MIGRATE : MASSIVE INTEGRATION OF POWER ELECTRONICS DEVICE.

WP3 DISSEMINATION WORKSHOP

Lille
October 16th
Welcome to ENSAM.

Thanks to all of you for attending this event.

Thanks to ENSAM and L2EP for hosting this event.
AN OVERVIEW

- EU funded project (Horizon 2020)
- Started on January 1st of 2016, and will end December 31 of 2019.
- 11 TSO
- 12 universities
- 1 manufacturer
• 5 technical Work Packages

- **WP1**
  Power System stability issues under high penetration of PE

- **WP2**
  Real Time Monitoring and Control

- **WP3** (Highlighted)
  Control and operation of a grid with 100% converter based devices

- **WP4**
  Protection schemes in transmission networks with high PE penetration

- **WP5**
  Power quality in transmission networks with high PE penetration
WHY WP3?

What if there is nothing to “follow”?
Inverters (at least some of them) need to be “grid forming”, they have to create the voltage waveform on their own.

Synchronous machines create voltage waveforms with the same frequency.
Converters measure the grid frequency.
Converters provide active and reactive power at the measured frequency.

Is inertia a real need? And what is inertia?
## ON THE MENU: (TODAY)

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<td>14h</td>
<td>Introduction to WP3</td>
<td>Room Tresca</td>
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<td><strong>Presentation of achieved work</strong></td>
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<tr>
<td>14h15</td>
<td>Local control of grid forming inverter and model order reduction for 100% power electronic power systems</td>
<td>L2EP Room Tresca</td>
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<tr>
<td>15h25</td>
<td>Towards a 100% power electronics system: grid-forming control and system-level analysis</td>
<td>ETHZ Room Tresca</td>
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<td>16h00</td>
<td>Grid-following control and fast frequency regulation in low-inertia systems</td>
<td>ETHZ Room Tresca</td>
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<td>16h35</td>
<td>Operation of the Irish grid without synchronous machine</td>
<td>UCD Room Tresca</td>
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<td>17h15</td>
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<td>17h35</td>
<td>Requirement guideline for grid codes</td>
<td>RTE Room Tresca</td>
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<td>20h</td>
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**ON THE MENU: (TOMORROW)**

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• Enjoy this event!

• For more information:

  https://www.h2020-migrate.eu/downloads.html

• All papers and deliverables are freely accessible
Local control of grid forming inverter and model order reduction for 100% power electronic power systems

F. COLAS, X. GUILLAUD, T. QORIA, Q. COSSART
Power electronic converters are becoming more and more important in the transmission system.

The VSC is placed between an AC grid and DC grid.

The control has to take into account:

1. The interest of VSC owner
2. The AC grid services
3. The DC grid (or the source connected on the DC grid) constraints
In case 1 and 2, the first aim of the converter is to exchange some active power $P$ between the AC and DC grid.

1. A reference for this power has to be clearly identified $P^*$
2. The dynamic of the power controlled has to be addressed

In case 3, the power is exchanged between the AC grid and the storage element but the average value of the power is used to provide the losses of the converter.
**AC system services.**

a) Frequency support:

b) Inertial support

c) Management of the reactive power: The source can support the voltage at its point of common connection or follow a reactive power reference

**DC grid (or the source connected on the DC grid) constraints**

a) Small variation on the DC bus voltage ( +/- 0.05 pu)

b) Possibility to limit the frequency support to a given level of power.
Assumptions

- In a transmission system, the resistance can be neglected.
- The connection impedance is quite high: (0.06 to 0.15 pu). Most of the time, it is the leakage inductance of the connection transformer.

This inductance plays a crucial role in the stability analysis.
The following assumptions are made.

• The grid operates in three-phase balanced conditions.
• The following analyses are valid as long as the converter doesn’t reach its physical limitations (current or voltage)

• Model in per unit
  • base power \( P_b \) = nominal active power of the converter
  • base voltage \( V_b \) = nominal voltage of the grid
  • base angular frequency \( \omega_b \) = nominal angular frequency of the grid.
Generic considerations on power electronic converters

Two main types of connection to the grid

R,L connection

LCL connection

In the beginning of presentation, only the R,L connection is presented but all the conclusions of the analysis will be extended with some minor adaptations to the LCL connection.

Note: index ‘m’ stands for ‘modulated’: \( v_m \) : modulated voltage by the converter
Fundamental thinkings on the grid forming control
Fundamental thoughts on the grid forming control

The principle of the active power control is based on a quasi static model:

\[ \bar{V}_m = V_m e^{j\theta_m} \quad \bar{V}_g = V_g e^{j\theta_g} \]

From this static model, the principle of power control can be deduced:

\[ P \approx \frac{V_m V_g}{X} \sin(\theta_m - \theta_g) = \frac{V_m V_g}{X} \sin(\psi) \]

\[ \psi = \theta_m - \theta_g \]
Fundamental thinking on the grid forming control

\[
\begin{align*}
\bar{V}_m &= V_m e^{j \theta_m} \\
\bar{V}_g &= V_g e^{j \theta_g}
\end{align*}
\]

From this static model, the principle of power control can be deduced:

\[
P \approx \frac{V_m V_g}{X} \sin(\theta_m - \theta_g) = \frac{V_m V_g}{X} \sin(\psi)
\]

\[
\psi = \theta_m - \theta_g
\]
Power control by the current: grid feeding control

The control of an actual converter takes place in the time domain.

Need to switch from phasor domain to time domain.

\[
\overline{I} = Ie^{j(\theta_g - \varphi)}
\]

\[
\overline{V}_m = V_m e^{j\theta_m}
\]

\[
\overline{V}_g = V_g e^{j\theta_g}
\]

\[
v_m = V_m \sqrt{2} \cos(\omega_m t + \theta_m)
\]

\[
v_g = V_g \sqrt{2} \cos(\omega_g t + \theta_g)
\]

\[
v_m = V_m \sqrt{2} \cos(\delta_m)
\]

\[
v_g = V_g \sqrt{2} \cos(\delta_g)
\]

In steady state: \(\omega_m = \omega_g\)

<table>
<thead>
<tr>
<th>phasor angle</th>
<th>time domain angle</th>
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<tbody>
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<td>(\theta_g)</td>
<td>(\delta_g = \omega_g t + \theta_g)</td>
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<tr>
<td>(\theta_m)</td>
<td>(\delta_m = \omega_m t + \theta_m)</td>
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</table>
To have an accurate power control, an estimate of the grid angle ($\tilde{\delta}_g$) is needed.
In steady state $\psi_{ref}$ is constant. If an integrator is added in the control then: \[ P = P^* \]

A filter is added on the power. It yields to a possible control scheme.
Fundamental thoughts on the grid forming control

From this first scheme, two other schemes may be defined:

An estimate of the grid frequency is used in the control.

A fixed frequency is used in the control.
In steady state: \( \omega_m = \omega_g \quad \tilde{\omega}_g = \omega_g \)

Then: 
\[ \Delta \omega = 0 \quad P = P^* \]

In steady state: \( \omega_m = \omega_g \)

Then: 
\[ \Delta \omega = \omega_g - \omega_{gn} \]

\[ P = P^* + \frac{1}{m_p} (\omega_g - \omega_{gn}) \]
Short analysis on scheme A and scheme B

For both schemes, it is possible to add an outer loop for the frequency support. It is also possible to limit the participation of the converter to the frequency support.

$m_p$ can be adjusted with respect to the dynamic of the power loop.

$R$ is linked with the frequency droop control and load sharing in case of a frequency support.
Short analysis on scheme B

Scheme B is equivalent to a VSM/VSG formulation with

\[ 2H = \frac{1}{m_p \omega_c} \]
\[ K = \frac{1}{m_p} \]

Scheme B brings an inertial effect which depends on \( \omega_c \) and \( m_p \)
When \( H \) is chosen, it is possible to adjust \( m_p \) and \( \omega_c \) to get a desired dynamics for the power loop
This is the classical droop relation of speed governors for synchronous generators

With this scheme:

- $m_p$ is associated with the droop control and cannot be used to stabilize the power loop any more.
- $\omega_c$ is associated with the inertial effect

For certain values of $H$, the system may be poorly damped. It may be needed to add a derivative effect on the power to stabilize the loop

It is not possible to limit the power devoted to the frequency support as in scheme B
Practical implementation of the grid forming control
Practical implementation of the grid forming control

The AVR defines the magnitude of the voltage.

The grid angle is defined by one of the 3 schemes.

An inverse Park transformation defines the modulated voltage.

Calculation of the modulated voltage reference.

Voltage Regulator

P, Q, V calculation

v, i

P

Q

V

v_mdl_ref

v_mqr_ref = 0

Scheme A, B or C

Calculation of the modulated voltage reference

Inverse Park Transformation

\[ v_{m\text{ ref}} = \text{Inverse Park Transformation} \]

\[ P, Q, V \text{ calculation} \]

Low level control

\[ \delta_{m\text{ ref}} \]

\[ v_{m\text{ ref}} \]

P

P*

V*

\[ \text{Instantaneous value control} \]
Practical implementation of the grid forming control

\[ P \approx \frac{V_m V_g}{X} \sin(\theta_m - \theta_g) \]

is a quasi static model for the active power.

This is a second order dynamic system with extremely low damping.

Transfer function \[ T_{p\delta}(s) \]

Active power after a step on the angle.

A transient damping resistance is needed in the control.
Practical implementation of the grid forming control

- **P, Q, V calculation**
- **Voltage Regulator**
  - $V$, $i$
  - $v_{md\,ref}$, $v_{mq\,ref} = 0$
- **Scheme A, B or C**
  - Calculation of the modulated voltage reference
- **P, Q, V calculation**
  - $V$, $Q$, $P$
  - $v_{md\,ref}$
- **Inverse Park Transformation**
  - $P$, $Q$, $V$ calculation
- **Park Transformation**
  - $s\,\omega_{fyr}$
  - $1 + s\,\omega_{fyr}$
- **Instantaneous value control**
  - $v_{m\,ref}$
- **Low level control**
  - $V^*$
  - $P^*$
Pole placement method or optimal control design for the current and voltage controllers.
Simulation results (Power step)

**Scheme A**: Let’s choose

The filter: \( \omega_c = 32 \text{ rad} / \text{s} \)

With this value: first order dominant pole. The choice of the gain is modifying the time response

300 ms: response time

The dynamic behaviour is nearly insensitive to the variation of SCR

A quasi static analysis can explain this result
Simulation results (Power step)

**Scheme C**: Let’s choose

A droop coefficient: \( m_p = 4\% \)

Inertial coefficient: \( H = 5s \)

Since \( 2H = \frac{1}{m_p \omega_c} \), \( \omega_c = 2.5 \text{ rad/s} \)

A derivative action is needed on the active power to stabilize the loop

The dynamic behaviour is sensitive to the variation of SCR

A quasi static analysis can also explain this result since the gain of the closed loop system is linked with the SCR.
Simulation results (Power step)

**Scheme B**: Let’s choose

An inertial coefficient: \( H = 5s \)

Since \( 2H = \frac{1}{m_p \omega_c} \)

An infinite choice for the parameters \( \omega_c, m_p \)

For a smaller value of \( m_p \), the system is slower

For a larger value of \( m_p \), the system is less damped

As for Scheme C, the dynamics is sensitive to the SCR. In any case, the system stays stable.
Simulation results (Inertial effect and load sharing)

The aim of these simulations is to study:
- Evaluate the inertial effect of each control during load change
- The active power dynamics

