Unlocking the Hidden Capacity of the Electrical Grid through Power Electronics

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Outline

✓ Unlocking the hidden capacity of the el. grid through power electronics:
  ✓ in the distribution through Smart Transformer
  ✓ in the transmission through HVDC with voltage control

✓ Integrating power electronics into the electrical grid:
  ✓ Grid following operation: impedance detection and correct PLL modelling
  ✓ Grid forming operation: facing weak and low inertia grid challenges
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Goal: To make electric grids more sustainable and intelligent by means of power electronics-based transformer, mostly in view of the mobility electrification.

Realization: Investigation and development of a highly efficient and reliable Smart Transformer that allows DC connection and offers grid services, with the goal to defer or avoid grid infrastructure upgrade.

Project Volume: 2 Mio. € (ERC Grant)
LV-Engine Project Overview

• Releases capacity within existing LV network for connection of future LCT generation and load prior to costly reinforcement.

• Provides distribution network with increased flexibility and adaptability to cope with uncertainties in how energy will be generated and consumed.

• Significant reduction in 11kV/LV network reinforcement caused by the uptake of LCTs & electrification of heat & transport sectors.

• Lay ground works for future LVDC network reducing customer losses (avoided losses of ~£100m annually by 2040 in EV charging)

Financial Savings:

• £62m by 2030
• £528m by 2050
• 16% of GBs 11kV/LV GM subs by 2050

Carbon Savings:

• 523 kt.CO₂ by 2030
• 2,032 kt.CO₂ by 2050

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The Smart Transformer

Smart control

Infinite solutions to be
Meshed Grid Operation

✓ Meshed 1: at LV ac bus
✓ Meshed 2: the terminal of LV ac feeders
✓ Meshed 3: LV dc and LV ac-1
✓ Meshed 4: LV dc and LV ac-2
Meshed Grid Operation

ST Achievements in:

b) High DG penetration
c) High load demand
d) Combined High DG and high load demands

Grid Assets update can be deferred, further changes in the production/consumption can be dynamically accommodated with light infrastructures.
ST-based load control: Real Time Frequency Regulation service

Real Time Frequency Regulation: Irish test case

Impact on the Irish system

Max Wind penetration
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Frequency support provision by HVDC systems

- Power variation in Area 1 ≈10% total load
- The HVDC can work at constant power
  - Large frequency variation in Area 1
  - No frequency variation in Area 2
- The HVDC can provide frequency support
  - Reduced frequency drop in Area 1
  - Area 2 sees a frequency deviation
1. Terminal 2 identifies load sensitivity (e.g., every 15 minutes)

\[ K_p = \frac{P_L(t_k) - P_L(t_{k-1})}{P_L(t_{k-1})} \cdot \frac{V_L(t_k) - V_L(t_{k-1})}{V_L(t_{k-1})} \]

2. Terminal 1 measures a frequency variation

3. Terminal 2 varies the load voltage to extract the same amount of energy needed to support frequency in Area 1

\[ \frac{\Delta V_L}{V_0} = \frac{\Delta P_1}{P_L K_p} \]
ENSURE: Neue EnergieNetzStruktURen für die Energiewende

- **Goal:** Development of solutions for optimal operations of the future German grid in scenarios with high integration of RES.

- **Realization:** Holistic, systematic approach for analyzing new grid topologies and control, and for integrating new technologies in the supply system.

- **Project Volume:** 40 Mio. € (Total), 600.000 € (CAU budget)

- **Partner:** 23 (Universities, Industries, Grid operators, Civil Societies)
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EEMSWEA: Mittelspannungsnetzanalyse

- **Ziel:** Analyse der elektrischen Eigenschaften von Mittelspannungsnetzen in Hinsicht auf eine Optimierung bei hoher Einspeisung aus Windenergieanlagen und Verbesserung der Oberschwingungsbelastung

- **Realisierung:** Entwicklung eines mobilen Mess- und Analysesystems zur Einspeisung harmonischer Ströme und zur Messung der Netzimpedanz

- **Projektvolumen:** 3.8 Mio. €
  2.9 Mio. € (CAU)
Night: resonance at 1.8 kHz with a magnitude $|Z_g|=1.3\,\Omega$ and capacitive phase angle in a frequency range between 1.6kHz and 4.8kHz;

Day: the magnitude at 1.8 kHz is $|Z_g|=0.5\,\Omega$ due to the changing operation of loads and generators by the grid customers.
Resonance Identification

- By using time-domain data, the transfer function of impedance can be obtained by vector fitting method;
- The main idea is to use a rational function to approximate poles \( \{a_m\} \);

\[
f(s) = \sum_{m=1}^{N} \frac{r_m}{s - a_m} + d + es
\]

\(N\) is the approximation order, \(d\) and \(e\) are optional for the rational function.

