MIGRATE WP3 : OPERATING A SYSTEM WITH 100 % POWER ELECTRONICS

Guillaume DENIS, Thibault PREVOST, RTE, 28th February 2019, Berlin

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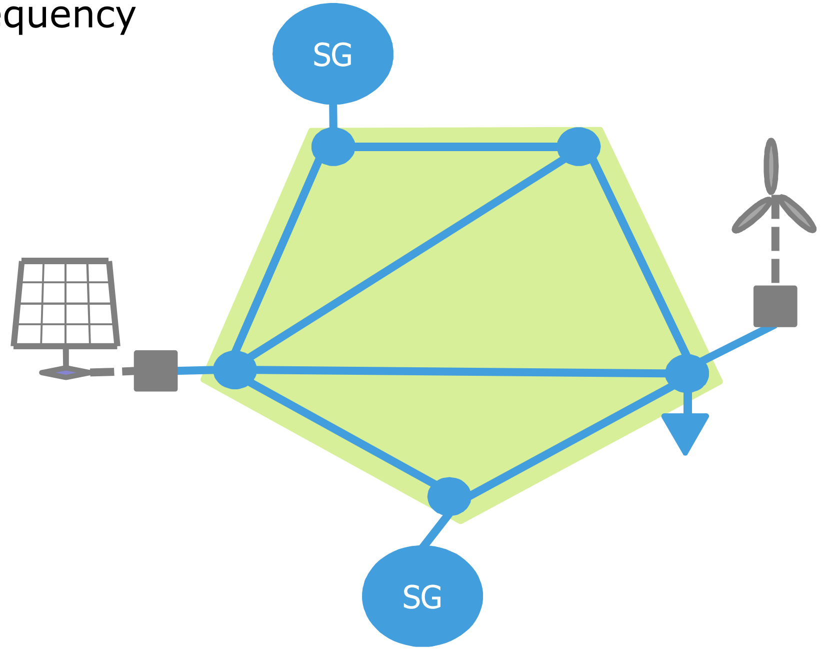
THE INITIAL QUESTION

Today inverters connected to the grid are "grid-following": they measure the frequency and adapt their current injection to provide active/reactive power with the same frequency



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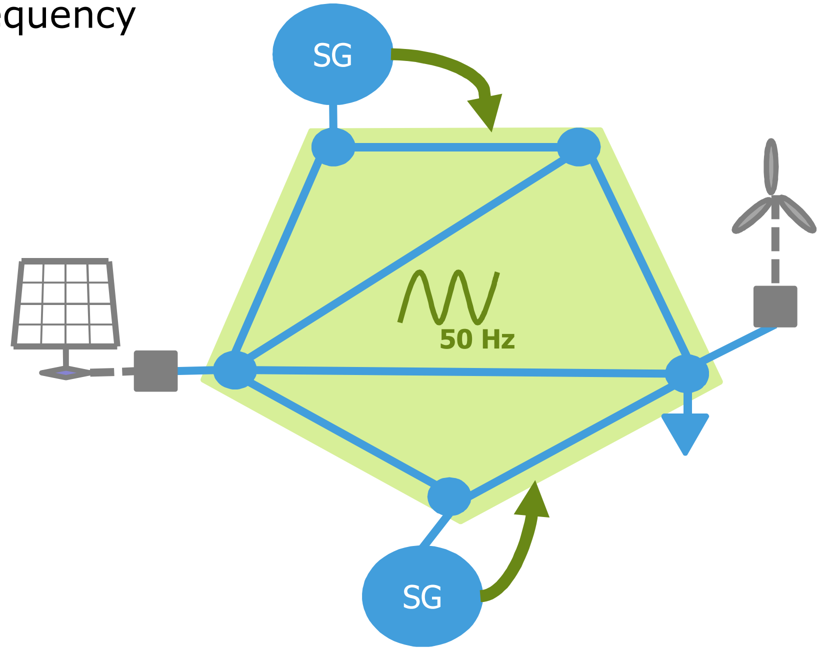

Synchronous machines create voltage waveforms with the same frequency.

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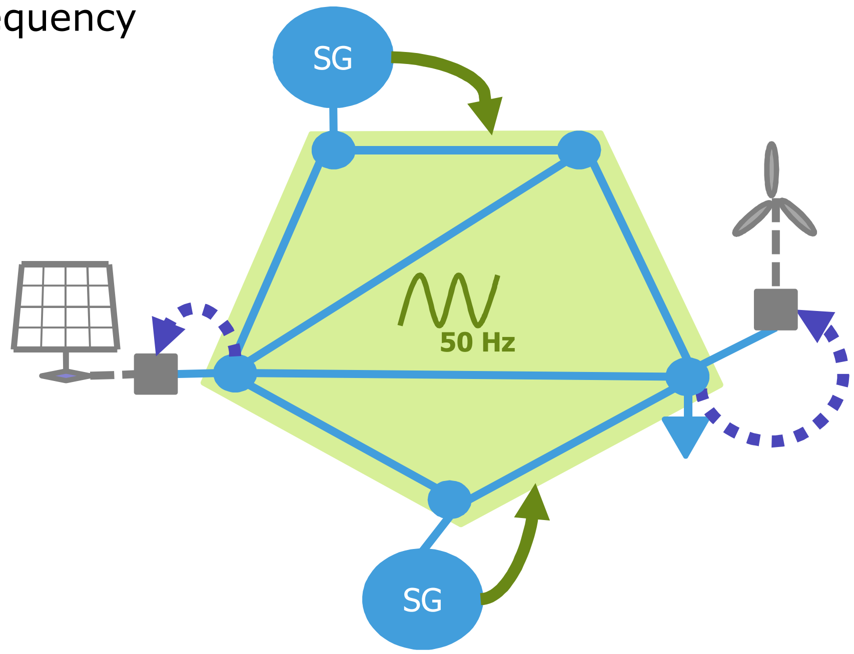

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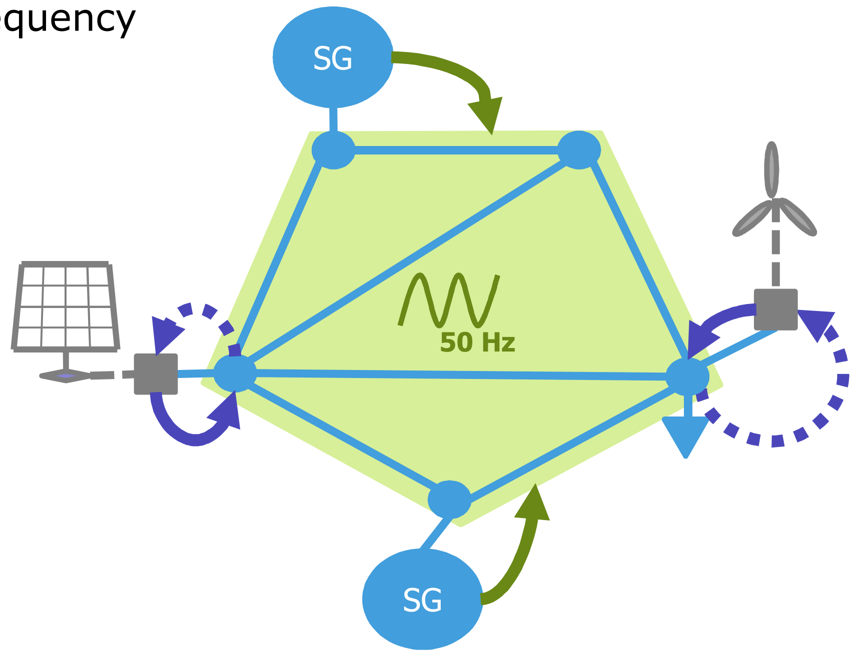

Synchronous machines create voltage waveforms with the same frequency.

