Lecture 8: Grid Faults and Disturbances
ELEC-E8402 Control of Electric Drives and Power Converters
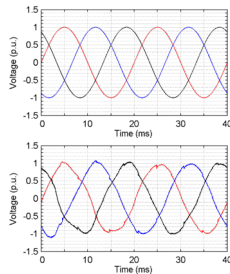
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Learning Outcomes

After this lecture and exercises you will be able to:

▶ Explain modeling concepts for unbalanced 3-phase grid voltages

▶ Explain the relation between the positive- and negative-sequence grid-voltage components vs. balanced and unbalanced grid faults

▶ Calculate the current references based on the active and reactive power references in unbalanced conditions
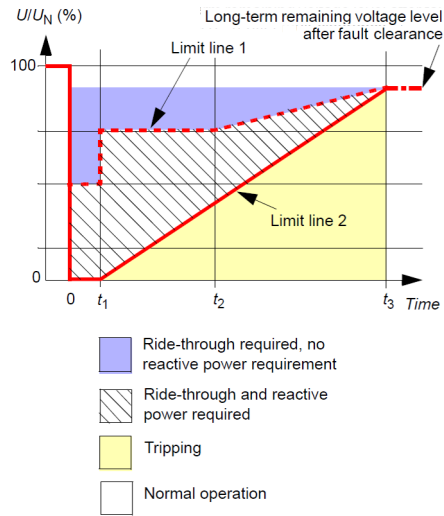
Introduction

- ▶ Ideal phase voltages at the point of common coupling (PCC)
  - ▶ Sinusoidal
  - ▶ Balanced
  - ▶ Constant frequency and amplitude
- ▶ In the real world
  - ▶ Non-sinusoidal voltages, i.e. voltage harmonics
  - ▶ Unbalanced phase voltages
  - ▶ Grid faults
  - ▶ Variations in frequency
- ▶ Converter should comply with relevant standards and grid codes
  - ▶ Standards are specific to area (e.g. IEC in Europe, and IEEE in U.S.)
  - ▶ Grid codes are grid (country) specific, defined by the authority responsible for the grid
  - ▶ Standard may consider a single equipment or a system connected to a grid
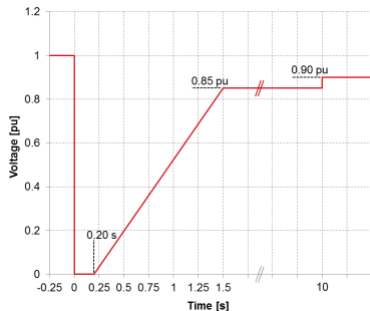 - ▶ Grid codes are relevant to power producing plants

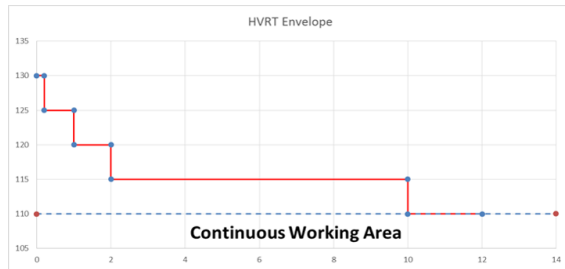# Examples: What Grid Codes May Require From a Production Unit?

- Operation during varying grid frequency
  - Converter shall remain connected and operate within the specified frequency ranges and time periods
  - Change in active power in response to a grid frequency change
- Operation during voltage deviations
  - Shall remain connected and operate within the specified voltages and time periods
  - Fault ride through, disconnection if needed
- Control of reactive power
- Ac-voltage control
- Capability to provide fault current
- Compliance testing and simulations

Figure: ABB, more: http://www.tuulivoimayhdistys.fi/filebank/806-SannaUski.pdf.

