Le réseau de transport d'électricité

HVDC-Pro dissemination workshop

Inertia management in France and Europe, a TSO perspective about future trends and some ongoing research

28/4/2022

Thibault PREVOST
thibault.prevost@rte-france.com

Agenda

Inertia in France and Europe

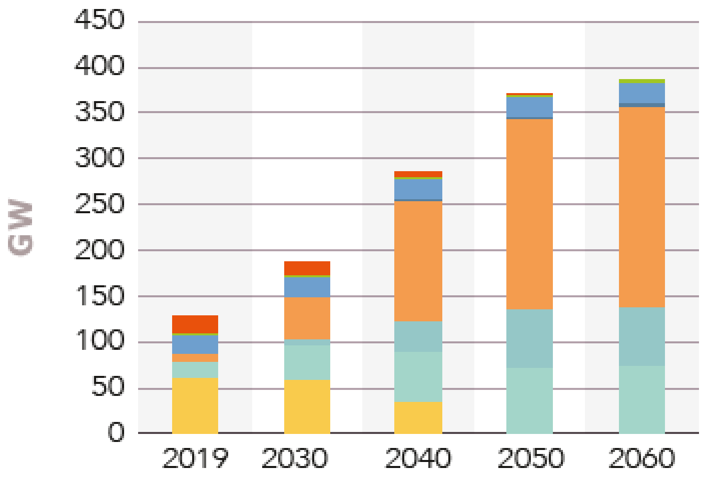
OSMOSE WP3

French system Evolution

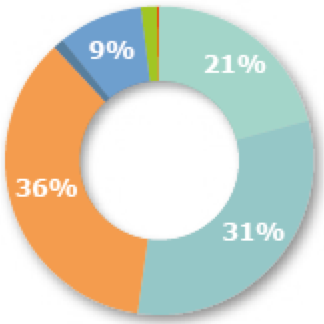
Scénario M0 : 100 % renouvelable en 2050

Sources de production d'électricité

Capacités installées par filière



Bilan énergétique annuel en 2050



(capacités installées/production)

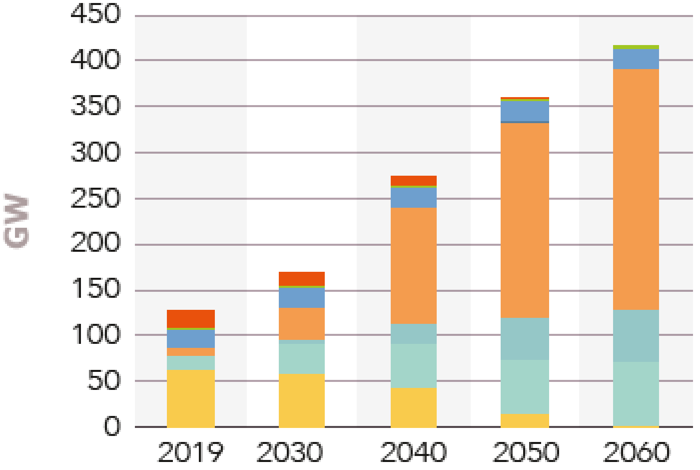
Filière	2050
Nucléaire existant	-
Nouveau nucléaire	-
Éolien terrestre	74 GW / 149 TWh
Éolien en mer	62 GW / 224 TWh
Photovoltaïque	208 GW / 255 TWh
Énergies marines	3 GW / 9 TWh
Hydraulique (hors STEP)	22 GW / 63 TWh
Bioénergies	2 GW / 12 TWh
Thermique existant*	0,5 GW / 0,5 TWh

French system Evolution

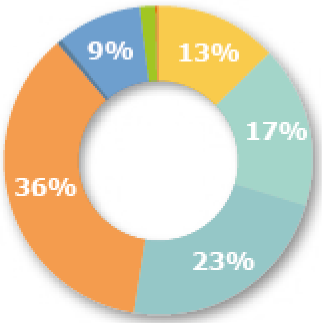
Scénario M1 : Répartition diffuse

Sources de production d'électricité

Capacités installées par filière



Bilan énergétique annuel en 2050



(capacités installées/production)