Converters measure the grid frequency.

Converters provide active and reactive power at the measured frequency.

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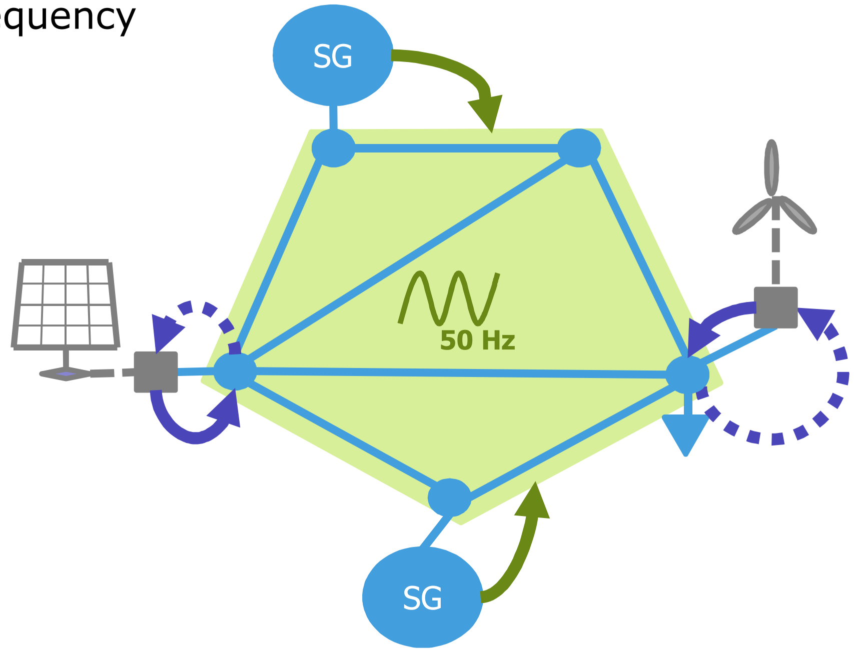

Synchronous machines create voltage waveforms with the same frequency.

Converters measure the grid frequency.

Converters provide active and reactive power at the measured frequency.

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.

OVERVIEW OF WP3 CHALLENGE

MIGRATE: Requirement for systems with high share of PE-interfaced devices:

Acceptable level of stability
while keeping costs under control

WP3: Control and operation of **large transmission systems** with **100%** converter-based devices

"to be forced to reset our brain"

Partners:

- 5 TSOs: EirGrid, REE, RTE, TenneT, TSO GmbH, Terna
- 3 universities: ETH Zürich, L2EP, University College Dublin

WP3 : THE PROBLEM ANALYSIS IN 2016 [D3.1]

Ideal electrical sources

3ph - Voltage Sources

Perfectly synchronized at f_n

Infinite power supply

Infinite energy storage

[D3.1] « Description of system needs and test cases », TSOs of MIGRATE project, Deliverable 3.1, 2016

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Physical constraints of PE-based system

Limited Bandwidth and Current of VSC

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Topology imposed and variable

Additional constraint of WP3

Compatibility with other sources (SG, gf, IM)

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Specific to AC ONSHORE Power System

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VSC Grid-Forming Function :

Ideal electrical sources

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

Physical constraints of PE-based system

- Limited Bandwidth and Current of VSC
- No communication
- Limited power and finite energy
- Topology imposed and variable

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WP3 : THE PROBLEM ANALYSIS 2018 [D3.2] [D3.3] [D3.4]

Ideal electrical sources	VSC Grid-Forming Function :	Physical constraints of PE-based system
3ph - Voltage Sources	As close as possible from **Voltage Source**	Limited Bandwidth and Current of VSC
Perfectly synchronized at f_n	**Stable synchronization** around nominal frequency	No communication
Infinite power supply	Decentralized **Load Sharing** services	Limited power and finite energy
Infinite energy storage	New **operational** rules	Topology imposed and variable

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WP3 : THE PROBLEM ANALYSIS 2018 [D3.2] [D3.3] [D3.4]

VSC Grid-Forming Function :

Ideal electrical sources

- 3ph - Voltage Sources
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VSC Grid-Forming Function :

- As close as possible from **Voltage Source**
- **Stable synchronization** around nominal frequency
- Decentralized **Load Sharing** services
- New **operational** rules

Physical constraints of PE-based system

- Limited Bandwidth and Current of VSC
- No communication
- Limited power and finite energy
- Topology imposed and variable

Additional constraint of WP3

- Compatibility with other sources (SG, gf, IM)

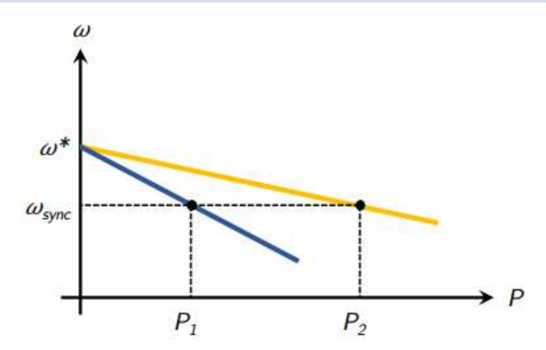
RESULT 1: GRID-FORMING CONTROLS

Three-different controls independently tuned on defined test-cases for robustness

L2EP — ETH zürich

Filtered frequency droop

- $\omega = \omega_{ref} + m_p \frac{(P_{ref} - P)}{T_p s + 1}$



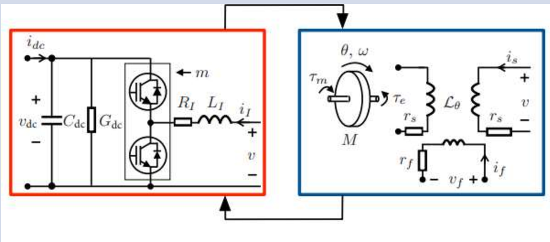
Dispatchable Virtual oscillator

- Under transmission system assumption :

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta_k = \frac{\eta}{v_k^{\star 2}}(p_k^\star - p_k),$$