PE characteristics:
- Rated power $P = 1\text{GW}$ for both VSCs
- $E_g = 320\ \text{kV \ ph-ph}$
- $P_{load0} = 50\text{MW}$
Simulation results (Inertial effect and load sharing)

Load change at $t = 5s$ with low inertia effect:

**Strategy C**

$P_0 = 50\, MW$

**Strategy A**

$P_0 = 0\, MW$

Control parameters:

- $H_{VSC\_1} = 3s$
- $Tr_{PLL} = 50\, ms$

Active power regulation in SS

Small inertia
**Simulation results (Inertial effect and load sharing)**

Load change at $t = 5s$ with more inertia effect:

**Strategy C**

- $P_0 = 50$ MW
- Control parameters:
  - $H_{VSC_1} = 3s$, $H_{VSC_2} = 3s$
  - $Tr_{PLL} = 50ms$

No frequency support:

**Strategy B**

- $P_0 = 0$ MW

Graphs showing active power and frequency responses for Converter 1 and Converter 2.
Simulation results (Inertial effect and load sharing)

Load change at \( t = 5s \) with more inertia effect:

- **Strategy C**
  - \( P_0 = 50 \text{ MW} \)
  - Control parameters:
    - \( H_{VSC\_1} = 3s \)
    - \( H_{VSC\_2} = 3s \)
    - \( Tr_{PLL} = 50 \text{ms} \)

- **Strategy B**
  - \( P_0 = 0 \text{ MW} \)

No frequency support:

- Load sharing
- Active power [p.u.]
- Frequency [p.u.]
It is possible to define 3 main schemes for droop control

Schemes A and B provide an accurate power control in steady state. Possibility to have an outer loop for the frequency support and to limit the amount of power which support the frequency

Schemes B and C provide an inertial effect

**Schemes B gathers all the properties**

Schemes B and C are sensitive to variation of SCR but stay stable in any case

After testing the control around a normal operating point, the behavior of grid forming control has to be analyzed
Current limitation algorithms
Current limitation in a grid forming converter

Since the grid forming converter is a voltage source, a current limitation has to be implemented to protect it against various events on the grid.

### Short circuit
Connection of a load close to the grid forming converter
Tripping of a line close to the grid forming converter

Three possible solutions:

- Switching to grid following control with a current loop
- Keeping the grid forming control and current saturation
- Keeping the grid forming control and introducing a virtual inductance
Current limitation in a grid forming converter

Current Saturation Algorithm

Virtual Impedance

Linearization

Current Control

Voltage Control

Primary Control
An anti windup has to be implemented in the voltage controller

$$\begin{align*}
|i_{sd}^*| &= m_i n(I_{max_{SAT}}, |i_{sq}^*|) \\
|i_{sq}^*| &= m_i n(\sqrt{I_{max_{SAT}}^2 - i_{sd}^*^2}, |i_{sq}^*|)
\end{align*}$$
The parameters are chosen to obtain a magnitude of $I_{\text{max}}$ in case of a bolted short-circuit.
Current limitation in a grid forming converter
Current limitation in a grid forming converter

The CSA limits the current to $I_{\text{max SAT}}$ whereas a large overcurrent is noticed with the virtual impedance

Self resynchronization for both limitation algorithms
Current limitation in a grid forming converter

Self resynchronization with the Virtual Inductance

Instability with CSA

Idea: Take advantage of the good properties of both controls by hybridization of the controls
Current limitation in a grid forming converter

Currently:
- work to improve the critical clearing time with grid forming converter

Future:
- Unbalanced fault

Hybrid Current Limitation Control
The droop control answers to the main requirements asked for control of a converter

- Clear power reference
- Possibility to support the frequency with a limited amount of power (Scheme B)
- Frequency Support
- Inertial Support with various value of inertia – possibility to have no inertia if needed

Study of the grid forming converter in case of current limitation

- Proposition of an Hybrid Current Limitation Control
Currently:
Work to increase the critical clearing time with grid forming converters

Future:
Unbalanced fault

Everything has been validated in experimentation
Local control of grid forming inverter and model order reduction for 100% power electronic power systems

F. COLAS, X. GUILLAUD, T. QORIA, Q. COSSART

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Illustrative example on the Irish grid simulation

- Power system description
  - 14 Generators
  - 47 Loads
  - 85 Lines
  - 40 Transformers
- Short-circuit simulation based on 2 classical tools
  - EMT
  - Phasor

How to obtain an accurate enough reduced order model?
Model Order Reduction: general principle

\[ \frac{dx_{\text{diff}}}{dt} = f(x_{\text{diff}}, x_{\text{alg}}, u) \]
\[ 0 = g(x_{\text{diff}}, x_{\text{alg}}, u) \]
\[ y = h(x_{\text{diff}}, x_{\text{alg}}, u) \]
\[ x_{\text{diff}} \in \mathbb{R}^{N_{\text{diff}}}, x_{\text{alg}} \in \mathbb{R}^{N_{\text{alg}}}, u \in \mathbb{R}^{p}, y \in \mathbb{R}^{q} \]

\[ \|y - y_r\| < \epsilon \]
\[ N_{\text{diff}_r} \ll N_{\text{diff}} \]

\[ \frac{dx_{\text{diff}_r}}{dt} = f_r(x_{\text{diff}_r}, x_{\text{alg}_r}, u) \]
\[ 0 = g_r(x_{\text{diff}_r}, x_{\text{alg}_r}, u) \]
\[ y_r = h_r(x_{\text{diff}_r}, x_{\text{alg}_r}, u) \]
\[ x_{\text{diff}_r} \in \mathbb{R}^{N_{\text{diff}_r}}, x_{\text{alg}_r} \in \mathbb{R}^{N_{\text{alg}_r}}, u \in \mathbb{R}^{p}, y_r \in \mathbb{R}^{q} \]
### Phasor approximation by state residualization:

\[
\frac{dx_{\text{diff}}}{dt} = f(x_{\text{diff}}, x_{\text{alg}}, u)
\]
\[
0 = g(x_{\text{diff}}, x_{\text{alg}}, u)
\]
\[
y = h(x_{\text{diff}}, x_{\text{alg}}, u)
\]
\[
x_{\text{diff}} \in \mathbb{R}^{N_{\text{diff}}}, x_{\text{alg}} \in \mathbb{R}^{N_{\text{alg}}}, u \in \mathbb{R}^p, y \in \mathbb{R}^q
\]

- **Residualization** of the states linked to the lines dynamics.

\[
\begin{align*}
\frac{L}{\omega_b} \frac{di_d}{dt} &= v_{1_d} - v_{2_d} - \frac{R_{i_d}}{\omega_b} i_d - \omega L i_q \\
\frac{L}{\omega_b} \frac{di_q}{dt} &= v_{1_q} - v_{2_q} - \frac{R_{i_q}}{\omega_b} i_q - \omega L i_d
\end{align*}
\]

\[
\|y - y_r\| < ?
\]
\[
tr(E) << N_{\text{diff}}
\]

\[
E \frac{dx_{\text{diff}_r}}{dt} = f(x_{\text{diff}_r}, x_{\text{alg}_r}, u)
\]
\[
0 = g(x_{\text{diff}_r}, x_{\text{alg}_r}, u)
\]
\[
y_r = h(x_{\text{diff}_r}, x_{\text{alg}_r}, u)
\]
\[
E = \text{diag}(\delta_i), \delta_i \in \{0; 1\}, \forall i, E \in \mathbb{R}^{N_{\text{diff}} \times N_{\text{diff}}}
\]
\[
x_{\text{diff}_r} \in \mathbb{R}^{N_{\text{diff}}}, x_{\text{alg}_r} \in \mathbb{R}^{N_{\text{alg}}}, u \in \mathbb{R}^p, y_r \in \mathbb{R}^q
\]
A lot of methods exist

\[
\begin{align*}
\frac{dx_{diff}}{dt} &= f(x_{diff}, x_{alg}, u) \\
0 &= g(x_{diff}, x_{alg}, u) \\
y &= h(x_{diff}, x_{alg}, u) \\
x_{diff} &\in \mathbb{R}^{N_{diff}}, x_{alg} \in \mathbb{R}^{N_{alg}}, u \in \mathbb{R}^{p}, y \in \mathbb{R}^{q}
\end{align*}
\]

\[
\begin{align*}
E \frac{dx_{diff}}{dt} &= f(x_{diff}, x_{alg}, u) \\
0 &= g(x_{diff}, x_{alg}, u) \\
y_r &= h(x_{diff}, x_{alg}, u) \\
E &= \text{diag}(\delta_i), \delta_i \in \{0; 1\}, \forall i \in \mathbb{R}^{N_{diff} \times N_{diff}} \\
x_{diff} &\in \mathbb{R}^{N_{diff}}, x_{alg} \in \mathbb{R}^{N_{alg}}, u \in \mathbb{R}^{p}, y_r \in \mathbb{R}^{q}
\end{align*}
\]

\[
\|y - y_r\| < ? \\
\text{tr}(E) << N_{diff}
\]

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<th>Applicability on nonlinear models</th>
<th>Variables preservation</th>
<th>Stability preservation</th>
<th>Bounded Error</th>
<th>Taking into account the simulated event and the observed variable</th>
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<td>Expected</td>
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Our proposal

- The proposed method is based on the residualization principle:

\[
\frac{dx_{diff}}{dt} = f(x_{diff}, x_{alg}, u) \\
0 = g(x_{diff}, x_{alg}, u) \\
y = h(x_{diff}, x_{alg}, u) \\
x_{diff} \in \mathbb{R}^{N_{diff}}, x_{alg} \in \mathbb{R}^{N_{alg}}, u \in \mathbb{R}^p, y \in \mathbb{R}^q
\]

Find the optimal \( E \) for a specific event

\[
\frac{dx_{diff}}{dt} = f(x_{diff}, x_{alg}, u) \\
0 = g(x_{diff}, x_{alg}, u) \\
y_{r} = h(x_{diff}, x_{alg}, u) \\
E = \text{diag}(\delta_i), \delta_i \in \{0; 1\}, \forall i, E \in \mathbb{R}^{N_{diff} \times N_{diff}} \\
x_{diff} \in \mathbb{R}^{N_{diff}}, x_{alg} \in \mathbb{R}^{N_{alg}}, u \in \mathbb{R}^p, y_{r} \in \mathbb{R}^q
\]

\[\|y - y_{r}\| < \epsilon\]

\[\text{tr}(E) \ll N_{diff}\]
Our proposal: steps description

- **Step 1**: Linearization of full model and reduced order model
  \[
  \begin{aligned}
  \frac{dx}{dt} &= Ax + Bu \\
  y &= Cx + Du \\
  x \in \mathbb{R}^{N_d, f}, u \in \mathbb{R}^p, y \in \mathbb{R}^q \\
  \end{aligned}
  \]
  \[
  \begin{aligned}
  E \frac{dx_r}{dt} &= Ax_r + Bu \\
  y_r &= Cx_r + Du \\
  x \in \mathbb{R}^{N_{d, f}}, u \in \mathbb{R}^p, y \in \mathbb{R}^q \\
  \end{aligned}
  \]

- **Step 2**: Participation factors study to obtain group of states which can be residualised together

- **Step 3**: Error computation for a specific event
  \[
  \epsilon_{i,j} = \int_{-\infty}^{\infty} |\epsilon_{i,j}(\omega)|^2 d\omega
  \]

- **Step 4**: Optimal problem resolution
  \[
  \begin{aligned}
  \min_E \epsilon_{i,j} &= \int_{-\infty}^{\infty} |\epsilon_{i,j}(\omega)|^2 d\omega \\
  \text{s.c. } E \in \mathbb{E}_{\epsilon_{\text{part}}}, \text{ tr}(E) \leq n
  \end{aligned}
  \]
Application on the Irish grid: short-circuit simulation

- All the generators have been replaced by grid forming inverters

- Event:
  - Short-circuit in Shellybanks
  - Visualization of a converter output current connected in Dunstown
• All the generators have been replaced by grid forming inverters

• Event:
  – Short-circuit in Shellybanks
  – Visualization of a converter output current connected in Dunstown

• Reduced order zone identification

<table>
<thead>
<tr>
<th>Converter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<td>Order (strategy 3)</td>
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Simulation Time (min)
Conclusion and perspectives

✓ Conclusion

→ A new MOR method:
  ▪ That is applicable to nonlinear models.
  ▪ That preserves the physical variables of the system.
  ▪ That is easily applicable.
  ▪ That adapts to the observed variable and the simulated event.
  ▪ That gives better results than the classically used phasor approximation.