Examples: Voltage Dip and Voltage Swell Envelopes

An example of the low voltage ride through (LVRT) envelope

An example of the high voltage ride through (HVRT) envelope

Examples: Fault Current Injection*

- ▶ During the fault, the converter has to prioritize reactive current I_q
- ▶ The *k*-factor shall be 2.5

$$k = \frac{\frac{\Delta I_q}{I_n}}{\frac{\Delta U}{U_n}}$$

- ▶ The current shall rise to the target value within 30-50 ms, and settle to the target value within 60-80 ms
- ▶ In asymmetrical fault, i.e. unbalanced voltages, the positive and negative sequence currents must be supplied in the ratio defined by k-factor

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*Fingrid: Grid Code Specifications for Power Generating Facilities VJV2018

Outline

Balanced Phase Voltages

$$u_{\mathrm{ga}}(t) = u_{\mathrm{g}} \cos(\omega_{\mathrm{g}} t)$$
$$u_{\mathrm{gb}}(t) = u_{\mathrm{g}} \cos(\omega_{\mathrm{g}} t - 2\pi/3)$$
$$u_{\mathrm{gc}}(t) = u_{\mathrm{g}} \cos(\omega_{\mathrm{g}} t - 4\pi/3)$$

▶ Corresponding space vector

$$\underline{u}_{\mathrm{g}}(t) = u_{\mathrm{g}} e^{\mathrm{j}\vartheta_{\mathrm{g}}(t)} = u_{\mathrm{g}\alpha}(t) + \mathrm{j} u_{\mathrm{g}\beta}(t)$$

rotates at the constant angular frequency of $\omega_{\mathrm{g}} = 2\pi f_{\mathrm{g}}$

▶ Angle of the vector is $\vartheta_{\mathrm{g}}(t) = \omega_{\mathrm{g}} t$
▶ Magnitude is constant $|\underline{u}_{\mathrm{g}}(t)| = u_{\mathrm{g}}$

Space vectors are expressed in stator coordinates, but the superscript s is dropped to simplify the notation.

Unbalanced Phase Voltages

$$u_{ga}(t) = 0.25u_g \cos(\omega_g t)$$
$$u_{gb}(t) = u_g \cos(\omega_g t - 2\pi/3)$$
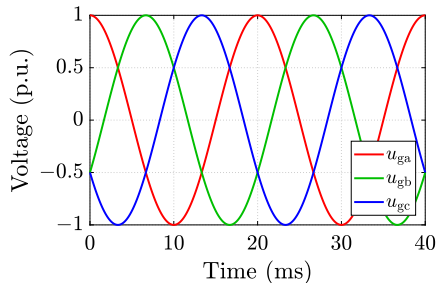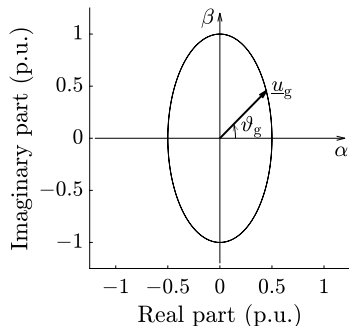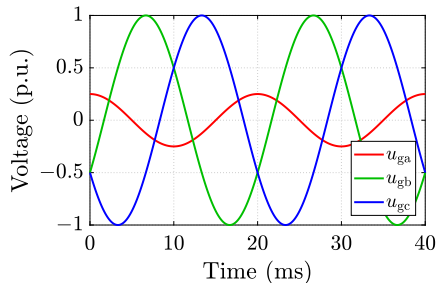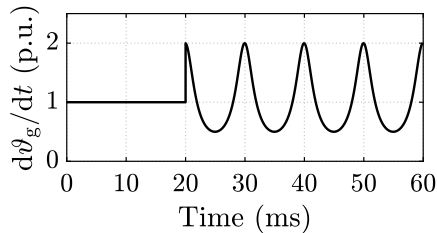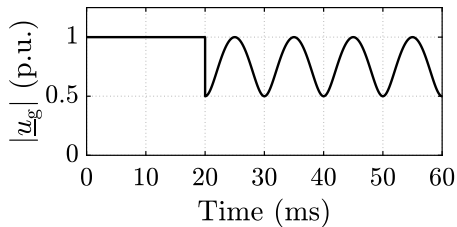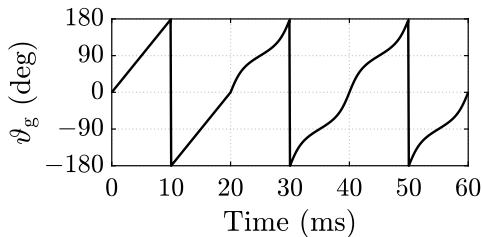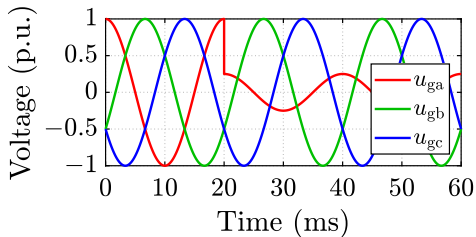$$u_{gc}(t) = u_g \cos(\omega_g t - 4\pi/3)$$