$$\|v_k\| = v_k^\star + \frac{\eta}{\alpha v_k^\star}(q_k^\star - q_k).$$

Matching control



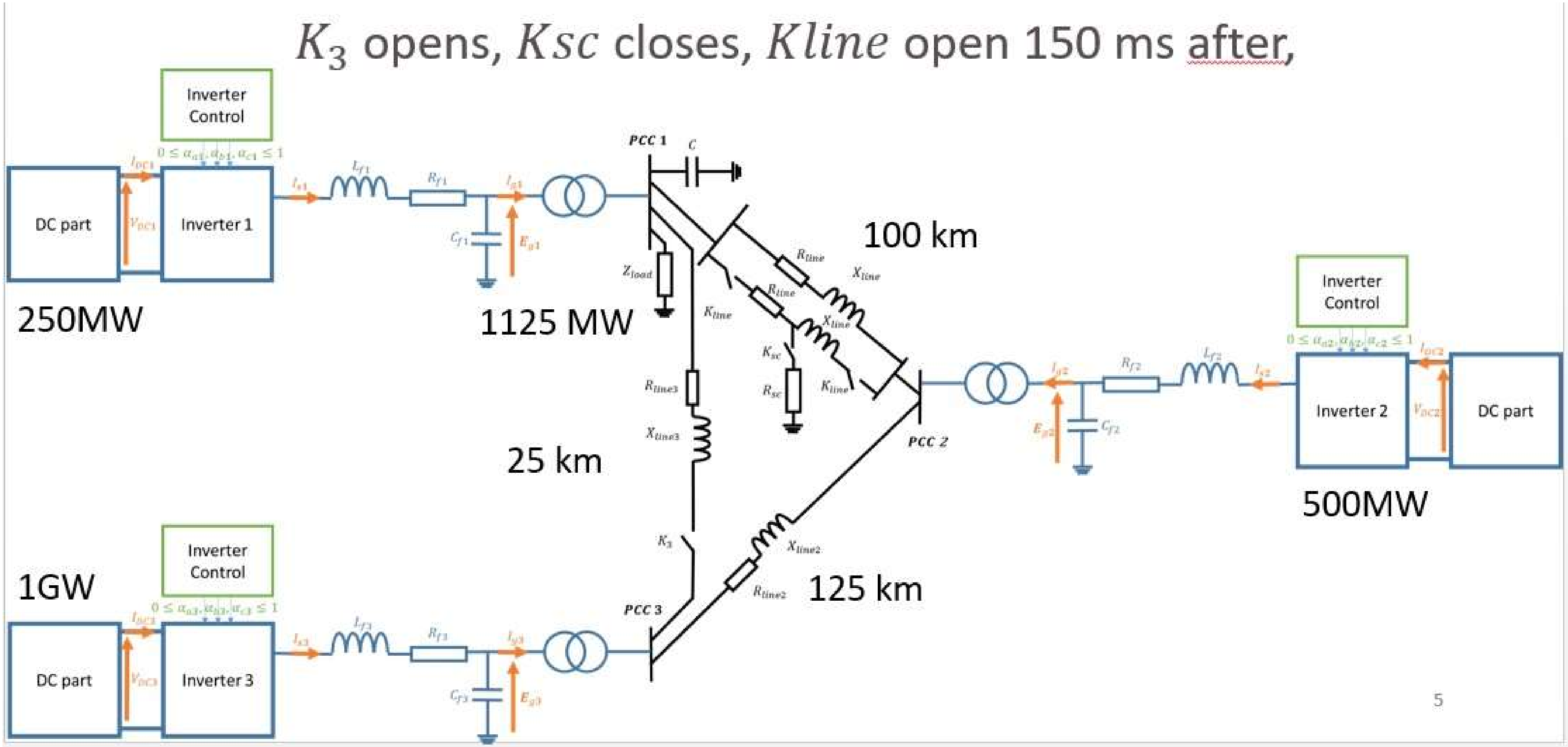
synchronous machine matching

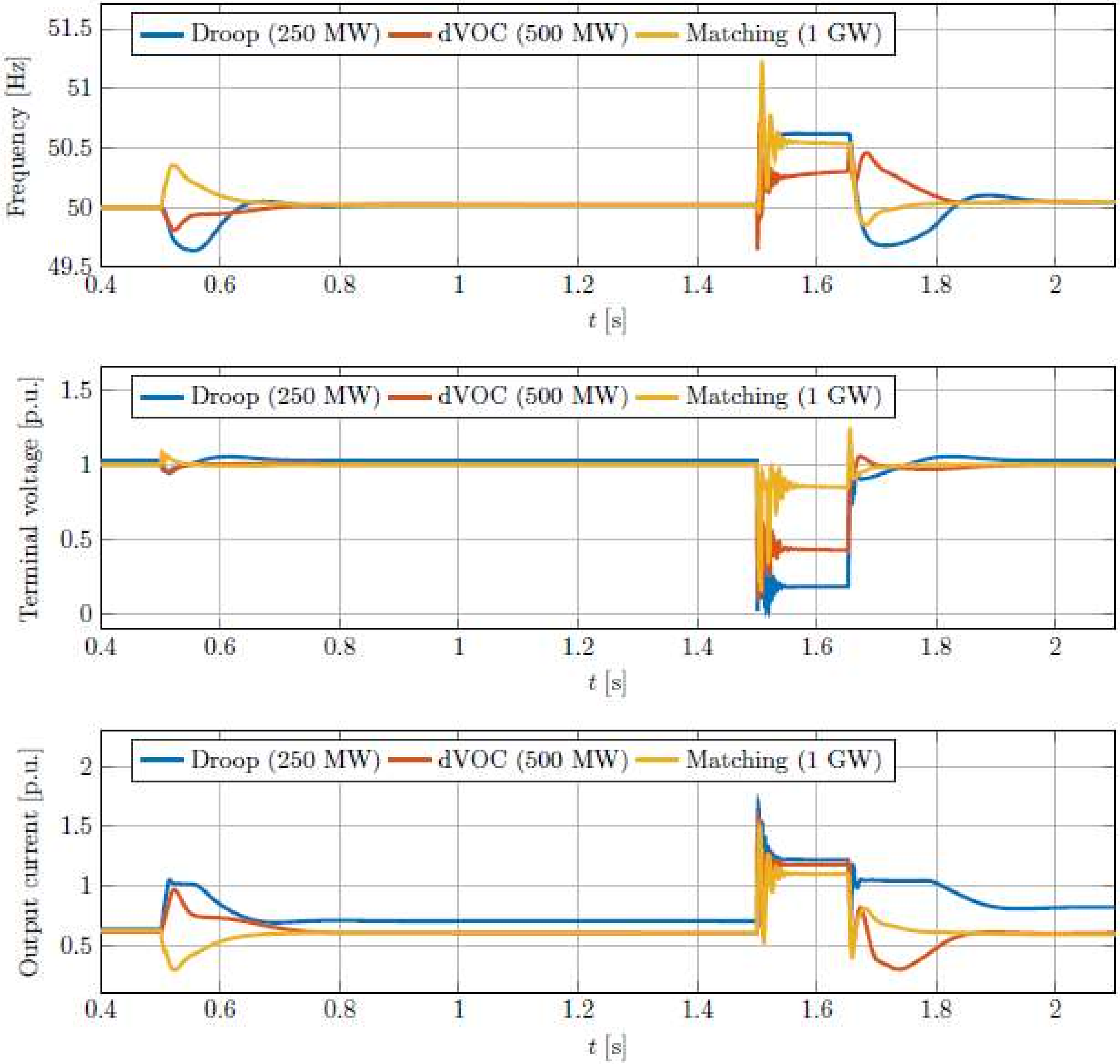
$$\mu = \mu^* + K_{ac}(P - P^*)$$

$$\mu^* = \frac{2V^*}{v_{dc}^*}$$

RESULT 1: GRID-FORMING CONTROLS

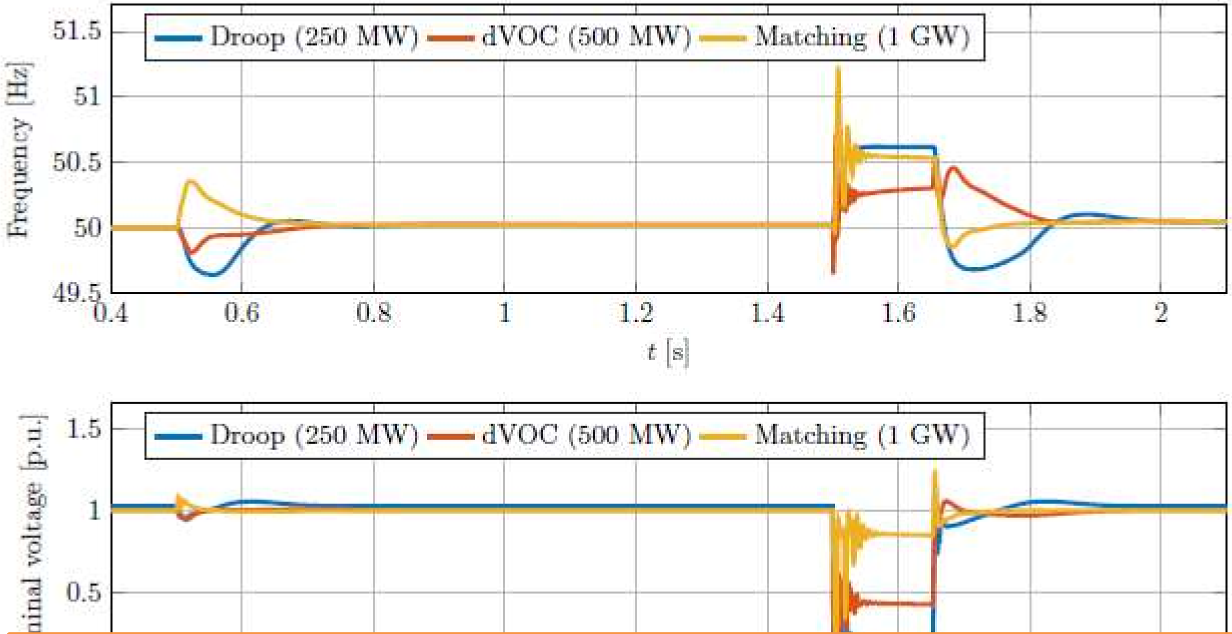
They turned out to be interoperable on 3-bus Benchmark





Events

- $t = 0.5$ s: line from PCC1 to PCC3 disconnected
- $t = 5$ s: short circuit near PCC1
- $t = 1.65$ s: short circuit is cleared



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Key finding :