✓ Perspectives

→ Application on more complex models (more detailed lines, unbalanced models, larger transmission systems).

→ Changing the models during the simulation when several events are simulated.

→ Choice of the desired size for the reduced model.

→ Nonlinear approach.

→ Study of other error criteria to minimize.
Towards a 100% power electronics system: grid-forming control and system-level analysis

MIGRATE WP3 Dissemination Workshop
Lille, 16-17 October 2019

Dominic Groß
Automatic Control Laboratory, ETH Zürich
We are replacing the foundation of today’s grid

**fuel**
- emissions & waste

**renewables**
+ clean & sustainable
We are replacing the foundation of today’s grid

**fuel**
- emissions & waste
- centralized bulk generation

**renewables**
+ clean & sustainable
+ distributed generation
We are replacing the foundation of today’s grid

- fuel
  - emissions & waste
  - centralized bulk generation
  + dispatchable generation

- renewables
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  - intermittent generation
We are replacing the foundation of today’s grid

**fuel & synchronous machines**
- emissions & waste
- centralized bulk generation
+ dispatchable generation
+ self-synchronization & inertia

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- no inherent sync. or inertia
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We are replacing the foundation of today’s grid

**fuel & synchronous machines**
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- slow actuation & control

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+ fast actuation & flexible control
Overview of today’s presentation

Improved grid-forming control of power converters

- dispatchable virtual oscillator control
- structural matching of machine dynamics
Overview of today’s presentation

Improved grid-forming control of power converters

- dispatchable virtual oscillator control
- structural matching of machine dynamics

System services & grid-forming converters

- ancillary service perspective on grid-forming controls
- the role of inertia and power source delays
Standard approach to converter control

1. acquiring & processing of \textbf{AC measurements}

2. synthesis of \textbf{references} (voltage/current)

3. cascaded PI controllers \textbf{track} reference

4. \textbf{actuation} via modulation

5. \textbf{fully controllable} DC source
Conceptually, converters are oscillators that have to synchronize
Cartoon summary of grid-forming control

Hypothetically, they could sync by communication (not feasible)
Cartoon summary of grid-forming control

**Colorful idea:** converters sync through physics & clever local control
Grid-forming converter control strategies

- **droop control**
  + good performance near steady state
  - stability certificates & region of attraction

- **synchronous machine emulation**
  + fully backward compatible
  - fast converter emulates slow machine

- **virtual oscillator control (VOC)**
  + robust & almost globally stable sync
  - cannot meet power specifications

- **dispatchable VOC**
  + almost globally stable sync
  + power & voltage specifications
Dispatchable virtual oscillator control
Model of a multi-converter system

- **converter terminal voltage** \( v_k \in \mathbb{R}^2 \)
System model & grid-forming specifications

Model of a multi-converter system

- **converter terminal voltage** $v_k \in \mathbb{R}^2$
- **line dynamics**: Π-model

Assumptions & Notation:

- network $\frac{r}{\ell}$ ratio constant
- line impedance $\|Y_{jk}\|$
System model & grid-forming specifications

Model of a multi-converter system
- **converter terminal voltage** \( v_k \in \mathbb{R}^2 \)
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System model & grid-forming specifications

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- **line $\ell/r$ ratio constant**

Assumptions & Notation:

- network $r/\ell$ ratio constant
- line impedance $\|Y_{jk}\|$
- node voltage $v_k \in \mathbb{R}^2$
- output current $i_{o,k} \in \mathbb{R}^2$

1. **nominal sync. frequency**:
   
   $v_k(t) = R(\omega_0 t)v_k(0)$

2. **voltage amplitude**:
   
   $\|v_k\| = v^\star$

3. **active & reactive power**:
   
   $v_k^\top i_{o,k} = p^\star_k$, $v_k^\top R(\frac{\pi}{2})i_{o,k} = q^\star_k$

$\theta^\star_12 = 12/30 \omega_0^\star$
System model & grid-forming specifications

Model of a multi-converter system

- **converter terminal voltage** \( v_k \in \mathbb{R}^2 \)
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Stabilize the steady-state behavior

- **nominal sync. frequency**
  \[ v_k(t) = R(\omega_0 t)v_k(0) \]
System model & grid-forming specifications

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Stabilize the steady-state behavior

- **Nominal sync. frequency**
  
  $v_k(t) = R(\omega_0 t)v_k(0)$

- **Voltage amplitude**
  
  $\|v_k\| = v^*$
System model & grid-forming specifications

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Stabilize the steady-state behavior
- **nominal sync. frequency**
  $$v_k(t) = R(\omega_0 t) v_k(0)$$
- **voltage amplitude**
  $$\|v_k\| = v^*$$
- **active & reactive power injection**
  $$v_k^\top i_{o,k} = p_k^*, \quad v_k^\top R(\pi/2) i_{o,k} = q_k^*$$
System model & grid-forming specifications

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Stabilize the steady-state behavior
- nominal sync. frequency
  \[ v_k(t) = R(\omega_0 t) v_k(0) \]
- voltage amplitude
  \[ \|v_k\| = v^* \]
- relative voltage angles
  \[ v_k(t) - R(\theta^*_{k1}) v_1(t) = 0 \]
Main results

1. reference dynamics admit **decentralized implementation**:

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k + \eta \left( R(\kappa) \left( \frac{1}{v^*} \begin{bmatrix} p_k^* & q_k^* \\ -q_k^* & p_k^* \end{bmatrix} v_k - i_{o,k} \right) + \alpha \left( v^* - \|v_k\|^2 \right) v_k \right)
\]

- rotation at \( \omega_0 \)
- synchronization through physics
- local amplitude regulation

2. quantifiable and intuitive stability conditions give engineering insights:

- \( v^*, p_k^*, q_k^* \) satisfy AC power flow equations
- power transfer "small enough" compared to network connectivity
- increase admittance \( \max_k \sum_j \|Y_{jk}\| \times \text{time-constant} \frac{\ell}{r} \Rightarrow \eta \) smaller
- upgrading or adding lines can destabilize the system
- time scale separation can be enforced by control magnitude \( \eta \alpha \) > sync \( \eta \) > line currents > conv. volt. > conv. curr.
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- **upgrading** or **adding** lines can **destabilize** the system
- **time scale separation** can be enforced by control

| magnitude (\( \eta \alpha \)) | sync (\( \eta \)) | line currents | conv. volt. | conv. curr. |
Main results (cont.)

3. **almost global stability** result:

If the stability condition holds, the system is **almost globally asymptotically stable** with respect to a **limit cycle** corresponding to a **pre-specified** solution of the **AC power-flow** equations at a **synchronous** frequency $\omega_0$. 
Main results (cont.)

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4. **dVOC** subsumes, justifies, and **improves** droop control and VOC:

**microgrid** ($\ell_{jk} = 0$, $p_k^* = q_k^* = 0$) = **averaged VOC** \[\text{Johnson, Dhople, Krein, '13}\]

\[
\frac{d}{dt} \theta_k = \omega_0 + \eta \frac{q_k}{\|v_k\|^2}
\]

(phase)

\[
\frac{d}{dt} \|v_k\| = -\eta \frac{p_k}{\|v_k\|^2} \|v_k\| + \eta \alpha \left( \|v_k\| - \frac{1}{v^*} \|v_k\|^3 \right)
\]

(magnitude)
Main results (cont.)

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   - **Transmission system** ($r_{jk} = 0$, $\|v\| \approx v^*$) $\approx$ **droop control**

     $\frac{d}{dt} \theta_k \approx \omega_0 + \frac{\eta}{v^*} (p^*_k - p_k)$  \hspace{1cm} \text{(phase)}

     $\frac{1}{\eta \alpha} \frac{d}{dt} \|v_k\| \approx - (\|v_k\| - v^*) + \frac{1}{\alpha v^*} (q^*_k - q_k)$  \hspace{1cm} \text{(magnitude)}
Experimental setup: 100% PE System

[Seo, Subotic, Johnson, Colombino, Groß, & Dörfler, APEC’19]
Improved dynamic response and robustness

black start of converter #1 under 500 W load
(making use of almost global stability)

connecting converter #2 while converter #1 is regulating the grid under 500 W load

250 W to 750 W load transient with two converters active

change of setpoint: $p^*$ of converter #2 updated from 250 W to 500 W
Machine matching control
Model reduction for low-inertia power systems

- model in **rotating frame** with **nominal** frequency $\omega_0$
Model reduction for low-inertia power systems

- model in **rotating frame** with **nominal** frequency $\omega_0$
- **internal oscillator model** with input $\omega_I$, $\mu$

\[
\frac{d}{dt} \theta_I = \omega_I, \quad m = \mu \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix},
\]

provides **angle / magnitude** reference for terminal **voltage**.
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provides **angle / magnitude** reference for terminal **voltage**.

---

**Model reduction based on DC/AC time-scale separation**

slow DC variables: $x = (\theta, \omega, \theta_I, v_{dc})$,  
\[
\frac{d}{dt} x = f(x, z, u)
\]

fast AC variables: $z = (i_s, i_I, v, i_T)$,  
\[
\epsilon \frac{d}{dt} z = f_z(x, z, u)
\]
singular perturbation$^1$: $\epsilon \to 0$
Main energy storage & power flows

- **nonlinear reduced order model** in rotating frame:

\[
\begin{align*}
\frac{d}{dt} \theta &= \omega - \omega_0 \\
M \frac{d}{dt} \omega &= -D \omega + \tau_m - \tau_e(x_r, u) \\
T \frac{d}{dt} \tau_m &= -\tau_m + \tau_m^* \\
\|v_{\text{ind}}\| &= l_m i_f \|\omega\|
\end{align*}
\]

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\frac{d}{dt} \theta_I &= \omega_I - \omega_0 \\
C_{dc} \frac{d}{dt} v_{dc} &= -G_{dc} v_{dc} + i_{dc} - i_{sw}(x_r, u) \\
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\|v_{sw}\| &= \frac{1}{2} \mu \|v_{dc}\|
\end{align*}
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- **interconnection** via torque \(\tau_e\) and switching current \(i_{sw}\)

- **analogies** & interpretation:

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<tr>
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<th>generator</th>
<th>converter</th>
<th>interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{1}{2} M \omega^2 )</td>
<td>( \frac{1}{2} C_{dc} v_{dc}^2 )</td>
<td>energy stored in device</td>
</tr>
<tr>
<td>( \tau_m )</td>
<td>( i_{dc} )</td>
<td>power supply</td>
</tr>
<tr>
<td>( \tau_e )</td>
<td>( i_{sw} )</td>
<td>power flow to grid</td>
</tr>
<tr>
<td>( \omega - \omega_0 )</td>
<td>( v_{dc} - v_{dc}^* )</td>
<td>power imbalance</td>
</tr>
<tr>
<td>( i_f )</td>
<td>( \mu )</td>
<td>“Excitation”</td>
</tr>
</tbody>
</table>
Main energy storage & power flows