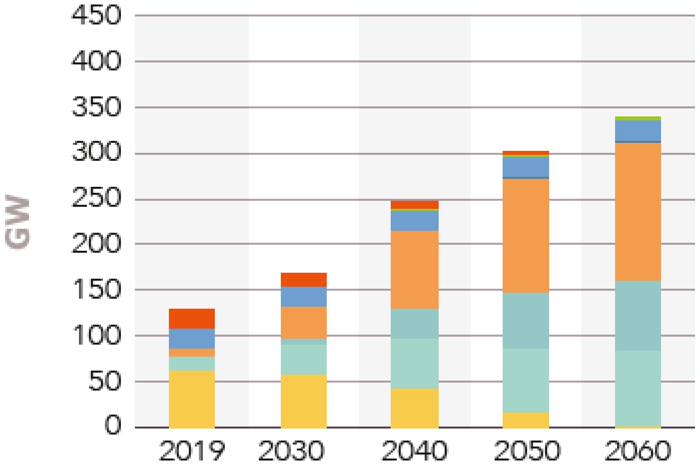
Filière	2050
Nucléaire existant	16 GW / 91 TWh
Nouveau nucléaire	-
Éolien terrestre	59 GW / 119 TWh
Éolien en mer	45 GW / 162 TWh
Photovoltaïque	214 GW / 255 TWh
Énergies marines	1 GW / 3 TWh
Hydraulique (hors STEP)	22 GW / 63 TWh
Bioénergies	2 GW / 12 TWh
Thermique existant*	0,5 GW / 0,5 TWh

French system Evolution

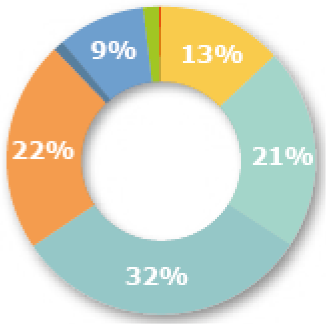
Scénario M23 : énergies renouvelables grands parcs

Sources de production d'électricité

Capacités installées par filière



Bilan énergétique annuel en 2050



(capacités installées/production)

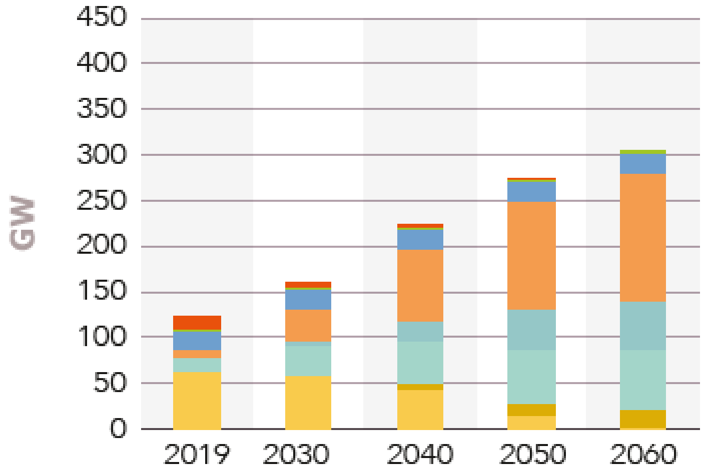
Filière	2050
Nucléaire existant	16 GW / 91 TWh
Nouveau nucléaire	-
Éolien terrestre	72 GW / 145 TWh
Éolien en mer	60 GW / 215 TWh
Photovoltaïque	125 GW / 153 TWh
Énergies marines	3 GW / 9 TWh
Hydraulique (hors STEP)	22 GW / 62 TWh
Bioénergies	2 GW / 12 TWh
Thermique existant*	0,5 GW / 0,5 TWh

French system Evolution

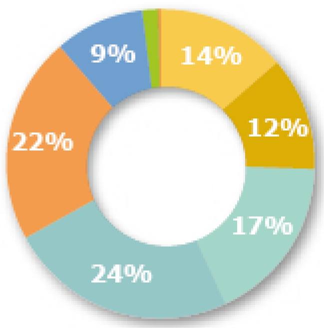
Scénario N1 : Énergies renouvelables + nouveau nucléaire 1