1. Stability and robustness are achieved if after grid disturbance the response of the imposed voltage magnitude and frequency is « slow enough »

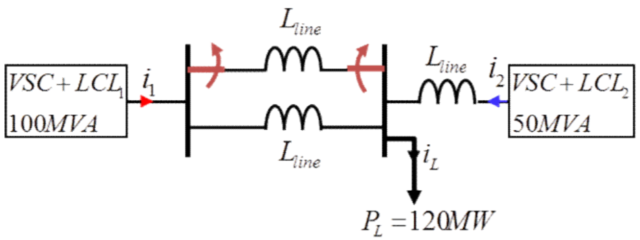
2. In small-signal, all the grid-forming control behave similarly, as seen from their output.

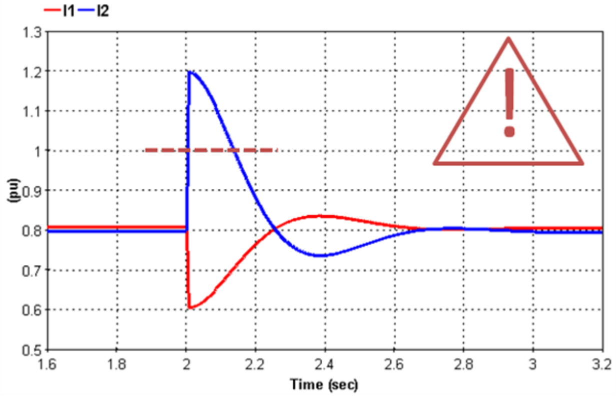
3. Interoperability of independently designed controllers

RESULT 2 : CURRENT-LIMITING STRATEGY

Slow voltage source are subject to overcurrent during stressing events

Problem :





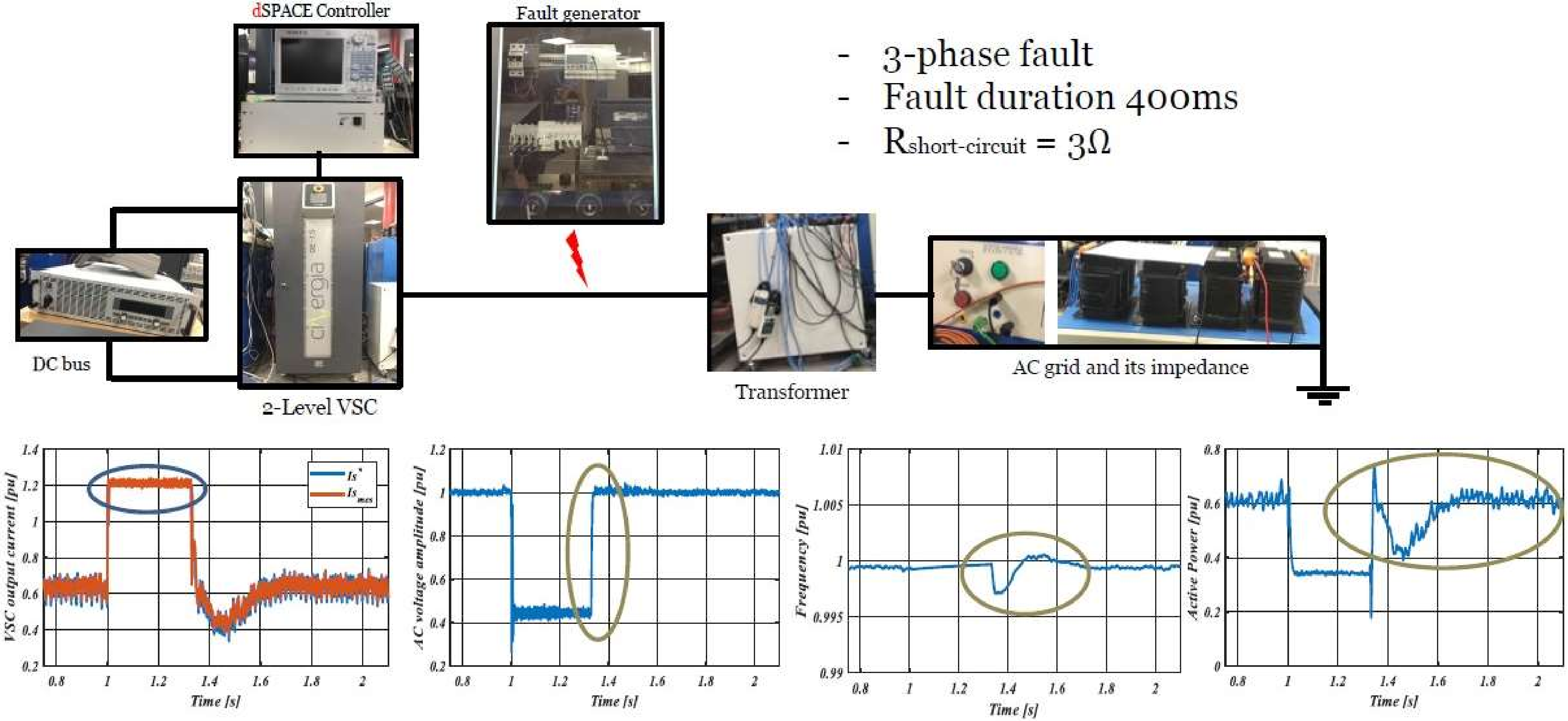
Proposed solution : Current loop saturation during first peak and virtual impedance afterwards