- **nonlinear reduced order model** in rotating frame:

\[
\frac{d}{dt} \theta = \omega - \omega_0 \\
M \frac{d}{dt} \omega = -D \omega + \tau_m - \tau_e(x_r, u) \\
T \frac{d}{dt} \tau_m = -\tau_m + \tau_m^* \\
\|v_{\text{ind}}\| = l_m i_f \|\omega\|
\]

\[
\frac{d}{dt} \theta_I = \omega_I - \omega_0 = \delta \omega_I \\
C_{dc} \frac{d}{dt} v_{dc} = -G_{dc} v_{dc} + i_{dc} - i_{sw}(x_r, u) \\
T_{dc} \frac{d}{dt} i_{dc} = -i_{dc} + i_{dc}^* \\
\|v_{\text{sw}}\| = \frac{1}{2} \mu \|v_{dc}\|
\]

- **converter control architecture** matched to **sync. machine control**

\[
\begin{bmatrix}
\delta \tau_m^* \\
\delta i_f \\
\delta \omega_I \\
\delta i_{dc}^* \\
\delta \mu
\end{bmatrix} =
\begin{bmatrix}
K_{gov} & 0 \\
K_{PSS}(s) & K_{AVR}(s)
\end{bmatrix}
\begin{bmatrix}
\delta \omega \\
\delta \|v\|
\end{bmatrix}
\]

\[
\begin{bmatrix}
\delta v_{dc} \\
\delta \|v\|
\end{bmatrix} =
\begin{bmatrix}
\delta \mu \\
K_m & * \\
K_{dc} & * \\
K_{PSS}(s) & K_{AVR}(s)
\end{bmatrix}
\begin{bmatrix}
\delta \omega \\
\delta \|v\|
\end{bmatrix}
\]

- **inertia** \( M = \frac{C_{dc}}{K_m} \), **governor gain** \( K_{gov} = \frac{K_{dc}}{K_m} \), **source delay** \( T = T_{dc} \)
Interactions between controls
High-fidelity EMT simulation

- check **compatibility** of different system-level controls
- virtual impedance **current-limiting**
- robustness to faults: tripping of a line & short circuit fault
Three-converter system: line tripping & short circuit fault

Events

- $t = 0.5$ s: line from PCC1 to PCC3 disconnected
- $t = 5$ s: short circuit near PCC1
- $t = 1.65$ s: fault cleared
Three-converter system: line tripping & short circuit fault

Events
- $t = 0.5 \text{ s}$: line from PCC1 to PCC3 disconnected
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Observations
- droop, dVOC, & matching are compatible
Three-converter system: line tripping & short circuit fault

**Events**
- \( t = 0.5 \text{ s}: \) **line** from PCC1 to PCC3 **disconnected**
- \( t = 5 \text{ s}: \) **short circuit** near PCC1
- \( t = 1.65 \text{ s}: \) fault cleared

**Observations**
- droop, dVOC, & matching are **compatible**
- virtual impedance **limits current** during transients
Three-converter system: line tripping & short circuit fault

Events

- \( t = 0.5 \text{ s}: \text{line from PCC1 to PCC3 disconnected} \)
- \( t = 5 \text{ s}: \text{short circuit near PCC1} \)
- \( t = 1.65 \text{ s}: \text{fault cleared} \)

Observations

- droop, dVOC, & matching are compatible
- virtual impedance limits current during transients
- system remains stable during & after faults
Ancillary service perspective
dVOC (inductive grid) & droop control

Approximate dynamics

\[
\frac{d}{dt} \theta = \omega_0 + \frac{\eta}{v^*} (p^* - p)
\]

\[
\frac{1}{\eta \alpha} \frac{d}{dt} \|v\| = v^* - \|v\| + \frac{1}{v^* \alpha} (q^* - q)
\]

Parameters

- active power droop \( \eta / v^* \)
- reactive power droop \( v^* / \alpha \)
- voltage time constant \( 1 / (\eta \alpha) \)
dVOC (inductive grid) & droop control

**Approximate dynamics**

\[
\frac{d}{dt} \theta = \omega_0 + \frac{\eta}{v^*} (p^* - p)
\]

\[
\frac{1}{\eta \alpha} \frac{d}{dt} \|v\| = v^* - \|v\| + \frac{1}{v^* \alpha} (q^* - q)
\]

**Parameters**

- active power droop \(\eta/v^*_2\)
- reactive power droop \(v^*/\alpha\)
- voltage time constant \(1/(\eta \alpha)\)

**Ancillary services**

- fast **primary frequency control** through active power droop
dVOC (inductive grid) & droop control

Approximate dynamics

\[
\frac{d}{dt} \theta = \omega_0 + \frac{\eta}{v^*^2} (p^* - p) \\
\frac{1}{\eta \alpha} \frac{d}{dt} \|v\| = v^* - \|v\| + \frac{1}{v^* \alpha} (q^* - q)
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Parameters

- active power droop \( \eta/v^*^2 \)
- reactive power droop \( v^* / \alpha \)
- voltage time constant \( 1 / (\eta \alpha) \)

Ancillary services

- fast primary frequency control through active power droop
- proportional voltage regulation through reactive power droop
dVOC (inductive grid) & droop control

**Approximate dynamics**

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**Parameters**

- active power droop \( \eta/v^*^2 \)
- reactive power droop \( v^*/\alpha \)
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**Ancillary services**

- fast **primary frequency control** through active power droop
- proportional **voltage regulation** through reactive power droop

**Properties**

- almost **global synchronization** (multi-converter black start)
dVOC (inductive grid) & droop control

Approximate dynamics

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- fast **primary frequency control** through active power droop
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Properties

- almost **global synchronization** (multi-converter black start)
- requires **fully controllable DC source** without significant **delays**
dVOC (inductive grid) & droop control

Approximate dynamics

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- services cannot be **enabled / disabled** individually
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Ancillary services

- fast primary frequency control through active power droop
- proportional voltage regulation through reactive power droop

Properties

- almost global synchronization (multi-converter black start)
- requires fully controllable DC source without significant delays
- services cannot be enabled / disabled individually
- potential adverse interactions with DC side & machine dynamics
Machine matching control

Approximate dynamics

\[ \frac{d}{dt} \theta = \omega \]
\[ M \frac{d}{dt} \omega = -D \omega + p_{dc} - p_{dem} \]
\[ T_{dc} \frac{d}{dt} p_{dc} = -p_{dc} + p^* + K_{dc}(\omega_0 - \omega) \]
\[ \tau_v \frac{d}{dt} ||v|| = v^* - ||v|| + m_q(q^* - q) \]

Parameters

- active power droop \( K_{dc} \)
- inertia \( M \), source resp. time \( T_{dc} \)
- reactive power droop \( m_q \)
- voltage filter time \( \tau_v > 50\text{ms} \)
Machine matching control

Approximate dynamics

\[
\frac{d}{dt} \theta = \omega \\
M \frac{d}{dt} \omega = -D\omega + p_{dc} - p_{dem} \\
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Ancillary services

- primary frequency control with source delay \(T_{dc}\)
Machine matching control

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\[ \frac{d}{dt} \theta = \omega \]
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Ancillary services

- primary frequency control with source delay \( T_{dc} \)
- inertia \( M = C_{dc}/K_m \) depends on energy storage & frequency mapping
Machine matching control

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- active power droop \(K_{dc}\)
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- voltage filter time \(\tau_v > 50\text{ms}\)

Ancillary services

- primary frequency control with source delay \(T_{dc}\)
- inertia \(M = C_{dc}/K_m\) depends on energy storage & frequency mapping
- voltage regulation: reactive power sharing or AVR
Machine matching control

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- active power droop $K_{dc}$
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Ancillary services

- primary frequency control with source delay $T_{dc}$
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- voltage regulation: reactive power sharing or AVR

Services depend on DC source

- no DC source ($p_{dc} = 0$) $\approx$ synchronous condenser $\approx$ STATCOM
Machine matching control

Approximate dynamics

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\frac{d}{dt} \theta = \omega
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M \frac{d}{dt} \omega = -D \omega + p_{dc} - p_{dem}
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- voltage regulation: reactive power sharing or AVR

Services depend on DC source

- no DC source \((p_{dc} = 0) \approx\) synchronous condenser \(\approx\) STATCOM
- DC source with no flexibility \((K_{dc} = 0) \approx\) fixed active power injection & AVR
Machine matching control

**Approximate dynamics**

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- no DC source ($p_{dc} = 0$) $\approx$ synchronous condenser $\approx$ STATCOM
- DC source with no flexibility ($K_{dc} = 0$) $\approx$ fixed active power injection & AVR
- DC source flexible $\approx$ sync. machine with AVR, governor, & PSS
**Nadir & RoCoF: inertia vs. response time**

### Aggregated system model

\[
m_s \frac{d}{dt} \omega_s = -d_s \omega_s + p - p_d
\]
\[
t_s \frac{d}{dt} p = -p + k_s \omega_s
\]

▶ **Structural matching** but parameters have **different** order of **magnitude**

- machine & turbine: \( t_s = 2s \) to \( t_s = 7s \), \( m_s = 3s \) to \( m_s = 10s \)
- converter: \( t_s = 0.01s \) to \( t_s = 0.30s \), \( C_{dc} \) small \( \implies \) \( m_s \) small
Nadir & RoCoF: inertia vs. response time

Aggregated system model

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\frac{m_s}{t_s} \frac{d}{dt} \omega_s = -d_s \omega_s + p - p_d \\
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▶ re-scaling time does not change frequency nadir \(|\omega_s|\infty\)
Nadir & RoCoF: inertia vs. response time

Aggregated system model

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\frac{m_s}{t_s} \frac{d}{dt} \omega_s = -d_s \omega_s + p - p_d \\
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▶ ratio \( m_s/t_s \) is main parameter affecting nadir
Nadir & RoCoF: inertia vs. response time

**Aggregated system model**

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▶ **re-scaling time** does not change **frequency nadir** \( |\omega_s|_{\infty} \)

▶ **ratio** \( m_s/t_s \) is **main parameter** affecting nadir

▶ **RoCoF** \( |\dot{\omega}_s|_{95\%} \) **averaged** from \( t_0 \) to \( t_{95\%} \)
How much inertia do we need in PE Systems?

**nadir & RoCoF vs. \( t_s \) and \( m_s \)**

- Typical values for \( t_s \)
  - PV \( \approx 10 \text{ms} \)
  - Battery \( \approx 50 \text{ms} \)
  - Wind turbine \( \approx 100 \text{ms to 300ms} \)
  - Hydro \( \approx 2 \text{s} \)
  - Steam \( \approx 7 \text{s} \)
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- VSC can withstand large RoCoF
How much inertia do we need in PE Systems?

![Image: Graphs showing nadir & RoCoF vs. $t_s$ and $m_s$]

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- **protection** relies on RoCoF
How much inertia do we need in PE Systems?

**nadir & RoCoF vs. \( t_s \) and \( m_s \)**

![Graph showing RoCoF and nadir vs. \( t_s \) and \( m_s \)]

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- **VSC** can withstand large RoCoF

- **protection** relies on RoCoF

**Two bus system**

![Graph showing \( \omega_g \) vs. \( t \)]

- **SM**: \( M_g = 10 \text{s}, T_g = 7 \text{s}, 5\% \text{ droop} \)
How much inertia do we need in PE Systems?

