**DEE-34206 Dynamics and Control of Grid-Connected Converters** Final exam, 20.12.2016

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Use of own programmable calculator is allowed.

**Problem 1** (max 8 points)

Power stage of a voltage-fed inverter with output-current control is as shown in Figure 1.

a) Develop the inverter average model in dq-domain at open-loop, $\left(\langle i_{\mathrm{in}}\rangle = \frac{3}{2}d_{\mathrm{d}}\langle i_{\mathrm{Ld}}\rangle + \frac{3}{2}d_{\mathrm{q}}\langle i_{\mathrm{Lq}}\rangle\right)$.

b) Draw the equivalent linear circuit in dq-domain (DC input port and two AC output ports).

c) How do you have to modify the duty ratio d and q-components (how to define $x_{\mathrm{d}}$ and $x_{\mathrm{q}}$ ) to make the inverter output currents independent of the grid voltage d and q-components? Justify the result using the average model.

d) How do you realize decoupling of the current d and q-components? Use the average model to obtain necessary control laws / scaling coefficients. Correct answers earn points only if you can justify them using the average model.

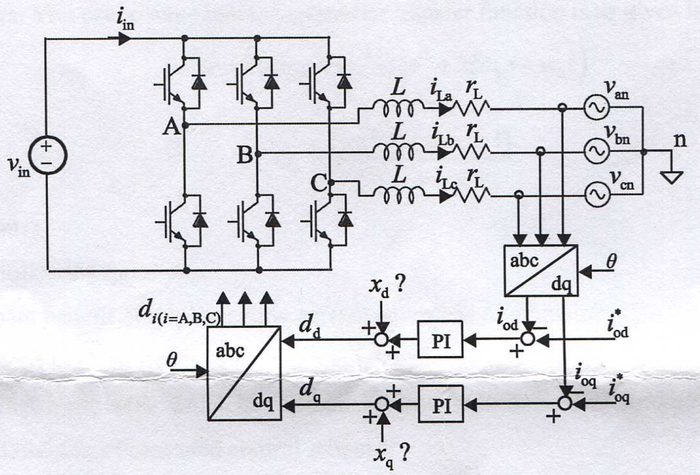


Figure 1: Voltage-fed inverter with output-current control.

**Problem 2** (max 4 points)

Instantaneous apparent power can be defined as the product of voltage space-vector and the complex-conjugate of current space-vector in the stationary reference frame as in (1).

a) Define real and imaginary power in the synchronous reference frame, i.e., in the dq-domain. The space vector is assumed to rotate at the fundamental grid frequency $\omega_s t$. (Useful formulas: $\boldsymbol{x}^{\alpha\beta} = \boldsymbol{x}^{\mathrm{dq}} \cdot e^{j\omega_s t}$, $(x\cdot y)^* = x^* \cdot y^*$, $\left(x^{j\theta}\right)^* = x^{-j\theta}$ , $j^2 = -1$ )

b) Explain based on the previous result how the real and imaginary power produced by three-phase inverter can be controlled independently.

$$s = v^{\alpha\beta}\cdot\left(i^{\alpha\beta}\right)^* \tag{1}$$

**Problem 3** (max 6 points)

The control block diagram of the phase-locked-loop is as shown in Figure 3. The feedforward term $\omega_{\mathrm{ff}}$ is a constant which improves the start-up. The Park's transformation can be linearized as $\hat{v}_{\mathrm{q}}' = \hat{v}_{\mathrm{q}} - V_{\mathrm{d}}\hat{\theta}$ where $\hat{v}_{\mathrm{q}}$ denotes the ideal grid voltage q-component.



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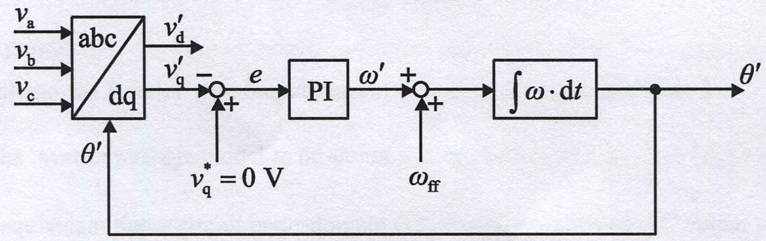


Figure 3: Phase-locked-loop.

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

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

c) The transfer function from reference to the controlled variable can be written as a second-order system as in (2). Find out the damping ratio $\xi$ and natural frequency $\omega_n$ in terms of controller parameters. You can assume that the controller transfer function is as given in (3).

$$G = \left(2\xi\omega_n s + \omega_n^2\right) / \left(s^2 + 2\xi\omega_n s + \omega_n^2\right) \tag{2}$$

$$G_c = \frac{(-1)\cdot K\left(s/\omega_z + 1\right)}{s} \tag{3}$$

**Problem 4** (max 6 points)

Give short answers to following questions.

1. What is the main benefit of implementing current control in dq-domain?
2. Why do you need to solve steady-state operating point?
3. Can you stabilize a converter which has an unstable pole in its control dynamics? How?
4. Give a short definition of cascaded control scheme?
5. How does phase-locked-loop affect the output impedance of a three-phase inverter?
6. How does grid-voltage feedforward affect the output impedance of a three-phase inverter?

**Problem 5** (max 6 points)

Three-phase LCL-filter is shown in Figure 4. 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), $\left(\mathbf{x}^{\alpha\beta} = \mathbf{x}^{dq} \cdot e^{j\omega_s t}\right), \left(\mathbf{T}^{abc\rightarrow\alpha\beta} \cdot \begin{bmatrix} k & k & k \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & k \end{bmatrix}^T\right)$.

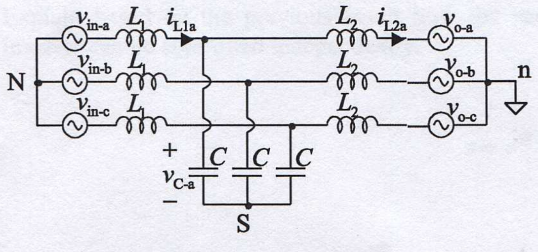


Figure 4: Three-phase LCL-type filter.

Hints:

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

$$\frac{d}{dt} v_C^{dq} = f\left(i_{L1d}, i_{L1q}, i_{L2d}, i_{L2q}\right)?$$

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