**DEE-34206 Dynamics and Control of Grid-Connected Converters** Final exam, 29.11.2017
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**Problem 1** (max 6 points)

Transfer function matrix of a grid-connected battery-interfacing inverter is given at open-loop in (1) and at closed-loop in (2). What transfer function should be analyzed in the following cases described below.

a) The discharging current of the battery $i_{\text{bat}}$ is controlled using DC-current feedback and the controller transfer function should be designed. DC-side dynamics are assumed to be dominated by d-components (real power).

b) Current control is implemented in dq-domain. *Crossover frequency* and *phase margin* of the AC-current control should be evaluated. It is assumed that PI-controlled parameters are already selected, i.e., controller transfer function is known.

c) Control design is already finished and the effect of grid voltage harmonics on the generated output currents should be analyzed.

d) *Control bandwidth* of the AC-current control should be determined.

e) Output admittance d-component should be re-shaped to have higher magnitude at the fifth harmonic. Changing the size of passive components is not allowed.

$$\begin{bmatrix} \hat{i}_{\text{bat}} \\ \hat{i}_{\text{od}} \\ \hat{i}_{\text{oq}} \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} & G_{15} \\ G_{21} & G_{22} & G_{23} & G_{24} & G_{25} \\ G_{31} & G_{32} & G_{33} & G_{34} & G_{35} \end{bmatrix} \begin{bmatrix} \hat{v}_{\text{bat}} \\ \hat{v}_{\text{od}} \\ \hat{v}_{\text{oq}} \\ \hat{d}_{\text{d}} \\ \hat{d}_{\text{q}} \end{bmatrix} \quad (1) \qquad \begin{bmatrix} \hat{i}_{\text{bat}} \\ \hat{i}_{\text{od}} \\ \hat{i}_{\text{oq}} \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} & G_{15} \\ G_{21} & G_{22} & G_{23} & G_{24} & G_{25} \\ G_{31} & G_{32} & G_{33} & G_{34} & G_{35} \end{bmatrix} \begin{bmatrix} \hat{v}_{\text{bat}} \\ \hat{v}_{\text{od}} \\ \hat{v}_{\text{oq}} \\ \hat{i}_{\text{od}}^{*} \\ \hat{i}_{\text{oq}}^{*} \end{bmatrix} \quad (2)$$

**Problem 2** (max 6 points)

Control block diagram of a phase-locked-loop is as shown in Figure 1. The feedforward term $\omega_{\text{ff}}$ is a constant which improves start-up. The Park's transformation can be linearized as $\hat{v}_{\text{q}}' = \hat{v}_{\text{q}} - V_{\text{d}}\hat{\theta}$ where $\hat{v}_{\text{q}}$ denotes the ideal grid voltage q-component.

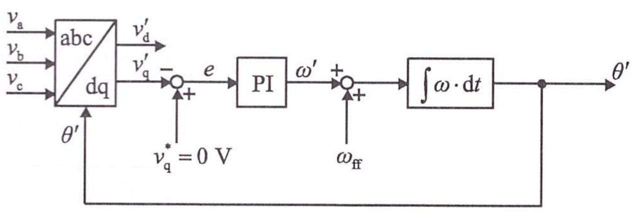


Figure 1: Phase-locked-loop.

a) Draw the linearized control block diagram and define control loop gain of the PLL.

b) Solve transfer function from the reference input $\hat{v}_{\text{q}}^{*}$ to the controlled variable $\hat{v}_{\text{q}}'$ in dq-domain.

c) The transfer function from reference to the controlled variable can be written as a second-order system as in (3). Find out the damping ratio $\xi$ and natural frequency $\omega_{\text{n}}$ in terms of controller parameters. You can assume that the controller transfer function is as given in (4).

$$G = \left(2\xi\omega_{\text{n}}s + \omega_{\text{n}}^{2}\right) / \left(s^{2} + 2\xi\omega_{\text{n}}s + \omega_{\text{n}}^{2}\right) \quad (3)$$

$$G_c = \frac{(-1)\cdot K\left(s/\omega_z + 1\right)}{s} \tag{4}$$

**Problem 3** (max 6 points)

Figure 2 shows a simple power electronics -based power system. Answer the following questions:

a) Which converter is responsible of frequency control of the AC line? Justify how you determine this from the figure.
b) What variables are controlled using cascaded control scheme?
c) Which converter is responsible of regulating the RMS value of AC voltage? Justify based on Figure 2.
d) How can you decide the minimum voltage of the DC voltage source? (short answer please, no equations needed)
e) Consider you need to define an open-loop small-signal model for the load converter. What are the output variables of the small-signal model? Justify their selection.