=> Validated concept in simulation, currently tested experimentaly

RESULT 2 : CURRENT-LIMITING STRATEGY

Slow voltage source are subject to overcurrent during stressing events

- 3-phase fault
- Fault duration 400ms
- $R_{short\text{-}circuit} = 3\Omega$



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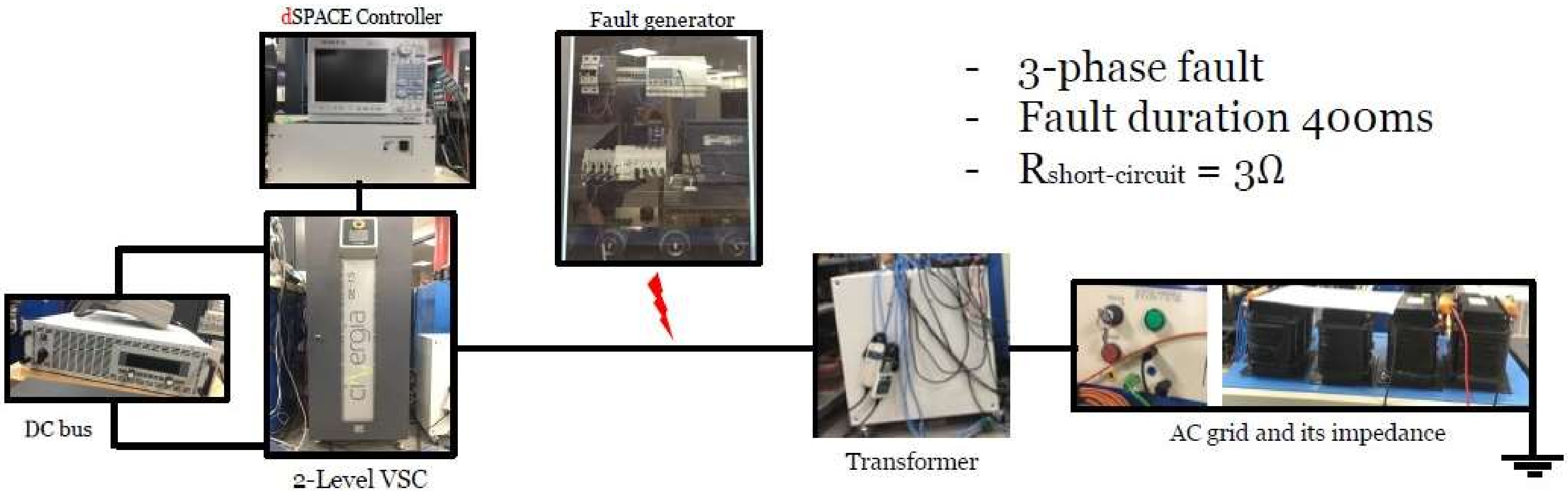

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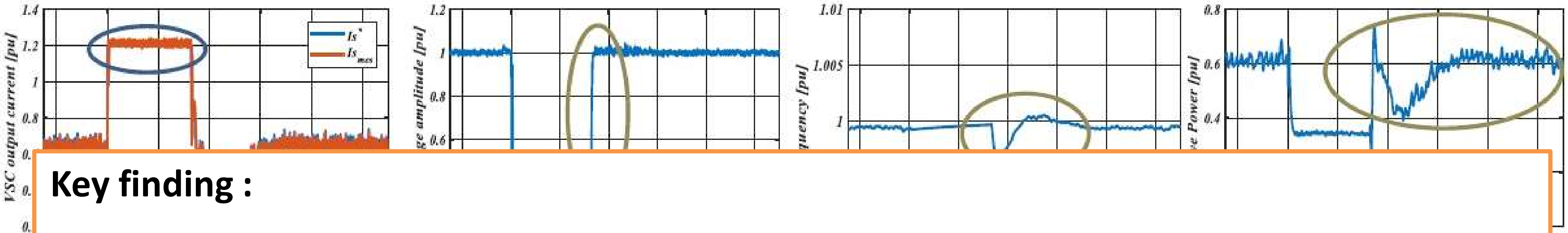


Key finding :

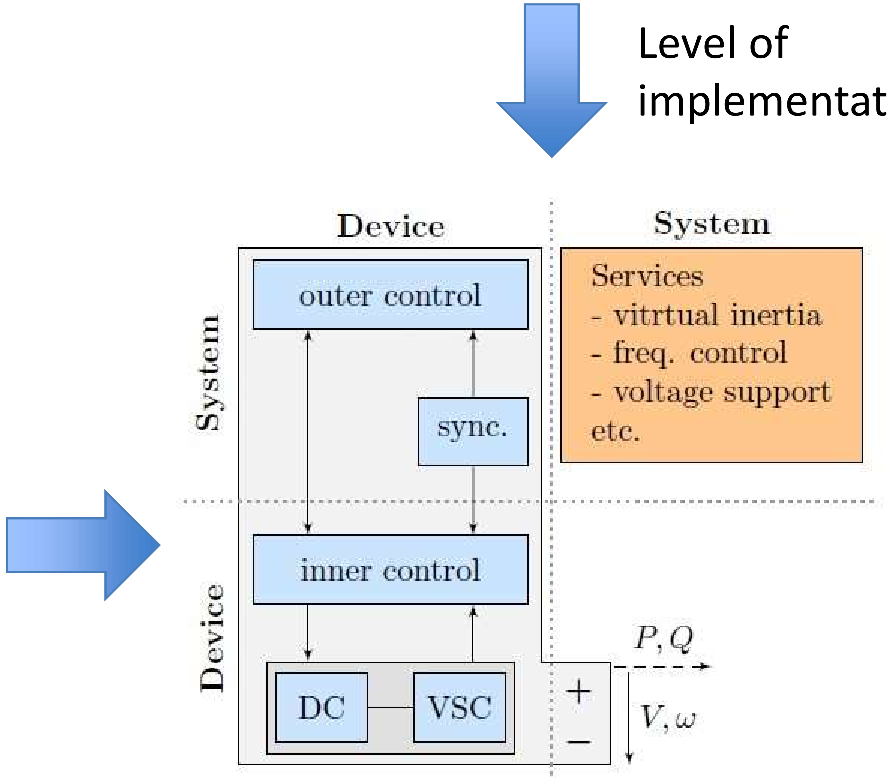
The developed current-limiting strategy is compatible with all three grid-forming controllers and real reduced size inverters.

RESULT 3: NEW ANCILLARY SERVICES

How to adjust grid-forming (GF) behavior to system needs ?

Level of implementation

Level of expressed needs



=> Efforts on abstraction and categorization of system-level behaviours to distinguish system vital needs and system possible optimization

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- **Proposed services**

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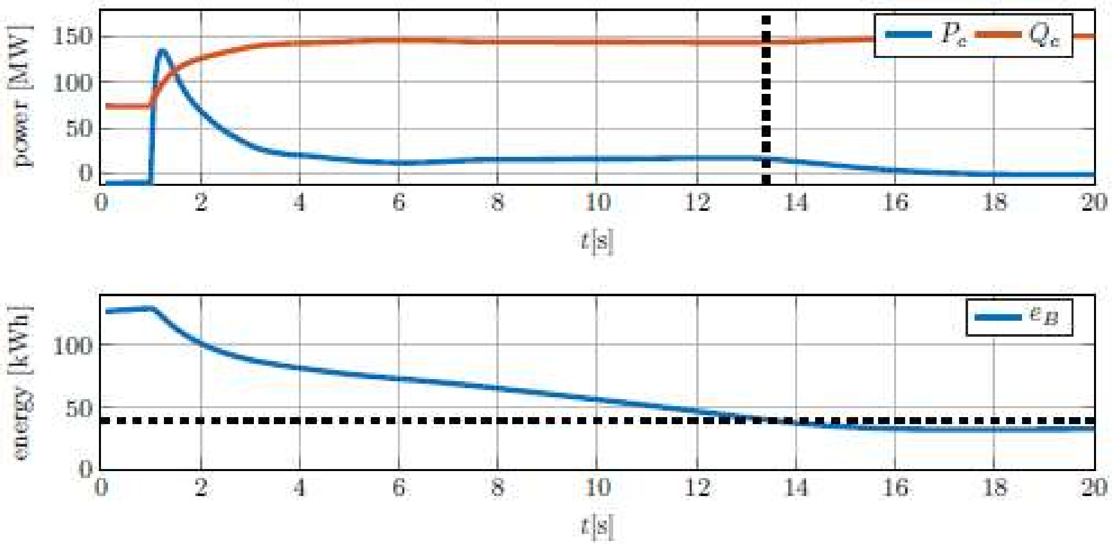
1. GF with limited storage



