Aalto University
School of Electrical
Engineering

Lecture 6: Grid-Connected Converters

ELEC-E8402 Control of Electric Drives and Power Converters

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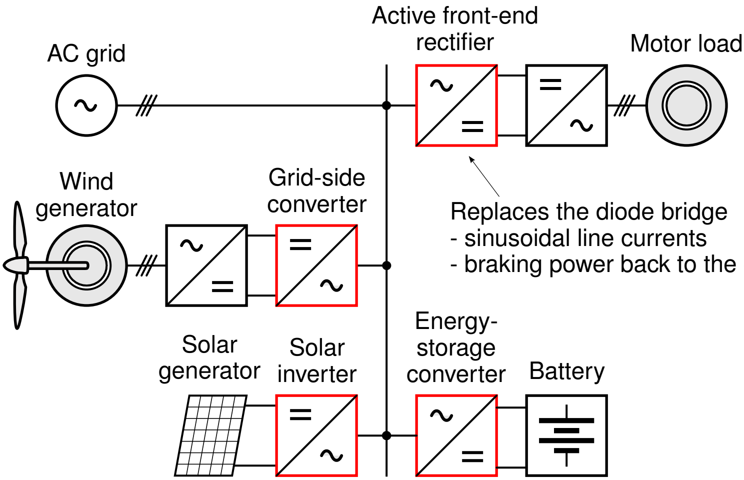
Learning Outcomes

After this lecture and exercises you will be able to:

- Explain the operating principle of the grid converter
- Explain the principle of grid-voltage orientation
- Calculate the operating point of the grid converter
- Tune a simple DC-voltage controller

Balanced 3-phase grid, having zero impedance, will be assumed in this lecture

Typical Applications: Renewable Energy and 4-Quadrant Drives



Replaces the diode bridge
- sinusoidal line currents
- braking power back to the grid

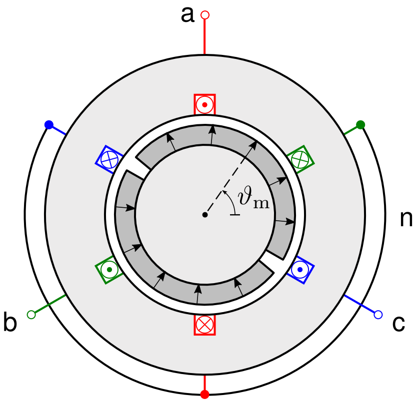
Example: 4-MW 690-V Grid-Side Converter of a Wind Generator

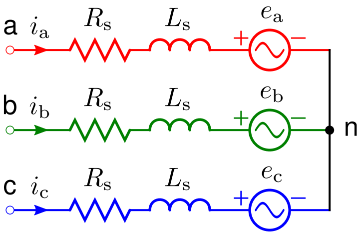
Figure: ABB ACS880

Inductive Filter and Grid Model

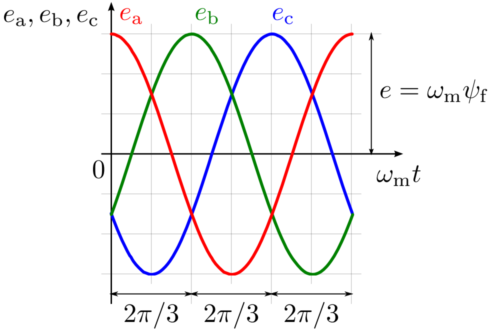
Grid-Voltage-Oriented Vector Control

Review: 3-Phase Permanent-Magnet Synchronous Machine





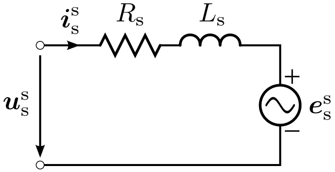
$$e_\mathrm{a} = -\omega_\mathrm{m}\psi_\mathrm{f}\sin(\vartheta_\mathrm{m})$$
$$e_\mathrm{b} = -\omega_\mathrm{m}\psi_\mathrm{f}\sin(\vartheta_\mathrm{m} - 2\pi/3)$$
$$e_\mathrm{c} = -\omega_\mathrm{m}\psi_\mathrm{f}\sin(\vartheta_\mathrm{m} - 4\pi/3)$$



$$e_\mathrm{a} = e\cos(\omega_\mathrm{m} t)$$

$$e_\mathrm{b} = e\cos(\omega_\mathrm{m} t - 2\pi/3)$$

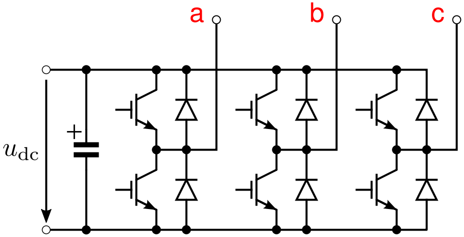
$$e_\mathrm{c} = e\cos(\omega_\mathrm{m} t - 4\pi/3)$$