 данной статьи

Typical values for \( t_s \):
- PV \( \approx 10\) ms
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frequency nadir not problematic
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Two bus system

SM: \( M_g = 10\) s, \( T_g = 7\) s, 5% droop
VSC: \( T_c = 0.03\) s, 5% droop
How much inertia do we need in PE Systems?

**nadir & RoCoF vs. $t_s$ and $m_s$**

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**Two bus system**

- SM: $M_g = 10$s, $T_g = 7$s, 5% droop
- VSC: $T_c = 0.03$s, 5% droop
- $0.03$s $\leq M_c \leq 10$s: small impact
Conclusions & take home messages
Conclusions

- All **grid-forming controls** exhibit very **similar performance**
  - dVOC has **formal guarantees** & **subsumes** well-known controls
  - **matching** makes **DC side** dynamics & **limitations transparent** to **AC side**
  - dVOC and matching only **outperform** droop control in **special cases**
Conclusions

• All grid-forming controls exhibit very similar performance
  – dVOC has formal guarantees & subsumes well-known controls
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• Too much emphasis on synthetic inertia
  – RoCoF limits only critical for synchronous machines and protection
  – fast response of power converters compensates for a loss of inertia
  – low-inertia system re-synchronizes faster after contingencies
Conclusions

• All grid-forming controls exhibit very similar performance
  – dVOC has formal guarantees & subsumes well-known controls
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• Too much emphasis on synthetic inertia
  – RoCoF limits only critical for synchronous machines and protection
  – fast response of power converters compensates for a loss of inertia
  – low-inertia system re-synchronizes faster after contingencies

• Significant differences between low-inertia & 100 % PE Systems
  – 100 % PE: dynamics homogeneous, instability due to grid-following units
  – low-inertia: heterogeneous dynamics on multiple time-scales
  – Challenge: complex adverse interactions during transition
• **Barriers for resilient & sustainable** system
  – interference of new controls & methods with market paradigms?
  – **device limits**: converter DC & AC current limits, etc.
Open questions

• **Barriers** for resilient & sustainable system
  – interference of new controls & methods with market paradigms?
  – device limits: converter DC & AC current limits, etc.

• **Requirements** for new grid codes to ensure compatibility
  – system-level requirements independent of device-level controls
  – specify input-output behavior to ensure homogeneous dynamics
Open questions

• **Barriers** for **resilient & sustainable** system
  – interference of new **controls & methods** with **market paradigms**?
  – **device limits**: converter **DC & AC current** limits, etc.

• **Requirements** for new grid codes to ensure **compatibility**
  – **system-level** requirements **independent** of **device-level** controls
  – specify **input-output behavior** to ensure **homogeneous dynamics**

• **DC/AC converter** is a **“signal transformer”**
  – **DC side limitations**: delays, actuation limits, limited storage
  – cannot **pass on** all **disturbance** to all DC sources
Acknowledgements

Marcello Colombino

Irina Subotic

Florian Dörfler

Taouba Jouini
Grid-Following Control, Frequency Regulation & Stability in Low-Inertia Systems

MIGRATE WP3 Dissemination Workshop

Uros Markovic

ETH Zürich - Power Systems Laboratory
Adaptive Virtual Synchronous Machine
Problem Overview

- **Virtual synchronous machine** controller with *adaptive* control gains
- **Inertia** and *damping* constants are adjusted according to the *system state feedback*
- **Goal**: operate the system at *minimum cost*, while preserving the ENTSO-e *frequency thresholds* (nadir and RoCoF)
- A *trade-off* between the two objectives is achieved using an *LQR* approach
- **Decentralized, multi-inverter** strategy based on an *offline computation* is proposed
- **Sufficient** tuning *conditions* for ensuring asymptotic stability of the system have been derived
Multi-Machine Frequency Dynamics

Derivation of a **time-domain** expression for frequency of the **Center-Of-Inertia (COI)**

- \( M \) - inertia constant
- \( D \) - damping constant
- \( K \) - mechanical power gain
- \( F \) - power fraction generated by the turbine
- \( T \) - time constant
- \( R \) - droop gain
Multi-Machine Frequency Dynamics

\[ G(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{(sM_g + D_g) + \sum_{i \in \mathcal{N}_g} \frac{K_{g_i}(1 + sF_{g_i}T_{g_i})}{R_{g_i}(1 + sT_{g_i})} + \sum_{j \in \mathcal{N}_d} \frac{K_{c_j}}{R_{c_j}(1 + sT_{c_j})} + \sum_{k \in \mathcal{N}_v} \frac{sM_{c_k} + D_{c_k}}{1 + sT_{c_k}}} \]

- **generators**
- **droop converters**
- **VSM converters**
Multi-Machine Frequency Dynamics

\[ G(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{(sM_g + D_g) + \sum_{i \in N_g} \frac{K_{g_i}(1 + sF_{g_i}T_{g_i})}{R_{g_i}(1 + sT_{g_i})} + \sum_{j \in N_d} \frac{K_{c_j}}{R_{c_j}(1 + sT_{c_j})} + \sum_{k \in N_v} \frac{sM_{c_k} + D_{c_k}}{1 + sT_{c_k}}} \]

generators

droop converters

Time-domain frequency expression

\[ \omega(t) = -\frac{\Delta P}{MT\omega_n^2} - \frac{\Delta P}{M\omega_d} e^{-\zeta \omega_n t} \left( \sin(\omega_d t) - \frac{1}{\omega_n T} \sin(\omega_d t + \phi) \right) \]

Frequency nadir and RoCoF

\[ \omega_{\text{max}} = -\frac{\Delta P}{D + R_g} \left( 1 + \sqrt{\frac{T(R_g - F_g)}{M}} e^{-\zeta \omega_n t_m} \right) \]

\[ \dot{\omega}_{\text{max}} = -\frac{\Delta P}{M} \text{ optimization constraints} \]
Multi-Machine Frequency Dynamics

Individual generator frequencies
Uniform frequency response

Computational error [%]
Probability [%]
Adaptive Virtual Synchronous Machine

State-space model

\[
\begin{bmatrix}
\dot{\omega} \\
\ddot{\omega}
\end{bmatrix} =
\begin{bmatrix}
0 & \frac{I}{M} \\
-\frac{D + R_g}{MT} & -\left(\frac{1}{T} + \frac{D + F_g}{M}\right)
\end{bmatrix}
\begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix} +
\begin{bmatrix}
0 \\
\Delta P
\end{bmatrix}
\]

State feedback control

\[
\begin{bmatrix}
M \\
D
\end{bmatrix}_u =
\begin{bmatrix}
M^* \\
D^*
\end{bmatrix}_u +
\begin{bmatrix}
\Delta M \\
\Delta D
\end{bmatrix}_u
= \begin{bmatrix}
M^* \\
D^*
\end{bmatrix}_u - \begin{bmatrix}
K_m & \hat{K}_m \\
K_d & \hat{K}_d
\end{bmatrix}\begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix}_x
\]

Optimization problem

\[
\min_{x_i, u_i} \int_{t_{1,i}}^{t_{2,i}} \left( x_i^T Q x_i + \Delta u_i^T R_i \Delta u_i \right) dt
\]

s.t

\[
\dot{x}_i = A x_i + B_i \Delta u_i
\]

\[
\Delta u_i = -K_i x_i
\]
Adaptive Virtual Synchronous Machine

State-space model

\[
\begin{bmatrix}
\dot{\omega} \\
\ddot{\omega}
\end{bmatrix} = \begin{bmatrix}
0 & I \\
-D + R_g & -(1/T + D + F_g/M)T
\end{bmatrix} \begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix} + \begin{bmatrix}
0 \\
0
\end{bmatrix} \Delta P/TM
\]

State feedback control

\[
\begin{bmatrix}
M \\
D
\end{bmatrix} = \begin{bmatrix}
M^* \\
D^*
\end{bmatrix} + \begin{bmatrix}
\Delta M \\
\Delta D
\end{bmatrix} = \begin{bmatrix}
M^* \\
D^*
\end{bmatrix} - \begin{bmatrix}
K_m & \hat{K}_m \\
K_d & \hat{K}_d
\end{bmatrix} \begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix}
\]

Optimization problem

\[
\begin{align*}
\min_{x_i, u_i} & \quad \int_{t_1}^{t_2} (x_i^T Q x_i + \Delta u_i^T R_i \Delta u_i) \, dt \\
\text{s.t.} & \quad \dot{x}_i = A x_i + B_i \Delta u_i \\
& \quad \Delta u_i = -K_i x_i
\end{align*}
\]

\[
\frac{\partial f}{\partial D} \bigg|_{x_i^*, u_i^*} = 0; \quad \frac{\partial f}{\partial M} \bigg|_{x_2^*, u_2^*} = 0
\]

Linearization point: \(x_1^*\) or \(x_2^*\)?
Method A - Two Independent Controllers

- Assuming that the system **damping** has little effect in the **initial stages** of a frequency response, whereas the system **inertia** has low impact in the **later stages**

- Two phases are separated by the instance of **frequency nadir**, thus dividing response time into $[0, t_m)$ and $[t_m, +\infty)$, with $u_M = M$ and $u_D = D$ being the only control input
Method A - Two Independent Controllers

- Assuming that the system **damping** has little effect in the **initial stages** of a frequency response, whereas the system **inertia** has low impact in the **later stages**.

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\[
\begin{align*}
\begin{bmatrix}
\dot{\omega} \\
\ddot{\omega}
\end{bmatrix}
&= 
\begin{bmatrix}
0 & 1 \\
\frac{1}{TM^*} & \frac{T}{M^*} + \frac{1}{T}
\end{bmatrix}
\begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
-\frac{\Delta P}{TM^*^2}
\end{bmatrix}
\Delta M \\
\begin{bmatrix}
\omega_0 \\
\dot{\omega}_0
\end{bmatrix}
&= 
\begin{bmatrix}
0 & \dot{\omega}(0^+)
\end{bmatrix}
, \\
\Delta M &= -\begin{bmatrix} K_m & \dot{K}_m
\end{bmatrix}
\begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix}
\end{align*}
\]
Method A - Two Independent Controllers

- Assuming that the system **damping** has little effect in the **initial stages** of a frequency response, whereas the system **inertia** has low impact in the **later stages**

- Two phases are separated by the instance of **frequency nadir**, thus dividing response time into \([0, t_m)\) and \([t_m, +\infty)\), with \(u_M = M\) and \(u_D = D\) being the only control input

\[
\begin{align*}
\begin{bmatrix}
\dot{\omega} \\
\ddot{\omega}
\end{bmatrix}
&= 
\begin{bmatrix}
0 & 1 \\
-D^* + R_g & TM^*
\end{bmatrix}^{-1}
\begin{bmatrix}
-\frac{1}{M^* + 1/T} \\
D^* + F_g
\end{bmatrix}
\begin{bmatrix}
\dot{\omega} \\
\dot{\dot{\omega}}
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
-\omega_{ss}
\end{bmatrix}
\begin{bmatrix}
TM^*
\end{bmatrix}

\begin{bmatrix}
\dot{\omega}_0 \\
\dot{\omega}_0
\end{bmatrix}
&= 
\begin{bmatrix}
\omega_m - \omega_{ss} \\
0
\end{bmatrix}

\Delta D = -\begin{bmatrix}K_d & \dot{K}_d\end{bmatrix} \begin{bmatrix}
\dot{\omega} \\
\dot{\dot{\omega}}
\end{bmatrix}
\end{align*}
\]
Method A - Two Independent Controllers