Sources de production d'électricité

Capacités installées par filière



Bilan énergétique annuel en 2050



(capacités installées/production)

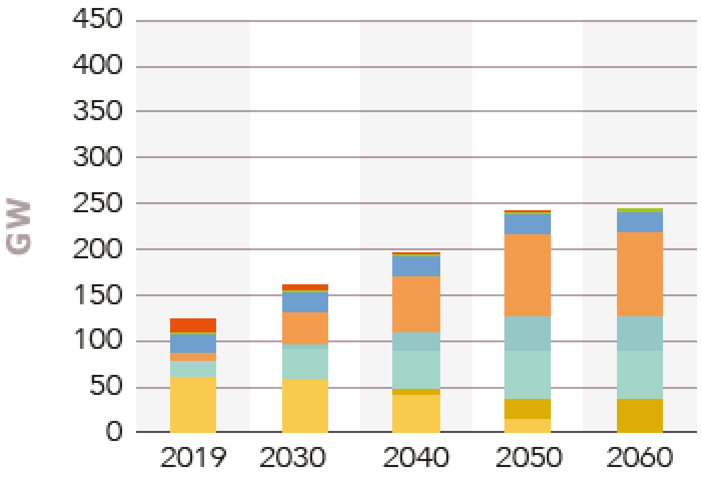
Filière	2050
Nucléaire existant	16 GW / 92 TWh
Nouveau nucléaire	13 GW / 79 TWh
Éolien terrestre	58 GW / 117 TWh
Éolien en mer	45 GW / 160 TWh
Photovoltaïque	118 GW / 144 TWh
Énergies marines	-
Hydraulique (hors STEP)	22 GW / 63 TWh
Bioénergies	2 GW / 12 TWh
Thermique existant*	0,5 GW / 0,5 TWh

French system Evolution

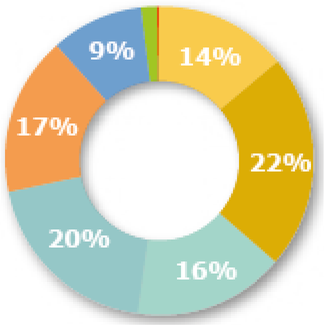
Scénario N2 : Énergies renouvelables + nouveau nucléaire 2

Sources de production d'électricité

Capacités installées par filière



Bilan énergétique annuel en 2050



(capacités installées/production)

Filière	2050
Nucléaire existant	16 GW / 93 TWh
Nouveau nucléaire	23 GW / 148 TWh
Éolien terrestre	52 GW / 104 TWh
Éolien en mer	36 GW / 129 TWh
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Énergies marines	-
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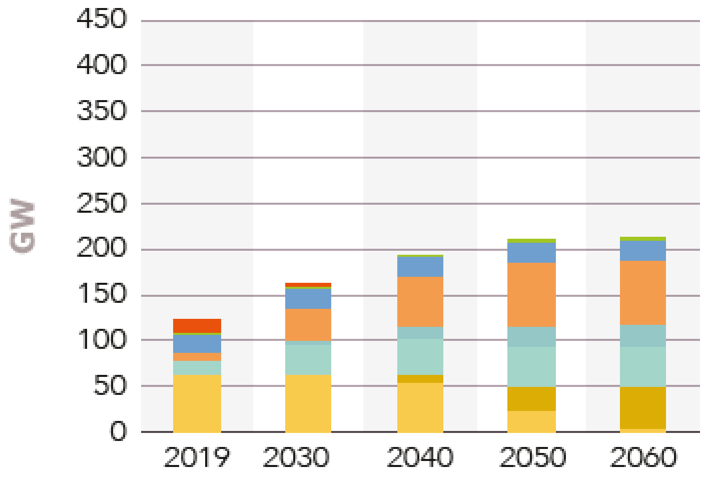
Bioénergies	2 GW / 12 TWh
Thermique existant*	0,5 GW / 0,5 TWh

