DEE-34206 Dynamics and Control of Grid-Connected Converters

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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, \( \left( \dot{i}_{dc} = \frac{3}{2} d_q \dot{i}_d + \frac{3}{2} d_q \dot{i}_q \right) \).

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 \( x_d \) and \( x_q \)) 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.

![Diagram of a voltage-fed inverter with output-current control.](image)

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 \( \omega \). (Useful formulas: \( x^* = x^* e^{j \theta} \), \( (x \cdot y)^* = x^* \cdot y^* \), \( (x^*)^* = x^* \), \( j^2 = -1 \))

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

\[
S = v^* \cdot (i^*)^*
\]  

(1)

Problem 3 (max 6 points)

The control block diagram of the phase-locked-loop is as shown in Figure 3. The feedforward term \( a_n \) is a constant which improves the start-up. The Park's transformation can be linearized as \( \dot{v}_q = \dot{v}_q - V_d \dot{\theta} \) where \( \dot{v}_q \) denotes the ideal grid voltage q-component.
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 \( \tilde{v}_e \) 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 \( \zeta \) and natural frequency \( \omega_n \) in terms of controller parameters. You can assume that the controller transfer function is as given in (3).

\[
G = \frac{2\xi \omega \, s + \omega_n^2}{(s^2 + 2\xi \omega_n \, s + \omega_n^2)}
\]

\[
G_c = \frac{1}{s} \cdot K \left( \frac{s}{\omega_n} + 1 \right)
\]

**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), \( \begin{pmatrix} x^d \end{pmatrix} = x^d \cdot e^{j \phi}, (T^{dq-\theta} \cdot \begin{bmatrix} k & k \\ 0 & k \end{bmatrix}) \cdot \begin{bmatrix} 0 & 0 \end{bmatrix} \).

Hints:

\[
\frac{d}{dt} v^d_{\text{in}} = f \left( v^d_{\text{in}}, i^d_{\text{in}}, v_{\text{out}}, v_{\text{out}}, v_{\text{out}} \right)\]

\[
\frac{d}{dt} v^q_{\text{in}} = f \left( i^d_{\text{in}}, i^q_{\text{in}}, i^d_{\text{in}}, i^q_{\text{in}} \right)\]

\[
\frac{d}{dt} i^d_{\text{in}} = f \left( v^d_{\text{in}}, v_{\text{in}}, v_{\text{out}}, v_{\text{out}}, v_{\text{out}} \right)\]