Grid-forming inverters in power grids

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Agenda

- Introduction
- Control of grid-forming inverters
- Grid impedance estimation
- Practical tests
- Conclusion
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Introduction

- "Grid-forming" means that an operating device participates actively on forming the grid voltage.
- Grid-forming inverters act as voltage sources.
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Introduction

- A high penetration of grid-forming inverters is inherently system stabilizing.

\[
\begin{align*}
f &= f_0 - k_p \cdot (P - P_0) \\
U &= U_0 - k_q \cdot (Q - Q_0)
\end{align*}
\]
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Introduction

- A high penetration of grid-forming inverters is inherently system stabilizing.

This approach can cover:

- Virtual inertia
- Uninterruptable power supply
- Black start capability…
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Control - challenge

\[ Z_k = R_k + j\omega L_k \]

\[ P = \frac{L_k s + R_k}{(L_k s + R_k)^2 + (\omega L_k)^2} (U^2 - U E_0 \cos \delta) - \frac{\omega L_k}{(L_k s + R_k)^2 + (\omega L_k)^2} U E_0 \sin \delta \]

\[ Q = \frac{\omega L_k}{(L_k s + R_k)^2 + (\omega L_k)^2} (U^2 - U E_0 \cos \delta) + \frac{L_k s + R_k}{(L_k s + R_k)^2 + (\omega L_k)^2} U E_0 \sin \delta \]

Difficulty: distribution grid

- angle/frequency deviation results in reactive power flow.
- Arbitrary spatial distribution
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Control - proposed algorithm

Feedback matrix $\mathbf{F}$

- $k_p$, $k_q$ reflect the droops
- angle feedforward: improve stability and transient behavior ($k_p'$, $k_q'$)

$$k_p = \frac{\Delta f}{P_{\text{max}}} \quad k_q = \frac{\Delta U}{Q_{\text{max}}}$$
With a higher resistive grid impedance the parameter $k_q'$ gets more relevance (here $L_k = 1 \text{ mH}$, $R_k = 0.4 \Omega$).
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Impedance estimation

- Active method with interharmonic injection (40 Hz, 60 Hz)
- Referenced resistance change to 174.2 mΩ
- Estimated value amounts 176 mΩ
- Accuracy around 1%

<table>
<thead>
<tr>
<th>before change</th>
<th>after change</th>
</tr>
</thead>
<tbody>
<tr>
<td>resistive [mΩ]</td>
<td>inductive [mH]</td>
</tr>
<tr>
<td>505.7</td>
<td>1.357</td>
</tr>
<tr>
<td>506.1</td>
<td>1.352</td>
</tr>
<tr>
<td>501.4</td>
<td>1.353</td>
</tr>
</tbody>
</table>
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Experimental results – voltage step

- Voltage step from 230 V\text{eff} to 245 V\text{eff} and back
- Grid impedance (0.345 $\Omega$, filter)
- Smooth settling with double angle feedforward
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Experimental results – frequency step

- Frequency step from 50 Hz to 49.5 Hz and back
- Smooth settling
- Instantaneous reaction
Conclusion

- **Grid-forming** inverters are inherently system stabilizing with regard to the power grid control.

- **Improved** control behavior due to the angle feedforward

- For an optimal controller design an impedance estimation tool was applied.