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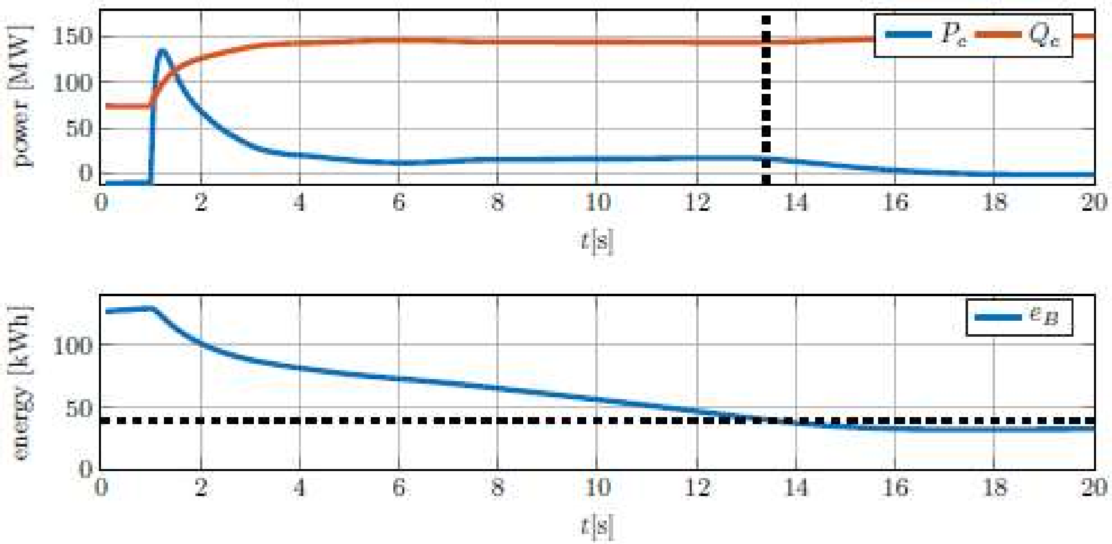
How to adjust grid-forming (GF) behavior to system needs ?

- **Proposed services**

1. GF with limited storage
2. Adaptative GF parameters

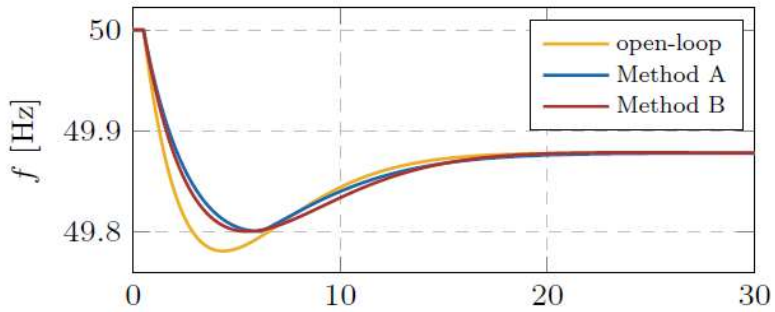


Frequency nadir and RoCoF

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

$$\dot{\omega}_{\max} = -\frac{\Delta P}{M}$$

optimization constraints



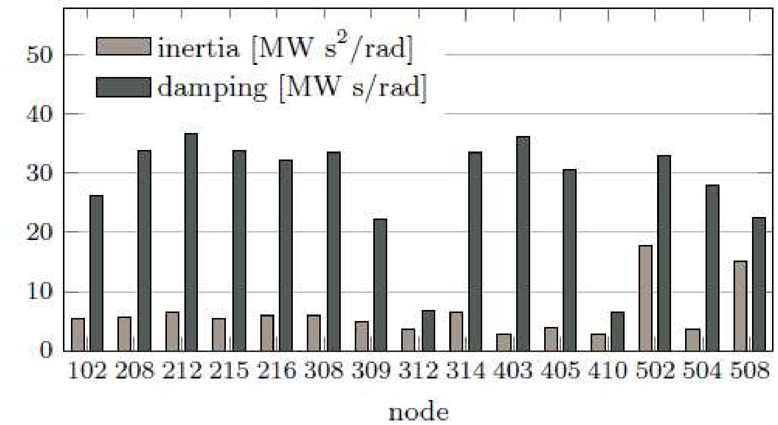
RESULT 3: NEW ANCILLARY SERVICES

How to adjust grid-forming (GF) behavior to system needs ?

- **Proposed services**

1. GF with limited storage
2. Adaptative GF parameters
3. Optimal GF placement

(a) Reinforcement with GF « electrical inertia »

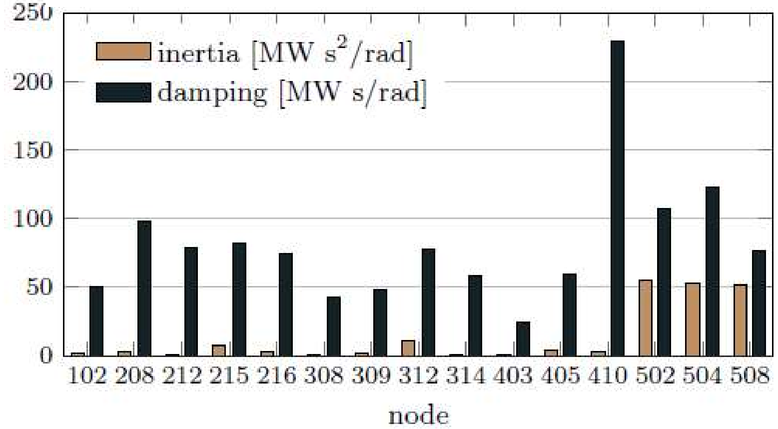


Objective

- minimize **disturbance amplification**
- Cost function for **disturbance response**:

$$\int_0^T r_G P_G^\top P_G + r_{VI} P_{VI}^\top P_{VI} + r_\omega \omega^\top \omega + r_{\dot{\omega}} \dot{\omega}^\top \dot{\omega} \, dt$$

(b) Reinforcement with grid-following « virtual inertia »



Test system

- detailed nonlinear 5 area model
- 10 generators, 59 buses

RESULT 3: NEW ANCILLARY SERVICES

How to adjust grid-forming (GF) behavior to system needs ?

