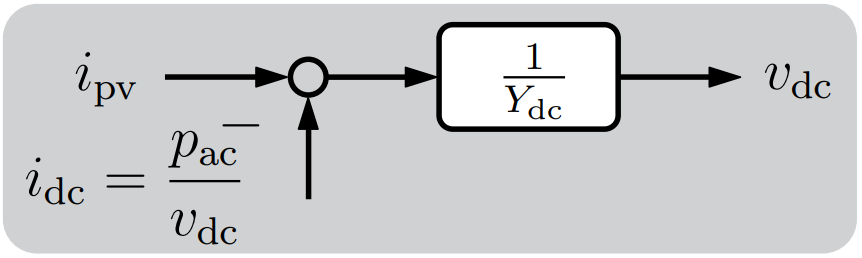


Control transfer function

Frequency-domain relation

Linearization

# DC-Link Capacitor

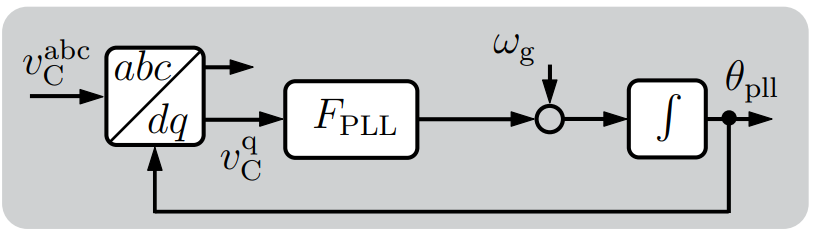


Plant dynamics

Power balance

Linearization

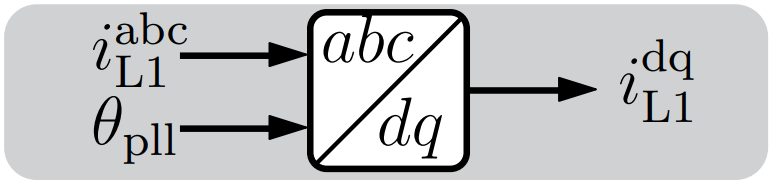
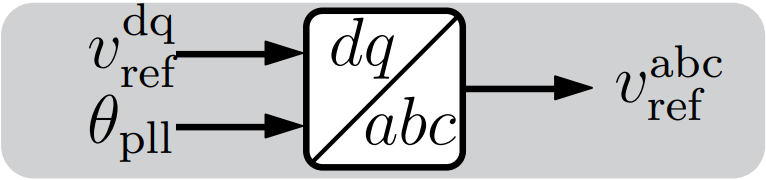
# Phase-Locked Loop (PLL)



Control transfer function

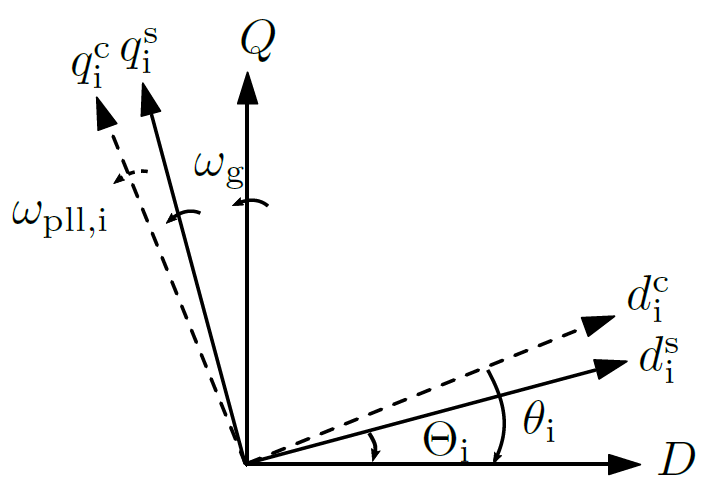
Linearization according to [1]

The small-signal transfer function influences the variables through Park and inverse Park transformation, e.g.

Detailed mathematical impacts are analyzed in the section reference frame

# Reference Frame



## System frame 🡪 control frame

Due to the PLL dynamics, variables with Park transformation are converted from the system to control frame.

Inverter-side inductor current

Grid-side capacitor current

Grid-side capacitor voltage

## Control frame 🡪 system frame

Due to the PLL dynamics, variables with inverse Park transformation are converted from the control to system frame.

Modulation index

If PR control is implemented, reference current obtained in the frame should be converted to the frame, which also requires inverse Park transformation, i.e.

## System 🡪 global frame

To facilitate the integration of multi-inverter system, a common global frame is defined.

Clockwise rotation

Anti-clockwise rotation

Each inverter has its own rotation frame. They can be aggregated only after being converted into the same global frame.

Consider inverter

Then

# Modulation Delay

The modulation delay in the complex frequency domain can be precisely modeled as:

If the delay is expanded in Euler’s form,

The delay transfer matrix can be described as below.

If the delay is expanded in Padé approximation,

The delay transfer matrix can be described as below.

It should be noticed that, the following format is not very strict, since all the elements in a transfer matrix should be real transfer functions according to [2].

# Impedance Model

|  |  |  |
| --- | --- | --- |
| Control | Without DVC | With DVC |
| PI |  |  |
| PR |  |  |

Where,

# Reference

The model development can refer [3, 4, 5, 6, 7]

|  |  |
| --- | --- |
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| [3] | Z. Yang, C. Shah, T. Chen, L. Yu, P. Joebges and R. De Doncker, "Stability Investigation of Three-Phase Grid-Tied PV Inverter Systems Using Impedance Models," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* p. doi: 10.1109/JESTPE.2020.3047964, 2020. |
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| [6] | Z. Yang, T. Chen, X. Luo, P. Schülting and R. W. De Doncker, "Margin Balancing Control Design of Three-Phase Grid-Tied PV Inverters for Stability Improvement," *IEEE Transactions on Power Electronics,* vol. 36, no. 9, pp. 10716-10728, 2021. |
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