An example of measured & estimated grid impedance in German grid.

- [Graph showing measured and estimated grid impedance.]
DFG-Schwerpunktprogramm: Stabilitätsbewertung von hybriden Stromnetzen

- **Ziel:** Formal evaluation of the stability of hybrid power electronics-based grids

- **Realization:** Development of accurate model and stability criteria for converter-based grids, considering the impact of the grid synchronization.

- **Project Volume:** 330,000 € (DFG-funded)

- **Partner:** EPFL (Lausanne, Switzerland)
Accurate modeling of the grid synchronization of converters through PLL

PLL-synchronized Power Converter

Impact of higher accurate modeling of the PLL in the stability analysis

Instabiles Umrichterverhalten nach einem Phasensprung

Small Signal Model (1. Order)

Higher accurate model (2. Order)
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Grid-forming operation

- Industrial PhD in collaboration with the wind turbine manufacture ENERCON GmbH on the topic “converter control strategies for applications in grids with high power-electronics based generation”

- Behaviour of grid-forming converters and conceptual differences compared to state of the art grid-following units are investigated
✓ Results of small-signal stability analysis show the limitations of grid-following converters caused by their synchronization units when operating under weak grid conditions.

✓ A Monte-Carlo based analysis shows that under such operating conditions, not only the stability margin of the converter is decreased, but the interactions between synchronization units of converters operating nearby become stronger.
Robust stability of grid-forming converters has been investigated by means of $\mu$-analysis.

It requires the state-space representation of the control and of the plant, obtained adopting the component connection method (CCM).

The CCM for state-space representation of a complex system:

- Decomposition in separated subsystems with known state-space representation
- Interconnection matrices describe the connections between inputs and outputs of the subsystems

\[
\begin{align*}
\dot{x}_{\text{plant}} &= F_{\text{int}} x_{\text{plant}} + G_{\text{int}} u_{\text{plant}} \\
y_{\text{plant}} &= H_{\text{int}} x_{\text{plant}} + J_{\text{int}} u_{\text{plant}}
\end{align*}
\]

\[
\begin{align*}
F_{\text{int}} &= A_d + B_d (I - D_d L_{11})^{-1} C_d \\
G_{\text{int}} &= B_d L_{11} (I - D_d L_{11})^{-1} D_d L_{12} + B_d L_{12} \\
H_{\text{int}} &= B_d L_{21} (I - D_d L_{11})^{-1} C_d \\
J_{\text{int}} &= L_{21} (I - D_d L_{11})^{-1} D_d L_{12} + L_{22}
\end{align*}
\]

\[
\begin{align*}
A_d &= \text{diag}(A_{\text{sub}1}, A_{\text{sub}2}, \ldots, A_{\text{subn}}) \\
B_d &= \text{diag}(B_{\text{sub}1}, B_{\text{sub}2}, \ldots, B_{\text{subn}}) \\
C_d &= \text{diag}(C_{\text{sub}1}, C_{\text{sub}2}, \ldots, C_{\text{subn}}) \\
A_d &= \text{diag}(A_{\text{sub}1}, A_{\text{sub}2}, \ldots, A_{\text{subn}})
\end{align*}
\]
The μ-analysis allows the calculation of a stability margin of a controller for a MIMO system by defining an uncertainty set affecting the plant.
Grid-forming operation

Robust stability analysis of a LCL filter based synchronverter connected to the grid

- Effects of parameter variations on robust stability of a synchronverter have been investigated
- Following conclusions can be drawn:
  - Increase of virtual inertia $J$ does not necessarily correspond to an increase of the robust stability (if damping is not increased accordingly)
  - Robust stability against the defined set of high frequency uncertainties is augmented by the presence of high impedance between the converter and the grid

Conclusions

✓ Real-time services offered by Power Electronics:
  ✓ Smart Transformer: avoid or delay network reinforcement
  ✓ HVDC: offer service to the AC network

✓ Integration of Power Electronics into the grid:
  ✓ Grid Following: identify the electric grid impedance and modelling correctly the PLL
  ✓ Grid forming operation may reinforce the system stability