▶ Corresponding space vector $\underline{u}_g = u_{g\alpha} + ju_{g\beta}$ has an elliptical locus

▶ Magnitude $|\underline{u}_g|$ and rotation speed $d\vartheta_g/dt$ are oscillating at $2\omega_g$ and its multiples

Oscillations in the Magnitude and Angle

Positive and Negative Sequences

Unbalanced voltage as a combination of positive and negative sequences

$$\underline{u}_g(t) = \underline{u}_{g+}(t) + \underline{u}_{g-}(t) = u_{g+}e^{j(\omega_g t + \phi_{u+})} + u_{g-}e^{-j(\omega_g t + \phi_{u-})}$$
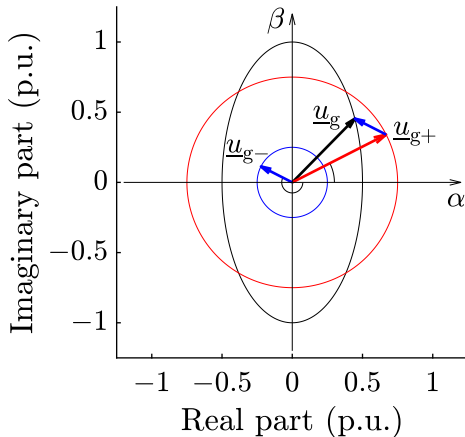
▶ Positive-sequence component
  ▶ vector with constant magnitude

    $$|\underline{u}_{g+}| = u_{g+}$$

  ▶ rotates counterclockwise at ω_g

▶ Negative-sequence component
  ▶ vector with constant magnitude

    $$|\underline{u}_{g-}| = u_{g-}$$

  ▶ rotates clockwise at ω_g

There is also the zero-sequence component in the unbalanced voltage, $u_0 = -0.25\cos(\omega_g t)$ in the example case. However, in three-wire systems, the zero-sequence current cannot flow and there is no power transfer due to the zero-sequence components.

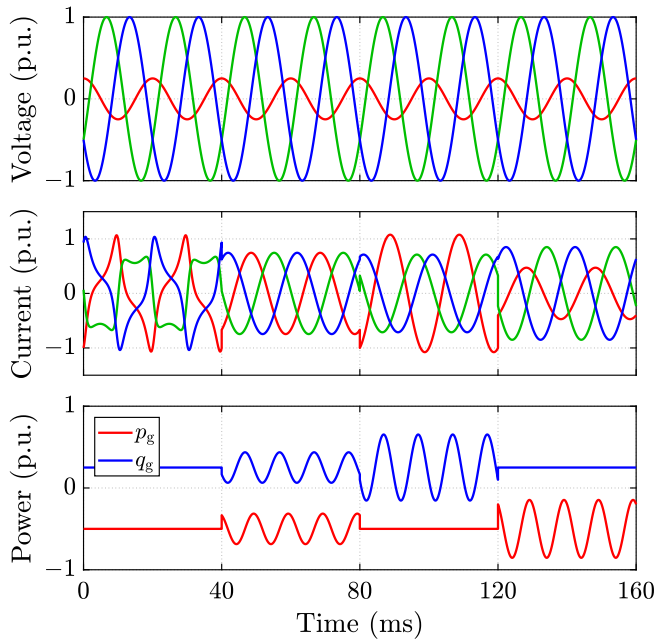# Instantaneous Active and Reactive Power in Unbalanced Conditions