- Assuming that the system **damping** has little effect in the **initial stages** of a frequency response, whereas the system **inertia** has low impact in the **later stages**

- Two phases are separated by the instance of **frequency nadir**, thus dividing response time into $[0, t_m)$ and $(t_m, +\infty)$, with $u_M = M$ and $u_D = D$ being the only control input

\[
\begin{align*}
\begin{bmatrix}
\dot{\omega} \\
\ddot{\omega}
\end{bmatrix}
&= \begin{bmatrix}
0 & \begin{array}{c}
-\frac{D^* + R_g}{TM^*} \\
\frac{1}{\left(\frac{D^* + F_g}{M^*} + \frac{1}{T}\right)}
\end{array} \\
-\frac{D^* + R_g}{TM^*} & -\left(\frac{D^* + F_g}{M^*} + \frac{1}{T}\right)
\end{bmatrix}
\begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
-\frac{\Delta P}{TM^*}\Delta M
\end{bmatrix}
\\
\begin{bmatrix}
\omega_0 \\
\dot{\omega}_0
\end{bmatrix}
&= \begin{bmatrix}
0 \\
\dot{\omega}(0^+)
\end{bmatrix}, \quad \Delta M = -\begin{bmatrix}
K_m & K_m \\
K_M & K_M
\end{bmatrix}
\begin{bmatrix}
\omega \\
\dot{\omega}
\end{bmatrix}
\end{align*}
\]
**Optimization problem**

\[
\begin{align*}
\min_{x_i, u_i} & \quad \int_{t_{1,i}}^{t_{2,i}} \left( x_i^T Q x_i + \Delta u_i^T R_i \Delta u_i \right) dt \\
\text{s.t} & \quad \dot{x}_i = A x_i + B_i \Delta u_i \\
& \quad \Delta u_i = -K_i x_i
\end{align*}
\]
**Method A - Two Independent Controllers**

**Optimization problem**

\[
\min_{x_i, u_i} \int_{t_1}^{t_2} \left( x_i^T Q x_i + \Delta u_i^T R_i \Delta u_i \right) dt
\]

s.t

\[
\dot{x}_i = A x_i + B_i \Delta u_i
\]

\[
\Delta u_i = -K_i x_i
\]

**Drawbacks:**

- inherently **suboptimal** (due to initial assumptions on \( M \) and \( D \))
- requires **complicated logical circuitry** for switching
- can lead to **frequency spikes** and **undesirable** behavior in real-world applications

---

**Diagram:**

- **M-LQR**
  - Cost Factors
  - Control Effort Factorization
  - Control Design
    - \( K_M, K_D \)
- **D-LQR**
  - Cost Factors
  - Control Design
    - \( R_{Q1, Q2} \), \( R_{Q1, Q2} \)

---

**Grid-Following Control, Frequency Regulation & Stability in Low-Inertia Systems**

Uros Markovic (PSL)

October 16, 2019 4 / 20
Method B - Two Dependent Controllers

- **No assumptions** regarding $M$ and $D$:

$$D = D(\omega, \dot{\omega}) = D^* - \left[ \hat{K}_d, \hat{K}_d \right] \begin{bmatrix} \omega - \omega_{ss} \\ \dot{\omega} \end{bmatrix}$$

$$M = M(\omega, \dot{\omega}) = M^* - \left[ \hat{K}_m, \hat{K}_m \right] \begin{bmatrix} \omega \\ \dot{\omega} \end{bmatrix}$$
Method B - Two Dependent Controllers

- **No assumptions** regarding $M$ and $D$:

  \[
  D = D(\omega, \dot{\omega}) = D^* - \left[ K_d \hat{K}_d \right]_{K_D} \begin{bmatrix} \omega - \omega_{ss} \\ \dot{\omega} \end{bmatrix}
  \]

  \[
  M = M(\omega, \dot{\omega}) = M^* - \left[ K_m \hat{K}_m \right]_{K_M} \begin{bmatrix} \omega \\ \dot{\omega} \end{bmatrix}
  \]

![Diagram showing iterative process for control design with penalties and factorization](image)
Parametrization & Implementation

- **Employing Bryson’s rule** for LQR initialization

\[ Q_1(\omega_{\text{max}})^2 = Q_2(\dot{\omega}_{\text{max}})^2 = R_i(\Delta u_{i,\text{max}})^2 \]
**Parametrization & Implementation**

- **Employing Bryson’s rule** for LQR initialization

\[ Q_1(\omega_{\text{max}})^2 = Q_2(\dot{\omega}_{\text{max}})^2 = R_i(\Delta u_{i,\text{max}})^2 \]

- **Mimicking traditional composite frequency response** characteristic (\(\beta\))

\[ \Delta P = \gamma f_n R_{c_i} \frac{\Delta P_{c_i}}{P_{c_i}} = \gamma f_n (D_{c_i} P_{c_i})^{-1} \Delta P_{c_i} \]

\[ \gamma = D_I P_0 + \frac{1}{f_n} \sum_{i \in N_c} \frac{P_{c_i}}{R_{c_i}} \]

---

**Optimal Control Design**

\[ \min_{x,u} \int_0^\infty (x^T Q x + u^T R u) \, dt \]

s.t. \( \dot{x} = A x + B u \)

\[ u = -K x \]

---

**Multi-LQR Approach**

\[ [\omega_{\text{max}}, \dot{\omega}_{\text{max}}] \]

---

**Grid-Following Control, Frequency Regulation & Stability in Low-Inertia Systems**

Uros Markovic (PSL)
Parametrization & Implementation

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\[ Q_1(\omega_{\text{max}})^2 = Q_2(\dot{\omega}_{\text{max}})^2 = R_i(\Delta u_{i,\text{max}})^2 \]

- Mimicking traditional **composite frequency response** characteristic (\( \beta \))

\[ \Delta P = \gamma f_n R_{c_i} \frac{\Delta P_{c_i}}{P_{c_i}} = \gamma f_n \left( D_{c_i} P_{c_i} \right)^{-1} \Delta P_{c_i} \]

\[ \gamma = D_i P_{l_0} + \frac{1}{f_n} \sum_{i \in N_c} \frac{P_{c_i}}{R_{c_i}} \psi_i \]

- **Local, multi-inverter** implementation

\[ \Delta P_{c_i} \xrightarrow{\gamma f_n \psi_i} \Delta P \xrightarrow{T_{PK}} K^* \xrightarrow{\lambda_i} K^*_{c_i} \]
Stability Condition

\[
\frac{M^*}{T} + D^* + F_g < \frac{M^* - \sqrt{M^*^2 - 4\hat{K}_m\Delta P}}{4\hat{K}_m/K_m}
\]
Modified Kundur 2-Area System comprised of **3 areas** and **6 generators**

- Three traditional generators are replaced with **converter-based units**
- Investigating the response to a **loss of synchronous generator** at node 5
- Prescribed **ENTSO-E requirements** \( \Delta f_{\text{max}} = 0.5 \text{ Hz} , \dot{f}_{\text{max}} = 1 \text{ Hz/s} \)
System Frequency Response

![Graphs showing frequency response and rate of change for different methods over time.]
Adaptive schemes fulfill their purpose of alleviating the disturbance.

Frequency is kept within prescribed ENTSO-E thresholds.

Activation of $\Delta M$ and $\Delta D$ reveals the distinctive nature of the two algorithms.

Method A is inherently restricted, which results in higher control effort and worse performance.

Method B proves to be the conceptually superior and more practical approach.

Severe contingency can be handled with a reasonable increase in energy utilization.

- **Method A**
  - Restricted
  - Higher control effort
  - Worse performance

- **Method B**
  - Conceptually superior
  - More practical

Severe contingency can be handled with a reasonable increase in energy utilization.
Virtual Induction Machine
Induction vs Synchronous Machine

**Induction Machine**

- operates at asynchronous speed
- AC supply for excitation
- field induced in the rotor (self-excited)
- standalone, but no black start mode
- no need for synchronization
- restricted to smaller units
- less complicated construction

![Induction Machine Diagram]

**Synchronous Machine**

- operates at synchronous speed
- DC excitation system
- separate excitation field
- standalone and black start mode
- synchronization unit required
- output frequency regulated better
- higher efficiency

![Synchronous Machine Diagram]
Induction vs Synchronous Machine

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- operates at asynchronous speed
- AC supply for excitation
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**Synchronous Machine**

- operates at synchronous speed
- DC excitation system
- separate excitation field
- **standalone and black start mode**
- synchronization unit required
- output frequency regulated better
- higher efficiency
**Induction Machine Emulation**

*IM model in a synchronous (dq)-frame:*

\[
\begin{align*}
    v_d^s &= R_s i_d^s + \dot{\psi}_d^s - \omega_s \psi_q^s \\
    v_q^s &= R_s i_q^s + \dot{\psi}_q^s + \omega_s \psi_d^s \\
    v_d^r &= 0 = R_r i_d^r + \dot{\psi}_d^r - \omega_r \psi_q^r \\
    v_q^r &= 0 = R_r i_q^r + \dot{\psi}_q^r + \omega_r \psi_d^r
\end{align*}
\]

\[
\psi_s = L_s i_s + L_m i_r \\
\psi_r = L_r i_r + L_m i_s
\]

\[
\begin{align*}
    \tau_e &= \frac{3}{2} \left( \psi_d^s \dot{i}_q^s - \psi_q^s \dot{i}_d^s \right) \\
    J \dot{\omega}_r &= \tau_m - \tau_e - \tau_d
\end{align*}
\]

*Final IM emulation model:*

\[
\begin{align*}
    \tau_m &= \frac{p_m}{\omega_r} \approx \frac{p}{\omega_r} \\
    \tau_e &= \frac{3}{2} \frac{R_r L_m^2}{R_r L_r + s L_r^2} i_d^s i_q^s = K_e i_d^s i_q^s \\
    \Delta \omega_r &= \frac{1}{J_s + K_d} (\tau_m - \tau_e) \\
    \omega_v &= \left( \frac{R_r}{L_r} + s \right) \frac{\dot{i}_q^s}{i_d^s} = K_v \frac{\dot{i}_q^s}{i_d^s} \\
    \omega_r &= \omega_0 + \Delta \omega_r \\
    \omega_s &= \omega_r + \omega_v
\end{align*}
\]
Induction Machine Emulation

IM model in a synchronous $(dq)$-frame:

\[ v_d^s = R_s i_d^s + \dot{\psi}_s^d - \omega_s \psi_q^s \]
\[ v_q^s = R_s i_q^s + \dot{\psi}_s^q + \omega_s \psi_d^s \]
\[ v_r^d = 0 = R_r i_r^d + \dot{\psi}_r^d - \omega_r \psi_q^r \]
\[ v_r^q = 0 = R_r i_r^q + \dot{\psi}_r^q + \omega_r \psi_d^r \]

\[ \psi_s = L_s i_s + L_m i_r \]
\[ \psi_r = L_r i_r + L_m i_s \]

\[ \tau_e = \frac{3}{2} \left( \psi_s^d i_s^q - \psi_s^q i_s^d \right) \]
\[ J \dot{\omega}_r = \tau_m - \tau_e - \tau_d \]