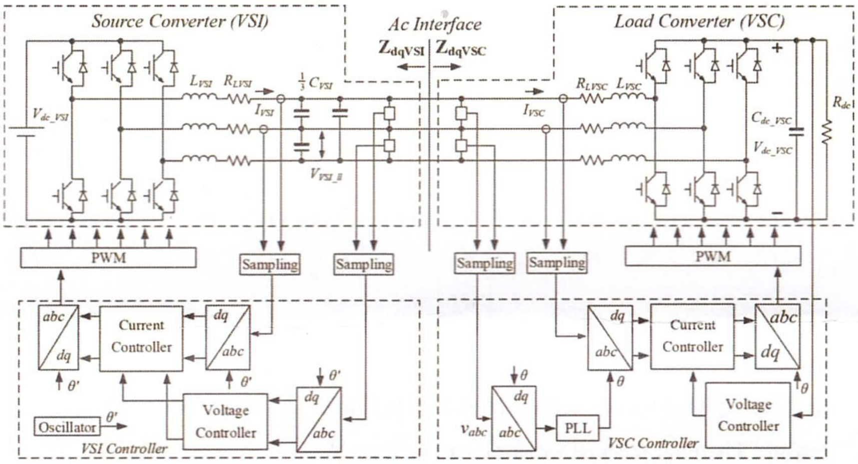


Figure 2: Control system of a power-electronics based AC system.

**Problem 4** (max 6 points)

Three-phase LCL-filter is shown in Figure 3. Solve the average state-space model of the filter in the dq-domain. You can assume that the three-phase input and output voltages are balanced. Draw the electrical circuits of the filter in dq-domain (separately for d and q-components).

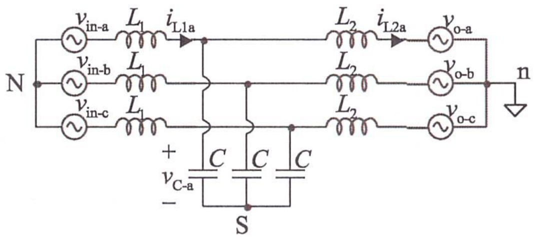


Figure 3: Three-phase LCL-type filter.

Hints:

$$\frac{\mathrm{d}}{\mathrm{d}t} i_{\mathrm{L1}}^{\mathrm{dq}} = f\left(v_{\mathrm{NS}}, v_{\mathrm{in\text{-}d}}, v_{\mathrm{in\text{-}q}}, v_{\mathrm{C\text{-}d}}, v_{\mathrm{C\text{-}q}}\right)?$$

$$\frac{\mathrm{d}}{\mathrm{d}t} v_{\mathrm{C}}^{\mathrm{dq}} = f\left(i_{\mathrm{L1d}}, i_{\mathrm{L1q}}, i_{\mathrm{L2d}}, i_{\mathrm{L2q}}\right)?$$

$$\frac{\mathrm{d}}{\mathrm{d}t} i_{\mathrm{L2}}^{\mathrm{dq}} = f\left(v_{\mathrm{nS}}, v_{\mathrm{C\text{-}d}}, v_{\mathrm{C\text{-}q}}, v_{\mathrm{o\text{-}d}}, v_{\mathrm{o\text{-}q}}\right)?$$

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**Problem 5** (max 6 points)
Grid voltage in unbalanced condition is given in stationary frame according to (5).

a) How is the grid voltage seen in the dq-domain? Give the amplitude and frequencies of different components.
b) A three-phase inverter is connected to the unbalanced grid defined in (5). The fundamental frequency of the grid is 50 Hz. A conventional SRF-PLL is used according Figure 1. How much does the PLL loop gain attenuate the effect of unbalance when it is as shown in Figure 4?
c) How does the unbalance affect power quality of the inverter?
d) What can you do to mitigate the effect of unbalance even more?

$$\mathbf{v}_{\text{grid}}^{\alpha\beta} = 230 \cdot e^{j\omega_s t} + 100 \cdot e^{j(-\omega_s)t} \tag{5}$$

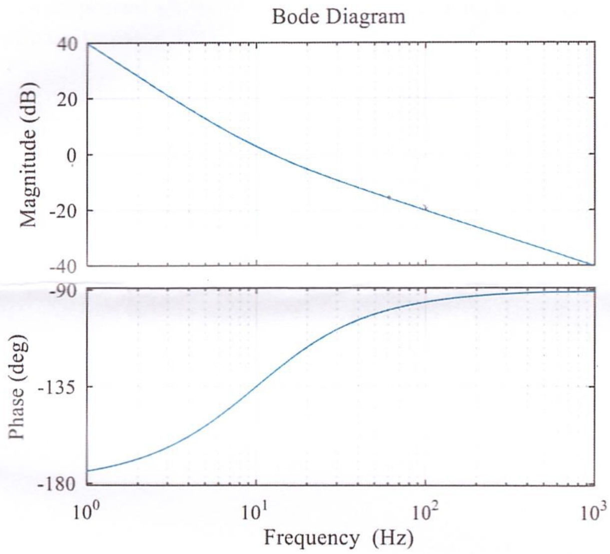


Figure 4: Control loop gain of the PLL in Problem 5.

Equations...

$\mathbf{x}^{\alpha\beta} = \mathbf{x}^{dq} \cdot e^{j\omega_s t}$

$e^{-jx} = \cos(x) - j\sin(x)$

$\mathbf{T}^{abc\rightarrow\alpha\beta} \cdot \begin{bmatrix} k & k & k \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & k \end{bmatrix}^T$