$$\underline{u}_{\mathrm{g}} = \underline{u}_{\mathrm{g}+} + \underline{u}_{\mathrm{g}-} = u_{\mathrm{g}+}\mathrm{e}^{\mathrm{j}(\omega_{\mathrm{g}}t+\phi_{\mathrm{u}+})} + u_{\mathrm{g}-}\mathrm{e}^{-\mathrm{j}(\omega_{\mathrm{g}}t+\phi_{\mathrm{u}-})}$$

$$\underline{i}_{\mathrm{g}} = \underline{i}_{\mathrm{g}+} + \underline{i}_{\mathrm{g}-} = i_{\mathrm{g}+}\mathrm{e}^{\mathrm{j}(\omega_{\mathrm{g}}t+\phi_{\mathrm{i}+})} + i_{\mathrm{g}-}\mathrm{e}^{-\mathrm{j}(\omega_{\mathrm{g}}t+\phi_{\mathrm{i}-})}$$

▶ Complex power

$$\begin{aligned}
\underline{s}_{\mathrm{g}} &= \frac{3}{2}\underline{u}_{\mathrm{g}}\underline{i}_{\mathrm{g}}^{*} = \frac{3}{2}(\underline{u}_{\mathrm{g}+} + \underline{u}_{\mathrm{g}-})(\underline{i}_{\mathrm{g}+} + \underline{i}_{\mathrm{g}-})^{*}\\
&= \underbrace{\frac{3}{2}u_{\mathrm{g}+}i_{\mathrm{g}+}\mathrm{e}^{\mathrm{j}(\phi_{\mathrm{u}+}-\phi_{\mathrm{i}+})} + \frac{3}{2}u_{\mathrm{g}-}i_{\mathrm{g}-}\mathrm{e}^{\mathrm{j}(\phi_{\mathrm{i}-}-\phi_{\mathrm{u}-})}}_{\text{constant}}\\
&\quad + \underbrace{\frac{3}{2}u_{\mathrm{g}+}i_{\mathrm{g}-}\mathrm{e}^{\mathrm{j}(2\omega_{\mathrm{g}}t+\phi_{\mathrm{u}+}+\phi_{\mathrm{i}-})} + \frac{3}{2}u_{\mathrm{g}-}i_{\mathrm{g}+}\mathrm{e}^{-\mathrm{j}(2\omega_{\mathrm{g}}t+\phi_{\mathrm{u}-}+\phi_{\mathrm{i}+})}}_{\text{oscillating}}
\end{aligned}$$

▶ Active power $p_{\mathrm{g}} = \mathrm{Re}\{\underline{s}_{\mathrm{g}}\}$ and reactive power $q_{\mathrm{g}} = \mathrm{Im}\{\underline{s}_{\mathrm{g}}\}$ oscillate at $2\omega_{\mathrm{g}}$
▶ Oscillations from p_{g} or q_{g} can be eliminated with proper control of $\underline{i}_{\mathrm{g}-}$

Consequences of Unbalanced Grid Conditions in Control

▶ Control is often synchronized with the grid-voltage vector

▶ Phase-locked loop (PLL) is used for tracking the vector

▶ PLL is designed to estimate positive and negative sequence components (instead of the oscillating magnitude, angle, and frequency)

▶ For controlling the instantaneous active and reactive powers, the converter should be able to inject and control positive- and negative-sequence currents
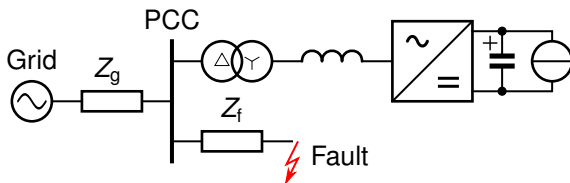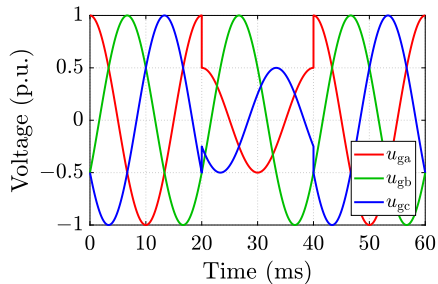
Outline