- **Proposed services**

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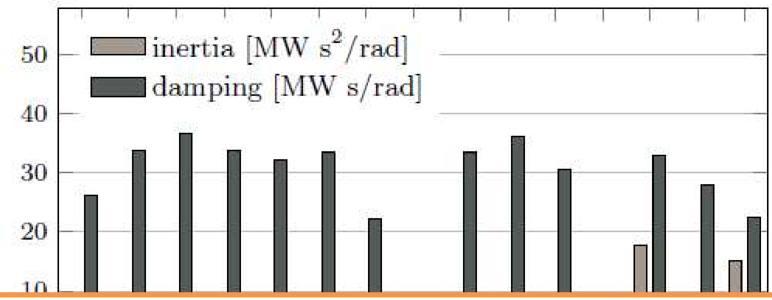
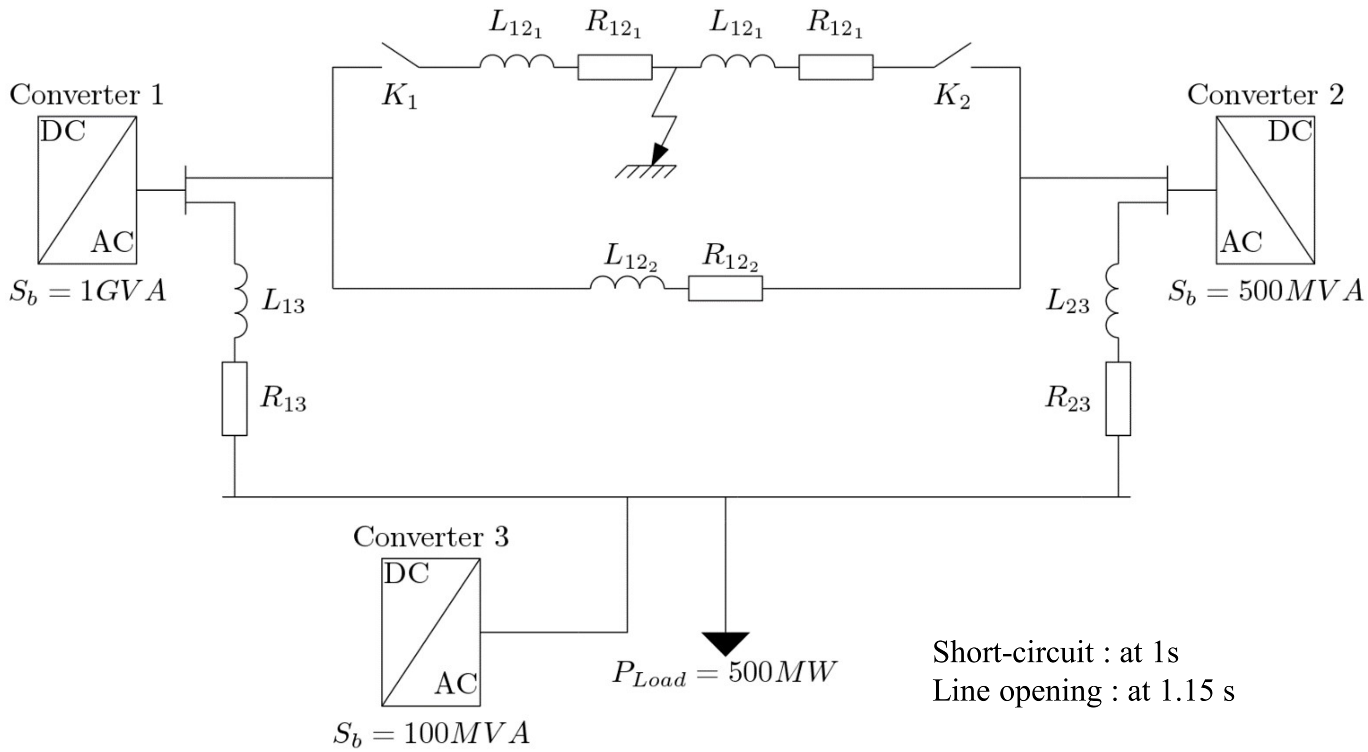


Key findings :

1. Power converters fast response & Flexibility required redefinition of system services
2. Services dependent on new technical constraints, ex : P/E ratio of batteries
3. Grid-forming control reduces the control effort compared to “virtual inertia”
4. Interference of new controls & services with market paradigms

RESULT 4: NEW LARGE SCALE MODELS

How to simulation large power system without synchronous machine ?



Short-circuit : at 1s
Line opening : at 1.15 s

RESULT 4: NEW LARGE SCALE MODELS

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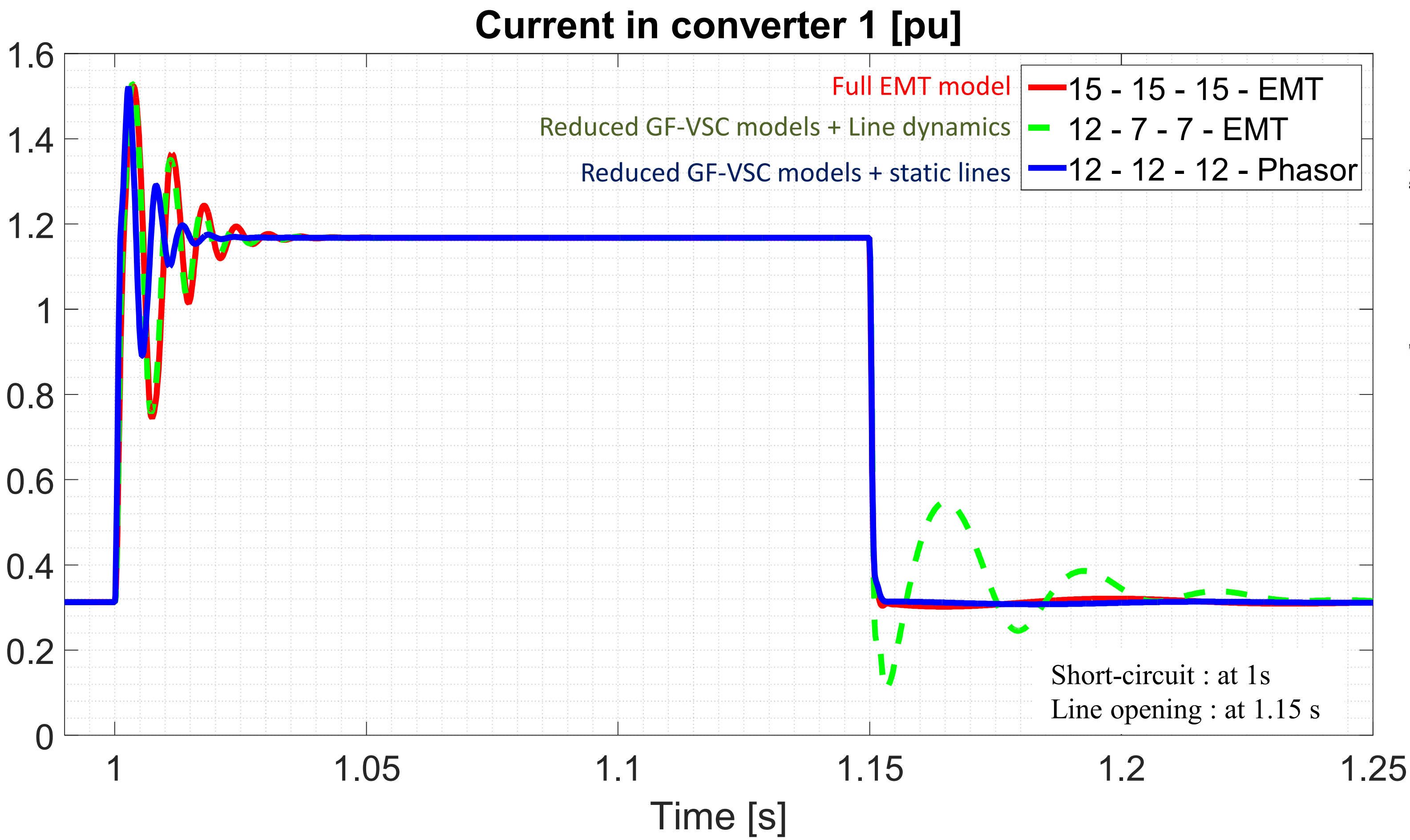