Final IM emulation model:

\[ \tau_m = \frac{p_m}{\omega_r} \approx \frac{p}{\omega_r} \]
\[ \tau_e = \frac{3}{2} \frac{R_r L_m^2}{R_r L_r + s L_r^2} i_s^d i_s^q = K_e i_s^d i_s^q \]
\[ \Delta \omega_r = \frac{1}{J_s + K_d} (\tau_m - \tau_e) \]
\[ \omega_r = \left( \frac{R_r}{L_r} + s \right) \frac{i_r^q}{i_r^d} = K_v \frac{i_r^q}{i_r^d} \]
\[ \omega_s = \omega_r + \omega_r = f \left( v_s^{dq}, i_s^{dq} \right) \]
\[ \omega_s = \omega_r + \omega_r = f \left( v_s^{dq}, i_s^{dq} \right) \]
**Final IM emulation model:**

\[
\tau_m = \frac{p_m}{\omega_r} \approx \frac{p}{\omega_r}
\]

\[
\tau_e = \frac{3}{2} \frac{R_r L_m^2 i^q_s i^d_s}{2 R_r L_r + s L_r^2} = K_e i^q_s i^d_s
\]

\[
\Delta \omega_r = \frac{1}{Js + K_d} (\tau_m - \tau_e)
\]

\[
\omega_\nu = \left( \frac{R_r}{L_r} + s \right) \frac{i^q_s}{i^d_s} = K_\nu \frac{i^q_s}{i^d_s}
\]

\[
\omega_r = \omega_0 + \Delta \omega_r
\]

\[
\omega_s = \omega_r + \omega_\nu
\]

- Replaces the conventional synchronization unit
- Only uses voltage and current measurements
- Implemented in SI instead of per unit
- Plug-n-play characteristics
Virtual Induction Machine vs PLL

\[
\omega_{\text{pll}} = \omega_n + K_p^{\text{pll}} \hat{e}_q + K_i^{\text{pll}} \varepsilon
\]

\[
\dot{\varepsilon} = \hat{e}_g
\]

\[
\dot{\theta}_{\text{pll}} = \omega_{\text{pll}} \omega_b
\]

**Redesigning inverter synchronization:**
- replacing PLL with a VIM

\[
\omega_s = \omega_0 + \Delta \omega_r + \omega_{\nu}
\]

\[
\omega_{\nu} = \left( \frac{R_r}{L_r} + s \right) \frac{i_d}{\hat{e}_g} + K_{\nu}
\]

\[
\Delta \dot{\omega}_r = \frac{1}{J} \left( \tau_m - \tau_e - \tau_d \right)
\]

\[
\tau_m = \frac{p}{\omega_0 + \Delta \omega_r}
\]

\[
\tau_e = \frac{3}{2} \frac{K_e}{R_r L_m^2 + s L_r^2} i_d^g i_q^g
\]

\[
\tau_d = K_d \Delta \omega_r
\]
Virtual Induction Machine vs PLL

\[
\omega_{pll} = \omega_n + K_p^{PLL} \hat{e}_g + K_i^{PLL} \varepsilon
\]
\[
\dot{\varepsilon} = \hat{e}_g
\]
\[
\dot{\theta}_{pll} = \omega_{pll} \omega_b
\]

Redesigning inverter synchronization:
- replacing PLL with a VIM
- preserving synchronization and order of the DAE system

\[
\omega_s = \omega_0 + \Delta \omega_r + \omega_\nu
\]
\[
\omega_\nu = \left( \frac{R_r}{L_r} + s \right) \frac{i_q}{i_d}
\]
\[
\Delta \dot{\omega}_r = \frac{1}{J} \left( \tau_m - \tau_e - \tau_d \right)
\]
\[
\tau_m = \frac{p}{\omega_0 + \Delta \omega_r}
\]
\[\tau_e = \frac{3}{2} \frac{R_r L_m^2}{R_r L_r + s L_r^2} \frac{1}{K_e} i_d i_q^* \]
\[
\tau_d = K_d \Delta \omega_r
\]
Virtual Induction Machine vs PLL

Redesigning inverter synchronization:
- replacing PLL with a VIM
- preserving synchronization and order of the DAE system
- standalone operation is achieved

\[
\dot{\theta}_{pll} = \omega_{pll} \omega_b
\]

\[
\omega_{pll} = \omega_n + K_{pll}^{p} \dot{e}_g + K_{pll}^{i} \varepsilon
\]

\[
\dot{\varepsilon} = \dot{e}_g
\]

\[
\dot{\theta}_{pll} = \omega_{pll} \omega_b
\]

\[
\omega_s = \omega_0 + \Delta \omega_r + \omega_\nu
\]

\[
\omega_\nu = \left( \frac{R_r}{L_r} + s \right) i_g^q i_d^g K_\nu
\]

\[
\tau_m = \frac{p}{\omega_0 + \Delta \omega_r}
\]

\[
\tau_e = \frac{3}{2} \frac{R_r L_m^2}{2 R_r L_r + s L_r^2} i_g^d i_g^q K_e
\]

\[
\tau_d = K_d \Delta \omega_r
\]
Virtual Induction Machine vs PLL

Grid-Following Control, Frequency Regulation & Stability in Low-Inertia Systems

Uros Markovic (PSL)

October 16, 2019 13 / 20
Start-up & Synchronization

- The controller possesses **soft-start** and **self-synchronization** capabilities
- Adequate **damping** characteristic and **acceptable transients**
- Initial **overcurrent spikes** resemble the characteristic response of an induction machine
- Active and reactive **power setpoints are met** in steady-state
Start-up & Synchronization

- The controller possesses **soft-start** and **self-synchronization** capabilities
- Adequate **damping** characteristic and acceptable transients
- Initial **overcurrent spikes** resemble the characteristic response of an induction machine
- Active and reactive **power setpoints are met** in steady-state
- Frequency of the output voltage **stabilizes at the synchronous frequency**
- Frequency slip term is very **volatile during transients**
Setpoint Variation & Reference Tracking

- **Smooth transition** during setpoint variations and **responsive reference tracking**
- **Small mismatch** between the active power output and the setpoint due to the **damping term** in the swing equation
Stability Analysis

- **Stability region** of a VIM-based unit resembles the one of a grid-forming inverter
- Justified by the preserved **standalone capabilities** of an induction machine
Stability Analysis

\[ \eta^* = 1 \]

\[ \Re(\hat{\lambda}) \]

PLL-Droop
VIM-Droop
VIM-VIE

\[ Uros Markovic (PSL) \]

Grid-Following Control, Frequency Regulation & Stability in Low-Inertia Systems

October 16, 2019 16 / 20
Understanding Stability of Low-Inertia Power Systems
SGs operate on drastically **longer timescales** than the transmission lines

- Faster VSC controls tend to **destabilize** the system in terms of **voltage** and **frequency**
- **Line dynamics** become of crucial importance for system **synchronization** and **stability**
Unit Interactions in a 2-bus System

\[ \eta \equiv \eta_f = \frac{p_{cf}}{p_{cF} + p_{cf}} \]
Unit Interactions in a 2-bus System

\[ \eta \equiv \eta_f = \frac{p_{cf}}{p_g + p_{cf}} \]
Unit Interactions in a 2-bus System

\[ \eta \equiv \eta_F = \frac{p_{cF}}{p_g + p_{cF}} \]
Unit Interactions in a 2-bus System
Impact of System Operating Point

![Graph showing the impact of system operating point](image-url)

- $p_c^* = 0.2$
- $p_c^* = 0.3$
- $p_c^* = 0.4$
- $p_c^* = 0.5$
- $p_c^* = 0.6$
- $p_c^* = 0.7$
- $p_c^* = 0.8$

$\zeta(\lambda)$ vs $\Re(\lambda)$
Key Takeaway Messages

- **Transition might be hard**
  - Preserving stability in transmission networks with high share of renewables might be harder than in the case of 100% inverter-based systems

- **Need for uniform regulation**
  - Current grid codes and converter mode classification lack foundation and tend to drastically differentiate between different operators and industries

- **Timescale separation**
  - One of the main contrasts between the traditional and low-inertia systems is a timescale separation between the respective controllers of synchronous and inverter-based generators, which leads to frequency and voltage instabilities under high penetration of renewables

- **Premise of line dynamics**
  - With the introduction of fast-acting PE devices, transmission line dynamics become drastically more important in networks with low rotational inertia

- **System operation point is of crucial importance**
Thank you for your attention!
Let’s discuss now...

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Modelling Approaches and Stability Assessment for 100% Converter-Based Systems

Xianxian Zhao, Priyankao Thakurta, Damian Flynn
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Contents

• Ireland 2030 Plan & Deliverable Objective
• Test System
• Grid-Forming Only Scenario
• Minimum Grid-Forming Share Scenario
• Distributed Grid-Forming Sharing Scenario
• Grid-Supporting Converter Design & Simulation
• Conclusions
This sums up our strategy for the next five years. It shows the external context we face, and the strategic approach we will take in response.

70% Ireland's target for electricity from renewable sources by 2030

95% Renewable electricity on the system at any one time by 2030

Our purpose
Transform the power system for future generations

Our primary goal
Lead the island’s electricity sector on sustainability and decarbonisation

Our supporting goals
Operate, develop and enhance the all-island grid and market
Work with partners for positive change
Engage for better outcomes for all
Ireland + N. Ireland - 2030

Cumulative (% time) vs. (Wind + PV) / Demand (%)
Objectives

• Identify the **operational boundaries** of a 100% converter-based system:
  – How many, and in which locations, should converters be grid-forming in a 100% converter based system?

• Assess the **ability** of a 100% converter-based system, with a minimum share of grid-forming converters, to cope with various disturbances
Ireland – 100% PE Case

- Major load centres
- PV generation
- Wind generation

Wind + PV capacity based on Low Carbon Living scenario

Wind + PV capacity locations based on 10 year TFS + TES
Test System

• Ireland + N. Ireland power system
  – 400, 275, 220, 110 kV networks
  – Equivalent loads at lower voltage levels

• Existing conventional plant replaced by converters of equivalent capacity
  – Converters sited in the same locations
  – Prime movers not represented

• No pumped storage, no demand response, no synchronous condensers, etc.
Ireland – Load / Generation Locations

- Major load centres
- N. Ireland units
- Ireland units

- Converters size: 217 – 580 MVA
- 82 buses, 14 converter locations
- Grid-forming converters using $P-f$ and $Q-V$ droop controls
- Grid-following converters follow P & Q setpoints
Grid-Forming Control
(Mimic synchronous generator)

\[ V_{dc} \rightarrow I_c \rightarrow Z_f \rightarrow V_o \rightarrow P, Q \rightarrow Z_f \rightarrow I \rightarrow Z_g \rightarrow \text{Grid} \]

\[ Q-V \text{ Droop Control} \]

\[ Q^* \rightarrow m_q \rightarrow V_{od}^* \rightarrow V_{ref} \rightarrow m_q \rightarrow v_{oq}^* = 0 \]

\[ P-f \text{ Droop Control} \]

\[ \Delta \theta_{vsm} \rightarrow \omega_b \rightarrow s \rightarrow \Delta \omega_{vsm} \rightarrow m_p \rightarrow P^* \]

\[ \text{Virtual Impedance} \]

\[ I_c \rightarrow I_{max} \rightarrow \infty \rightarrow 0 \rightarrow \text{Virtual Impedance} \]

\[ \text{Soft current limit} \]
Grid-Following Control
(Follow P & Q setpoints)

Follow P&Q setpoints

Phase-locked loop (PLL) follows grid frequency
Modelling Environment

Modelica
Analysis Conditions

- 3-phase faults (100 to 250 ms)
- 3-phase faults with line opening
- Line switching in/out
- Generator tripping
- Load tripping
Grid-Forming Only Scenario

3-phase fault applied @ all buses
Grid-Forming Only Scenario
(100 ms, 3-phase fault at bus Inchicore)
Grid-Forming Only Scenario
(100 ms, 3-phase fault at bus Inchicore)
Minimum Grid-Forming Share