Grid Faults

▶ Balanced: 3-phase faults (e.g. voltage dips and swells)
▶ Unbalanced: 1-phase and 2-phase faults
  (e.g. line-to-ground and line-to-line short circuits)
▶ Fault seen by the converter depends also on the impedances Z_g and Z_f
▶ Phase angle jumps are possible
▶ Transformers between the fault and the converter may affect the voltage dip
  seen by the converter

Example of an Unbalanced Fault

- 2-phase voltage dip as an example
- Dashed line shows the pre-fault voltage vector locus
- Negative-sequence and zero-sequence components appear during the fault

Outline

Harmonic-Producing Loads
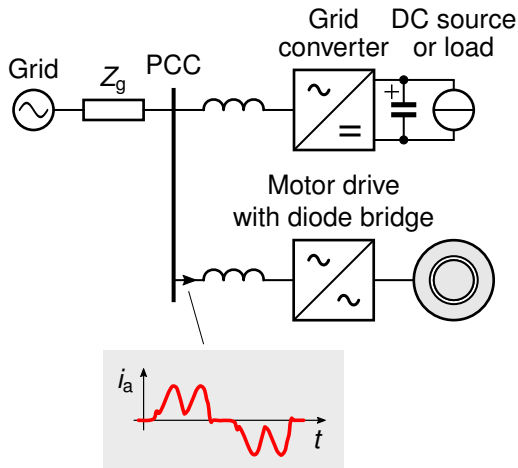
- Examples of high-power nonlinear loads
  - Diode and thyristor bridges
  - Cycloconverters
  - Arc furnaces
- Nonlinear loads draw nonsinusoidal currents from the grid
- Nonsinusoidal currents together with the nonzero grid impedance Z_g cause the PCC voltage to distort
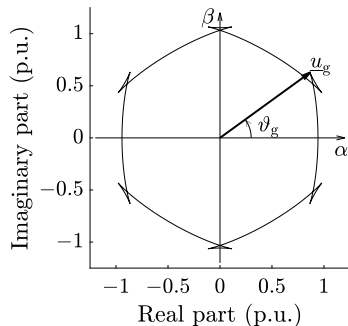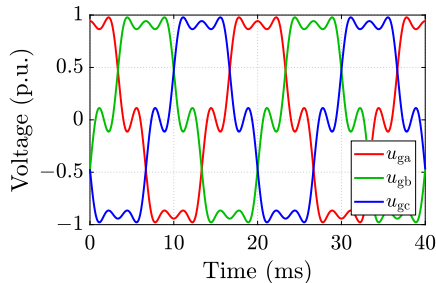
Distorted Phase Voltages

- Example case: voltage u_{ga} with harmonics

$$u_{ga}(t) = u_g \cos(\omega_g t) \\ - (u_g/5) \cos(5\omega_g t) + (u_g/7) \cos(7\omega_g t)$$

- Voltages u_{gb} and u_{gc} are shifted in phase
- Magnitude and rotation speed of the corresponding space vector are pulsating

For illustration purposes, this example case has unrealistically large harmonic content. Typically the maximum THD of the PCC voltage should be below 5%.
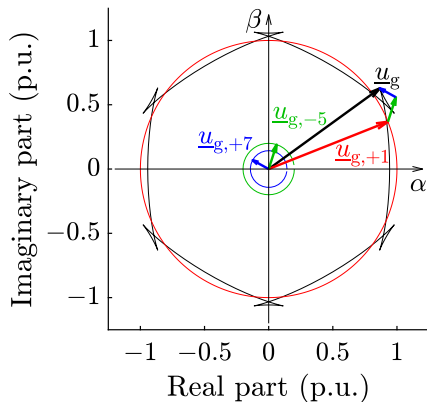
Distorted Voltage Space Vector