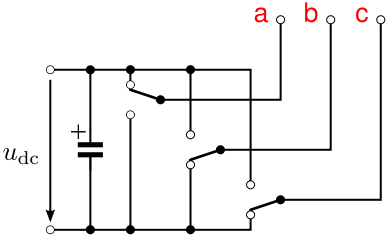
$$\boldsymbol{e}_\mathrm{s}^\mathrm{s} = \mathrm{j}\omega_\mathrm{m}\psi_\mathrm{f}\mathrm{e}^{\mathrm{j}\vartheta_\mathrm{m}} \qquad \vartheta_\mathrm{m} = \int \omega_\mathrm{m}\mathrm{d}t$$

At constant speed $\vartheta_\mathrm{m} = \omega_\mathrm{m} t$

2-Level Voltage-Source Converter



Main circuit

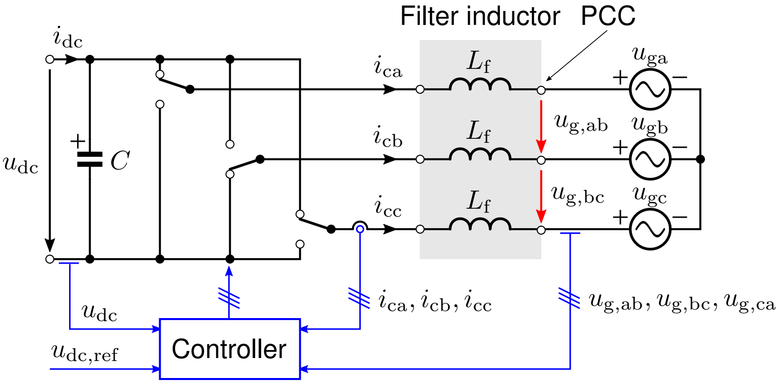


Equivalent circuit

- 2-level converters are typical in low-voltage applications (< 1 kV)
- 3-level converters in medium-voltage applications
- Modular multilevel converters in high-voltage applications (> 10 kV)

Grid Converter: What Is to Be Controlled?

- Active power: often via the DC-bus voltage controller
- Reactive power: displacement power factor
- Grid currents: typically 50-Hz sinusoidal waveforms are desired

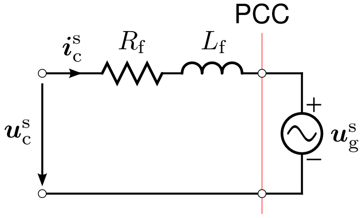


- Filter inductors L_f are connected between the converter and the point of common coupling (PCC)
  - Grid behind the PCC is modeled as a balanced 3-phase voltage source
  - Harmonics and unbalance may exist in practice (especially during grid faults)
- Control resembles that of a synchronous motor drive
  - Grid voltage $\sim$ back-emf
  - Filter inductor $\sim$ stator inductance
  - Grid-voltage measurement $\sim$ rotor-position measurement
- Grid converter can operate as a rectifier or as an inverter
  - Depends on the direction of the power flow

Space Vector Model: 3-Phase Grid Behind a Filter Inductor

Analogy to the synchronous machine model

- Converter voltage $\boldsymbol{u}_\mathrm{c} \sim \boldsymbol{u}_\mathrm{s}$
- Converter current $\boldsymbol{i}_\mathrm{c} \sim \boldsymbol{i}_\mathrm{s}$
- Filter inductance $L_\mathrm{f} \sim L_\mathrm{s}$
- Filter resistance $R_\mathrm{f} \sim R_\mathrm{s}$
- Grid voltage $\boldsymbol{u}_\mathrm{g} \sim \boldsymbol{e}_\mathrm{s}$
- Grid angular frequency $\omega_\mathrm{g} \sim \omega_\mathrm{m}$
- Grid-voltage angle $\vartheta_\mathrm{g} \sim \vartheta_\mathrm{m}$



$$\boldsymbol{u}_\mathrm{g}^\mathrm{s} = u_\mathrm{g} \mathrm{e}^{\mathrm{j}\vartheta_\mathrm{g}} \qquad \vartheta_\mathrm{g} = \int \omega_\mathrm{g} \mathrm{d}t$$

Voltage magnitude u_g and frequency ω_g are constant in normal conditions. In the following, $R_\mathrm{f} = 0$ will be assumed.