• Replace *in-turn* grid-forming converters by grid-following converters (same capacity)
  – Begin with remote locations ... urban locations
  – Recognition of existing *must-run* generator locations

• Apply 3-phase faults (100 - 250 ms) @ all buses

• Switch in/out network lines
Minimum Grid-Forming Share

System grid-forming (MVA) ratio

\[
SGFR_{100} = \frac{GF_{online}}{GF_{online} + g_{f\,online}} = 37.5\%
\]

3-phase fault applied @ all buses
Minimum Grid-Forming Share
(100 ms, 3-phase fault at bus Inchicore)
Minimum Grid-Forming Share
(100 ms, 3-phase fault at bus Inchicore)

*Grid-following* response

![Graph showing reactive and active power response over time for Whitegate and Moneypoint.](image-url)
Minimum Grid-Forming Share
(100 ms, 3-phase fault at bus Inchicore)

Grid-following response

- Whitegate
- Moneypoint
- Dublin Bay
- Coolkeeragh

Time (s)

$\Delta \omega_{PLL}$
Minimum Grid-Forming Share
(100 ms, 3-phase fault at bus Inchicore)

**Grid-forming** response

- **Reactive power (pu)**
  - Great Island: Solid blue line
  - Woodland: Dotted orange line
  - Aghada: Dashed yellow line

- **Active power (pu)**
  - Great Island: Solid blue line
  - Woodland: Dotted orange line
  - Aghada: Dashed yellow line
Minimum Grid-Forming Share

*(Slower PLL)*

\[ V_{dc} \]

\[ Z_f \]

\[ I \]

\[ V_t \]

\[ Z_g \]

Grid

\[ P^* \]

\[ V_t \]

\[ i_d^* \]

Current control

\[ i_d, i_q \]

\[ \Delta \theta_{pll} \]

\[ \frac{\omega_b}{s} \]

\[ \Delta \omega_{pll} \]

\[ V_{tq} \]

\[ dq \]

\[ abc \]

\[ I \]

\[ V_t \]

PI

Minimum Grid-Forming Share

*(Slower PLL)*
Minimum Grid-Forming Share
(100 ms, 3-phase fault applied at Inchicore)

Slower PLL
Minimum Grid-Forming Share

System grid-forming (MVA) ratio

$$SGFR_{100} = \frac{GF_{\text{online}}}{GF_{\text{online}} + g f_{\text{online}}}$$

$$= 37.5\%$$
Minimum Grid-Forming Share
Minimum Grid-Forming Share
(Line between Dunnstown-Kellis opened and reclosed)

**Grid-following response**

- **Active power (pu)**
  - Whitegate
  - Moneypoint

- **Reactive power (pu)**
  - Huntstown
  - Dublin Bay
  - Coolkeeragh

**Times (s)**

- 2
- 2.2
- 2.4
- 2.6
- 2.8
- 3
- 3.2
- 3.4
- 3.6
- 3.8
- 4
Observations

- PLL operation (of grid-following converters) is critical
- Minimum grid-forming set depends on fault duration
- Slower PLL response can improve system performance
- No major issues associated with line switching in/out operations
Distributed Grid-Forming Sharing

• Most converters will be small in size compared to conventional plant
  – Individual buses will consist of a non-uniform mix of grid-forming and grid-following converters
• ...
• Assume that individual buses consist of an adjustable mix of GF and gf converters
• Assess system stability for a range of fault conditions and GF/gf distributions
Major load centres

- Grid-forming converter
- Grid-following converter

Distributed Grid-Forming Sharing

North

- Cookeeragh
- Ballylumford
- Kilroot

South

- Moneypoint
- Aghada
- Great Island
- Whitegate

Dublin

- Dublin Bay
- Huntstown

- North Dublin
- South Dublin

- Kilroot
## Distributed Grid-Forming Sharing

<table>
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<th>Ireland (GF %)</th>
<th>North (GF %)</th>
<th>Dublin (GF %)</th>
<th>South (GF %)</th>
<th>Ballylumford North (near)</th>
<th>Tamnamore North (far)</th>
<th>Inchicore Dublin (near)</th>
<th>Shannonbridge Dublin (far)</th>
<th>Aghada South (near)</th>
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29.5% Grid-Forming Share
(100 ms, 3-phase fault applied at 3 locations)

*Grid-following responses*
PLL Instability Principle

\[ V_{dc} \]

\[ \Delta \theta_{pll} \]

\[ Z_f \]

\[ I \rightarrow V_t \]

\[ Z_g \]

\[ \text{Grid} \]

\[ X_g i_d^* + R_g i_q^* \]

\[ L_g i_d^* \]

\[ \Delta \omega_{pll} \]

\[ \Delta \theta_{pll} \]

\[ \frac{\omega_b}{s} \]

\[ V_t \sin \Delta \theta_{pll} \]
Grid-Supporting Converter Control
(for LVRT requirement and PLL stability)

\[ \sqrt{I_{\text{max}}^2 (1 - k^2)} \]

Current

\[ |i_q^*| \]

\[ i_d^* \]

\[ V_{th2} \]

\[ V_{th1} \]
Grid-Supporting Converter
(Active current reference design)
Grid-Supporting Converter
(Reactive current reference design)

\[ Q^* \rightarrow -Q^* \]
\[ V_t \rightarrow \frac{-Q^*}{V_t} \]
\[ \sqrt{I_{max}^2(1 - k^2)} \]
\[ i_q^* \]

\[ V_t \rightarrow \frac{-Q^*}{V_{th1}} - K_v(V_t - V_{th1}) \]

\[ V_t \rightarrow 0 \]

\[ V_{th1} \rightarrow V_t \]

\[ 1 \rightarrow 0 \]

\[ 0 \rightarrow \sqrt{I_{max}^2(1 - k^2)} \]
Grid-Supporting Converter

Major load centres
- Grid-forming converter
- Grid-supporting converter

System grid-forming (MVA) ratio

\[
SGFR_{100} = \frac{GF_{online}}{GF_{online} + gS_{online}} = 18.1\%
\]

3-phase fault applied @ all buses
Grid-Supporting Converter
(250 ms, 3-phase fault applied at Inchicore)

18.1% grid-forming share
Grid-Supporting Converter
(250 ms, 3-phase fault applied at Inchicore)

Grid-supporting response
Grid-Supporting Converter
(250 ms, 3-phase fault applied at Inchicore)

Grid-supporting response
Grid-Supporting Converter

for PMSG-based wind turbine system

• Previous assumption of *idealised* grid-supporting converters
• Effect of DC voltage control on stability of grid-side converter
• Effect of prime mover and its control on stability of grid-side converter
Grid-Supporting Converter

for PMSG-based wind turbine system

\[ \omega_r = y = f(x) \]

Maintain Vdc

MPPT
Grid-Supporting Converter

for PMSG-based wind turbine system
(250 ms, 3-phase fault applied at Inchicore)
Grid-Supporting Converter

for PMSG-based wind turbine system

(250 ms, 3-phase fault applied at Inchicore)
Conclusions

• Grid-forming only scenario is robust to applied disturbances on test system

• Performance of GF/gf mix system is subject to gf PLL ‘following’ capability

• *Distributed, small-scale* versus *large-scale* grid-forming can reduce system GF requirement

• Grid-supporting converters should improve upon grid-following converters
Modelling Approaches and Stability Assessment for 100% Converter-Based Systems

Xianxian Zhao, Priyanko Thakurta, Damian Flynn
University College Dublin
REQUIREMENT GUIDELINE FOR GRID CODES

Thibault PREVOST / Guillaume DENIS
RTE
Grid-forming and Grid code

In WP3, were developed « grid forming » controls from basic specifications, and individual tests.

They turned out to be compatible with each other, and have a small signal behavior that is very similar.

Question: is it possible to define « grid forming » through grid code requirements ?
Grid-forming and Grid code
From WP3 outputs

VSC Grid-Forming Function:

Necessary conditions

- Stiff Urms* (with limited voltage sensibility)
- f-P static droop around fn (with limited frequency dynamics)
- « Transient » stability during current limitation
- to survive islanding from the "main" grid

Ideal electrical sources

- 3ph - Voltage Sources
- Perfectly synchronized
- Infinite power supply
- Infinite energy storage

Physical constraints of PE-based system

- Voltage and Current of VSC
- Power and energy
- Frequency and phase
- Limited variable

Compatibility with other sources (SG, gf, IM)

From WP3 outputs

https://www.h2020-migrate.eu/downloads.html
What about Synchronous Generators?
They are GFM from their physics...

(Sub)transient reactance

\[ X'd \]

- **Small-signal**: Stiff voltage source
- **Large-signal**: High short-circuit current

Mechanical inertia

\[ H \]

- **Small-signal**: Limit the RoCoF
- **Large-signal**: High kinetic energy reserve

+ Primary voltage control
+ Speed regulation
The good questions for a TSO

- How to quantify the grid-forming requirement?
- How to be technically agnostic?
- How to Redefine the future stability analysis between small-signal studies and large-signal studies?
Motivations for external qualification of GF

Mot. 1/4 : Never been specified for synch. generators

- Present grid-code examples:
  - “The output RMS voltage at the source terminal must track a reference within a time response of 10 s”.
  - “The frequency must track an adjustable reference within a time response of 15 s”.

Today, there are no requirement for voltage stiffness of an electrical source under the second time scale.

Warning: No generalized values!
Motivations for external qualification of GF

Mot. 2/4 : Several VSC control structures claim to be grid-forming

Filtered frequency droop

Dispatchable Virtual oscillator

Matching control

Open source models

+ multiple other in Literature:
  
  Virtual Synchronous Machine (VSM), Virtual synchronous generators (VSG), Power Synchronization Control, Direct Voltage Control, Grid-supporting...

=> Should not enforce one control solution. (manufacturers do it better)
Motivations for external qualification of GF

Mot. 3/4 : They are no plenty ways to do grid-forming (with the definition we have)

Fig. 3: IEEE 9-bus system with large-scale converter systems.


=> Which appears to be behaving similarly, and are compatible when connected on the same grid.

=> And to be compatible with synchronous machines
Motivations for external qualification of GF

Mot. 4/4 : TSOs cannot enforce the technology

D6.3 in Migrate showed that the cost of the 2 solutions are in the same order.
How to integrate GF in a system

adapt speed of controls

Electrical « Inertia », will be configurable, depending on the choice made, primary frequency control may need to be adapted.

Behaving in grid forming implies a « small » storage on the DC side, size of this storage depends on : flexibility of the primary source and the speed of the other sources on the grid to handle.
Frequency-domain of frequency
« Frequency smoothing capability »


\[ \nu_c = 5Hz \]
Limited frequency dynamics in small-signal

Example of time-domain frequency profile

Warning: No generalized values!

ROCOF limited to 2 Hz/s (For proper frequency measurement)

Frequency Profile for 10% Pnom connection

4% of static droop

With secondary frequency regulation
New « transient » stability

Support Nominal Voltage as long as $I \leq I_{\text{max}}$, or stay $I_{\text{max}}$

« Stay Synchronized »
- Back to steady-state in 200ms
- Breaker remain close
- No control switch

For synchronous machine, the issue was the kinetic energy stored during faults.
For inverters, the issue is the overcurrent and synchronisation.
The most constraining event might be different.
Conclusion:

Grid code requirements for grid forming is not easy nor ready

But:
- there are many ways of implementing grid forming but a single grid forming behavior
- basic test cases already highlight necessary conditions, (but they might be others)
- external characterization using transfer function provides good results