▶ Distorted voltage vector

$$\underline{u}_{\mathrm{g}}(t) = \sum_m \underline{u}_{\mathrm{g},m}(t) = u_{\mathrm{g},m}\mathrm{e}^{\mathrm{j}(m\omega_{\mathrm{g}}t+\phi_m)}$$

▶ Typical harmonics

$$m = \pm 6n + 1, \quad n = 1, 2, \ldots$$

▶ Components rotate counterclockwise for $m > 0$ and clockwise for $m < 0$

▶ $m = \pm 1 \quad \Rightarrow \quad$ fundamental frequencies

Consequences of Harmonics in Control

- ▶ PLLs are designed to estimate fundamental frequency components and to reject harmonic-frequency components
- ▶ Impact of the grid-voltage harmonics on the total harmonic distortion (THD) is reduced by proper design of the current (or power) control
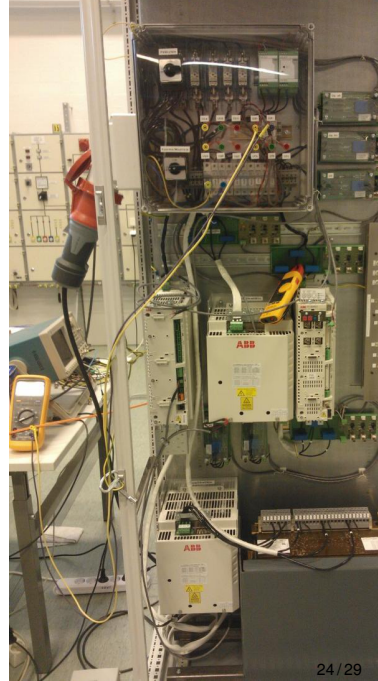- ▶ Harmonic components may cause oscillations in the active and reactive power

Outline

Experimental Setup

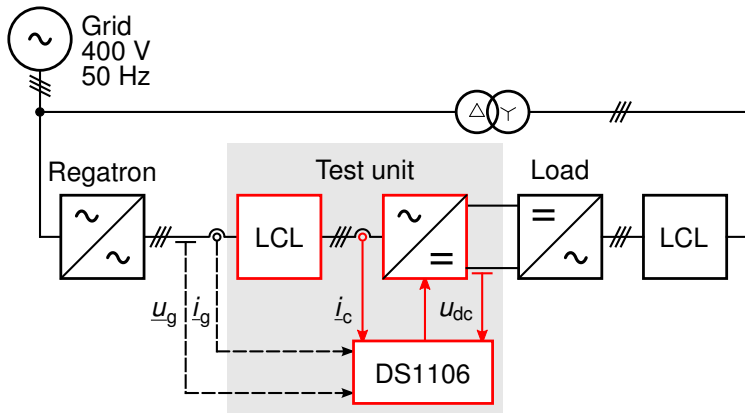- 12.5-kVA test converter
- 50-kVA 4-quadrant power supply (Regatron) for generating grid-voltage disturbances

4-Quadrant 3-Phase Power Source: Regatron

Output:
- Power: $0 \ldots 50$ kVA
- Voltage: $0 \ldots 280$ Vrms (L-N)
- Current: $0 \ldots 72$ A
- Frequency: $0 \ldots 1000$ Hz
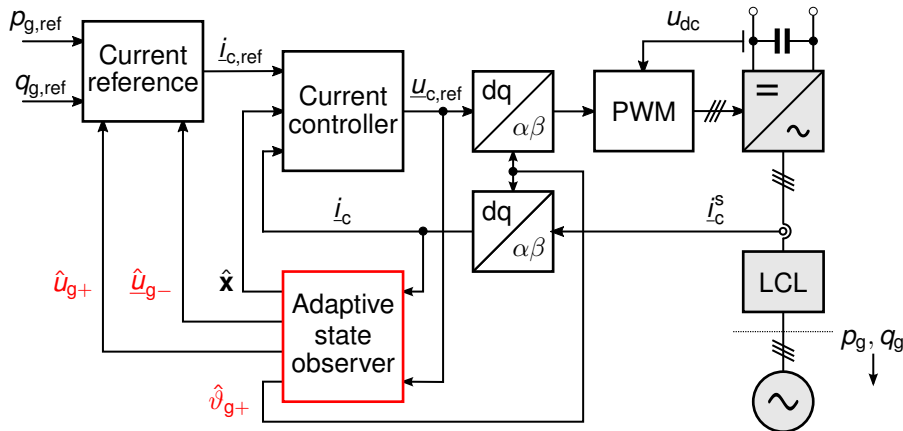- Frequency (full power): $16 \ldots 1000$ Hz