Inductive Filter and Grid Model

Grid-Voltage-Oriented Vector Control

Space-Vector Model: Synchronous Coordinates Rotating at ω_g

$$L_\mathrm{f}\frac{\mathrm{d}\boldsymbol{i}_\mathrm{c}}{\mathrm{d}t} = \boldsymbol{u}_\mathrm{c} - \boldsymbol{u}_\mathrm{g} - \mathrm{j}\omega_\mathrm{g} L_\mathrm{f}\boldsymbol{i}_\mathrm{c}$$

- Components of the space vectors

$$\boldsymbol{i}_\mathrm{c} = i_\mathrm{cd} + \mathrm{j}i_\mathrm{cq} \qquad \boldsymbol{u}_\mathrm{c} = u_\mathrm{cd} + \mathrm{j}u_\mathrm{cq} \qquad \boldsymbol{u}_\mathrm{g} = u_\mathrm{gd} + \mathrm{j}u_\mathrm{gq}$$

- Active power fed to the grid at the PCC

$$p_\mathrm{g} = \frac{3}{2}\,\mathrm{Re}\left\{\boldsymbol{u}_\mathrm{g}\boldsymbol{i}_\mathrm{c}^*\right\} = \frac{3}{2}\left(u_\mathrm{gd}i_\mathrm{cd} + u_\mathrm{gq}i_\mathrm{cq}\right)$$

- Reactive power at the PCC

$$q_\mathrm{g} = \frac{3}{2}\,\mathrm{Im}\left\{\boldsymbol{u}_\mathrm{g}\boldsymbol{i}_\mathrm{c}^*\right\} = \frac{3}{2}\left(u_\mathrm{gq}i_\mathrm{cd} - u_\mathrm{gd}i_\mathrm{cq}\right)$$

Grid-Voltage Coordinates

- Real axis (d-axis) of the coordinate system is fixed to the grid-voltage vector

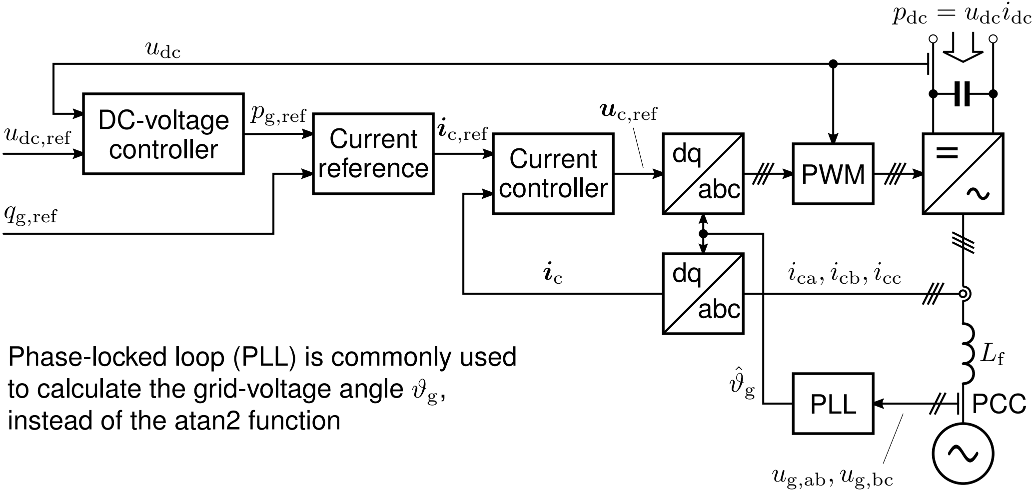
$$\boldsymbol{u}_{\mathrm{g}} = u_{\mathrm{gd}} + \mathrm{j}u_{\mathrm{gq}} = u_{\mathrm{g}} + \mathrm{j}0$$

- Active power and reactive power

$$p_{\mathrm{g}} = \frac{3}{2}u_{\mathrm{g}}i_{\mathrm{cd}} \qquad q_{\mathrm{g}} = -\frac{3}{2}u_{\mathrm{g}}i_{\mathrm{cq}}$$

Alternatively, the coordinate system could be fixed to the virtual grid flux.