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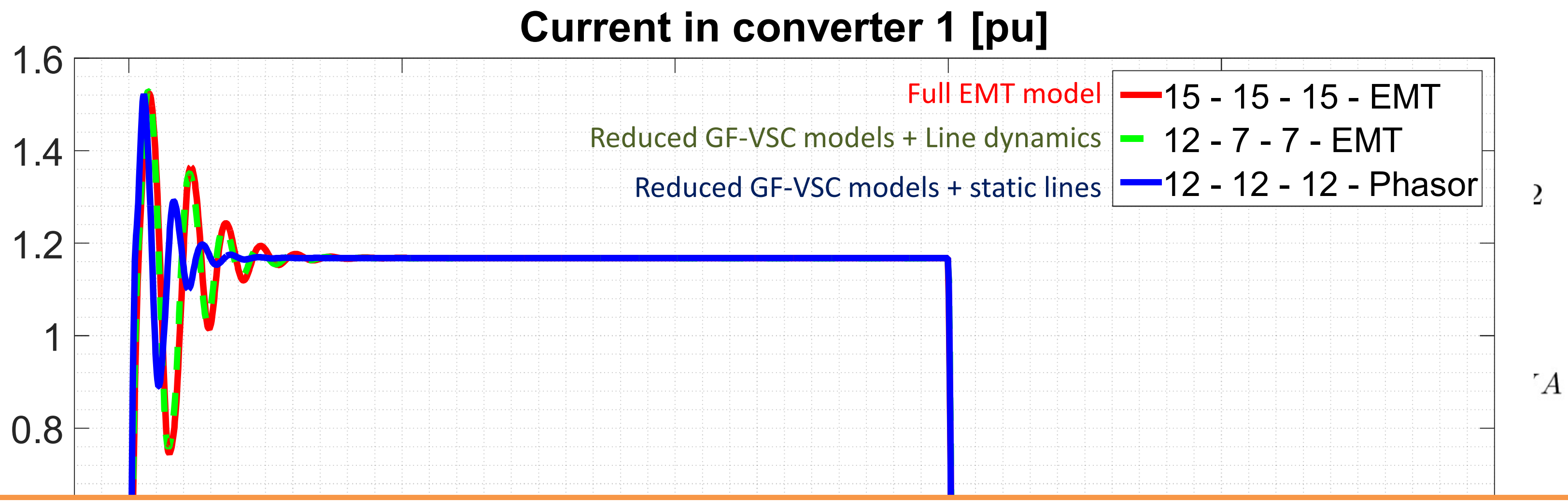


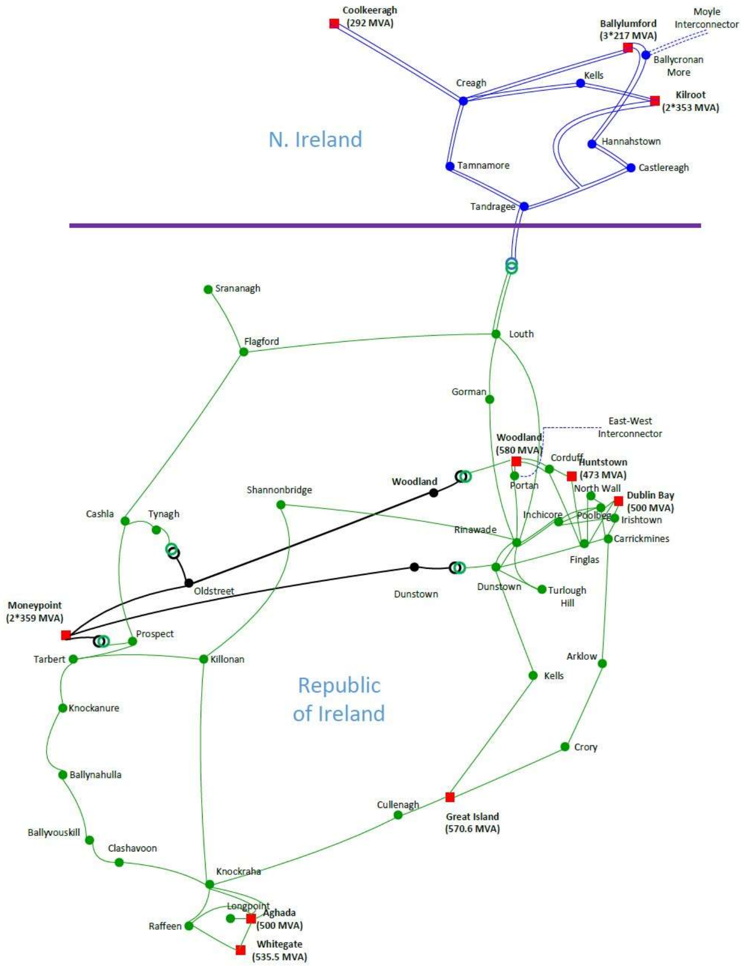
Key findings :

1. Not full EMT but lines dynamics along with some VSC controller states must be modelled

2. Depending on the transient event and localisation, accurate reduced models can still be used

RESULT 5: IRISH SYSTEM SIMULATION WITH 100 % POWER ELECTRONICS

Assessing the findings on a real case benchmark



RESULT 5: IRISH SYSTEM SIMULATION WITH 100 % POWER ELECTRONICS

Stability assessment for 100 ms, 3-phase faults for various distributed grid-forming / grid-following configuration

Ireland (GF %)	Ballylumf (near converter) North	Tamnam (far) North	Inchicore (near converter) Dublin	Shannonb (far) Dublin	Aghada (near converter) South	Ballyvoul (far) South
31.0	LG	LG	LG	LG	G	G
30.1	LG	LG	LG	LG	G	G
29.5	R	LG	LG	LG	G	G
28.9	R	R	R	LG	G	G
29.9	R	R	R	LG	G	G
28.8	R	R	R	LG	G	G
27.9	R	R	R	R	G	LG
26.3	R	R	R	R	R	R

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Key finding :
Following an **optimal placement procedure**, the level of designed grid-forming controlled PE capacity have been found to be **satifsfaying above 30 %** on the Irish System

CONCLUSIONS

1. **Grid-forming function performances have been unified** and defined from a system level perspective (techno-agnostic). The Grid-forming function gather the necessary conditions of a source to ensure proper and stable definition of **voltage waveform that resist to small-disturbance**, throughout a multi-sources grid.
2. Suitable **current-limiting strategy can protect sensible power-electronics devices** during stressful event without compromising their grid-forming function and without requiring costly oversizing.
3. **The Large inertia** historically provided by Synch. Gen. **is not a goal itself**. A minimum "electrical inertia" level is still needed, but probably lower than today. This level is characterized by a **frequency dynamic limitation (Rocof max),** driven by stability conditions and local needs of frequency measurement.
4. **Low inertia/faster systems** and Grid-forming converters open the path to **new services** to share the regulation efforts amongst capable sources. These services can improve the stability starting from today
5. The simulation of the **large scale Irish system** illustrated how all synchronous generation can realistically be **replaced by a limited capacity of the proposed Grid-forming algorithm** for power-electronics based converters

Thank you for your attention!