Operation modes:
- Voltage amplifier
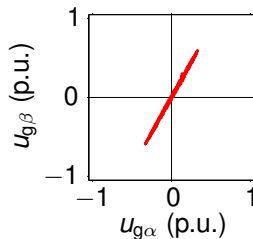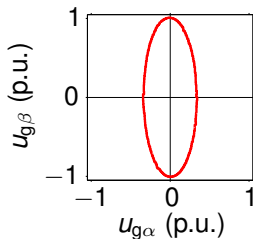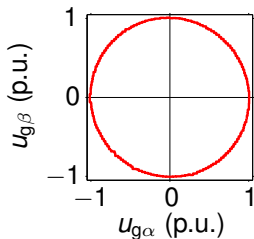- Grid simulator

Weight: 330 kg

Grid-Voltage Sensorless Control System

- ► Controller operates in positive-sequence grid-voltage coordinates
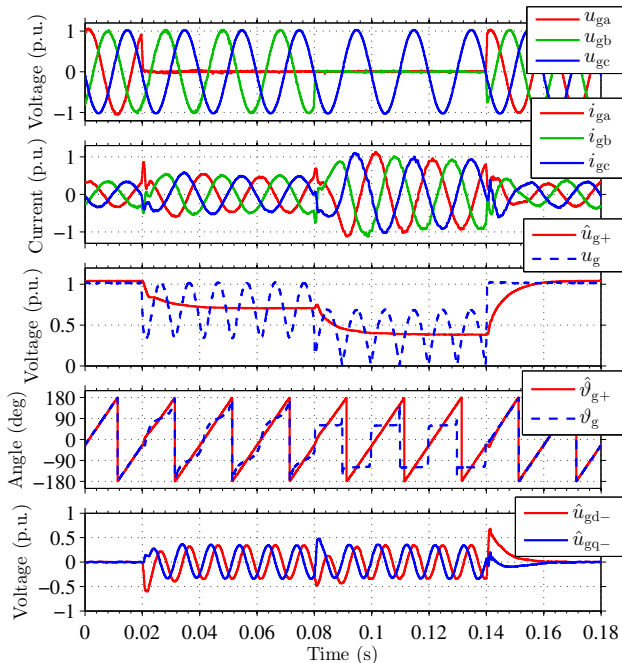- ► State-feedback current controller (damps also the LCL resonance)

Experimental Results: 1-Phase and 2-Phase Voltage Dips

▶ Grid-voltage sensorless control scheme is tested in three grid conditions
  1. Balanced grid
  2. Single-phase voltage dip down to zero
  3. Two-phase voltage dip down to zero

▶ Converter supplies the power of 0.3 p.u. to the grid

Grid voltages (abc)

Grid currents (abc)

Magnitude of the grid-voltage vector and estimated magnitude of the positive-sequence component

Angle of the grid-voltage vector and estimated angle of the positive-sequence component

Estimated negative-sequence grid-voltage component

Further Reading

▶ F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Pliant active and reactive power control for grid-interactive converters under unbalanced voltage dips," *IEEE Trans. Pow. Electron.*, vol. 26, 2011.

▶ H. Akagi, E. H. Watanabe, and M. Aredes, "Instantaneous power theory and applications to power conditioning," 2nd ed., Wiley, 2017.

▶ J. Kukkola and M. Hinkkanen, "State observer for grid-voltage sensorless control of a converter under unbalanced conditions," *IEEE Trans. Ind. Appl.*, vol. 54, 2018.