Grid-Voltage-Oriented Vector Control



Phase-locked loop (PLL) is commonly used to calculate the grid-voltage angle ϑ_{g}, instead of the atan2 function

Current References

- Components of the current reference $\boldsymbol{i}_{\mathrm{c,ref}} = i_{\mathrm{cd,ref}} + \mathrm{j} i_{\mathrm{cq,ref}}$

$$i_{\mathrm{cd,ref}} = \frac{2p_{\mathrm{g,ref}}}{3u_{\mathrm{g}}} \qquad i_{\mathrm{cq,ref}} = -\frac{2q_{\mathrm{g,ref}}}{3u_{\mathrm{g}}}$$

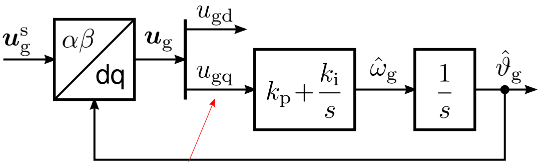
- Voltage u_{g} is constant in normal conditions
- Reactive power is often controlled to be zero, $i_{\mathrm{cq,ref}} = 0$

Phase-Locked Loop[1]

- Grid-voltage vector is measured

$$\boldsymbol{u}_{\mathrm{g}}^{\mathrm{s}} = u_{\mathrm{g}} \mathrm{e}^{\mathrm{j}\vartheta_{\mathrm{g}}}$$

- Angle ϑ_{g} can be noisy and it is not directly used in control
- PLL tracks ϑ_{g} and filters its noise and harmonics above the PLL bandwidth (without steady-state error)
- Additional filters and features could be included in the PLL



The PLL drives the signal u_{gq} to zero, leading to $\hat{\vartheta}_{\mathrm{g}} = \vartheta_{\mathrm{g}}$ and $u_{\mathrm{gd}} = u_{\mathrm{g}}$ in ideal conditions

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[1] Kaura and Blasko, “Operation of a phase locked loop system under distorted utility conditions,” *IEEE Trans. Ind. Appl.*, 1997.

DC-Bus Voltage Dynamics

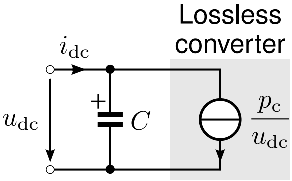
- Converter is assumed to be lossless

$$C\frac{\mathrm{d}u_\mathrm{dc}}{\mathrm{d}t} = i_\mathrm{dc} - \frac{p_\mathrm{c}}{u_\mathrm{dc}}$$

- Can be rewritten using the capacitor energy

$$\frac{\mathrm{d}W_\mathrm{dc}}{\mathrm{d}t} = u_\mathrm{dc}i_\mathrm{dc} - p_\mathrm{c} = u_\mathrm{dc}i_\mathrm{dc} - \frac{\mathrm{d}W_\mathrm{f}}{\mathrm{d}t} - p_\mathrm{g}$$

- Ideal power control: $p_\mathrm{g} = p_\mathrm{g,ref}$
- $\mathrm{d}W_\mathrm{f}/\mathrm{d}t = 0$ can be assumed
- Power $u_\mathrm{dc}i_\mathrm{dc}$ acts as a load disturbance



$$p_\mathrm{c} = \frac{3}{2}\mathrm{Re}\{\boldsymbol{u}_\mathrm{c}\boldsymbol{i}_\mathrm{c}^*\}$$

$$W_\mathrm{dc} = \frac{1}{2}Cu_\mathrm{dc}^2$$

$$W_\mathrm{f} = \frac{3}{2}L_\mathrm{f}i_\mathrm{c}^2$$

This model is used for tuning the DC-bus voltage controller, see exercises.

Further Details

- Additional functions for grid faults
  - Identification of both positive and negative sequences of the grid voltage
  - Current control for both positive and negative sequences
  - Grid-fault identification algorithms
  - Operation during the grid fault as set in grid codes
    (e.g. supporting the grid voltage by feeding the reactive power to the grid)
- LCL filter is more compact than the L filter
  - Resonance of the LCL filter has to be taken into account in the current controller
  - For example, a state-feedback controller can be used
- Active filtering of the grid-current harmonics is possible