French system Evolution

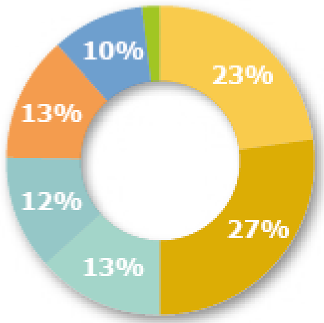
Scénario N03 : Énergies renouvelables + nouveau nucléaire 3

Sources de production d'électricité

Capacités installées par filière



Bilan énergétique annuel en 2050



(capacités installées/production)

Filière	2050
Nucléaire existant	24 GW / 149 TWh
Nouveau nucléaire	27 GW / 179 TWh
Éolien terrestre	43 GW / 87 TWh
Éolien en mer	22 GW / 78 TWh
Photovoltaïque	70 GW / 86 TWh
Énergies marines	-
Hydraulique (hors STEP)	22 GW / 63 TWh
Bioénergies	2 GW / 12 TWh
Thermique existant*	-

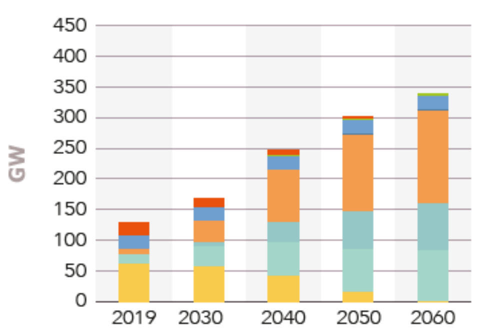
French system Evolution

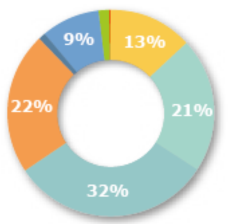
For this scenario with mainly inverter based generation we see that the inertia level will reach any level. From moderate to very low inertia.

There will also be a need to address the fast change of inertia from day to day.

Scénario M23 : énergies renouvelables grands parcs

Sources de production d'électricité





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French system Evolution

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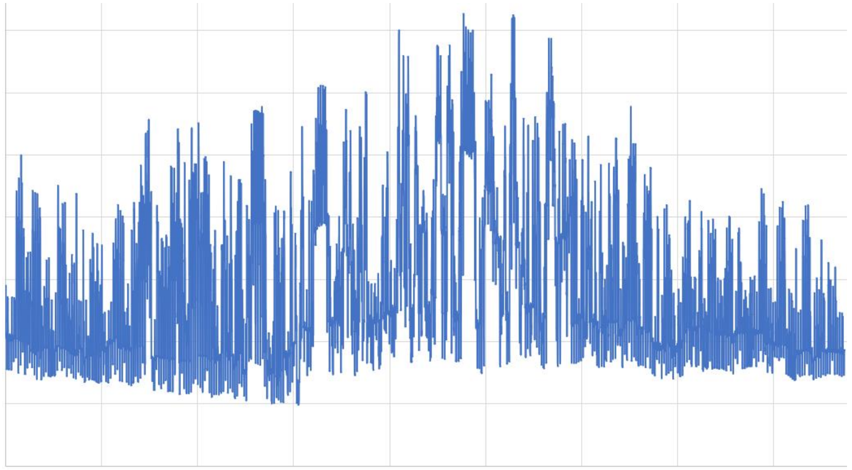
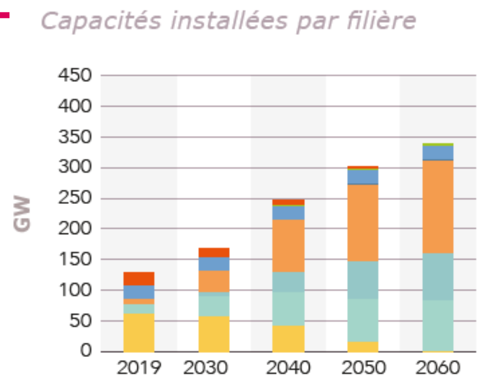
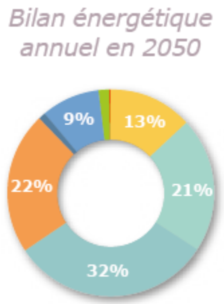


Scénario M23 : énergies renouvelables grands parcs

Sources de production d'électricité





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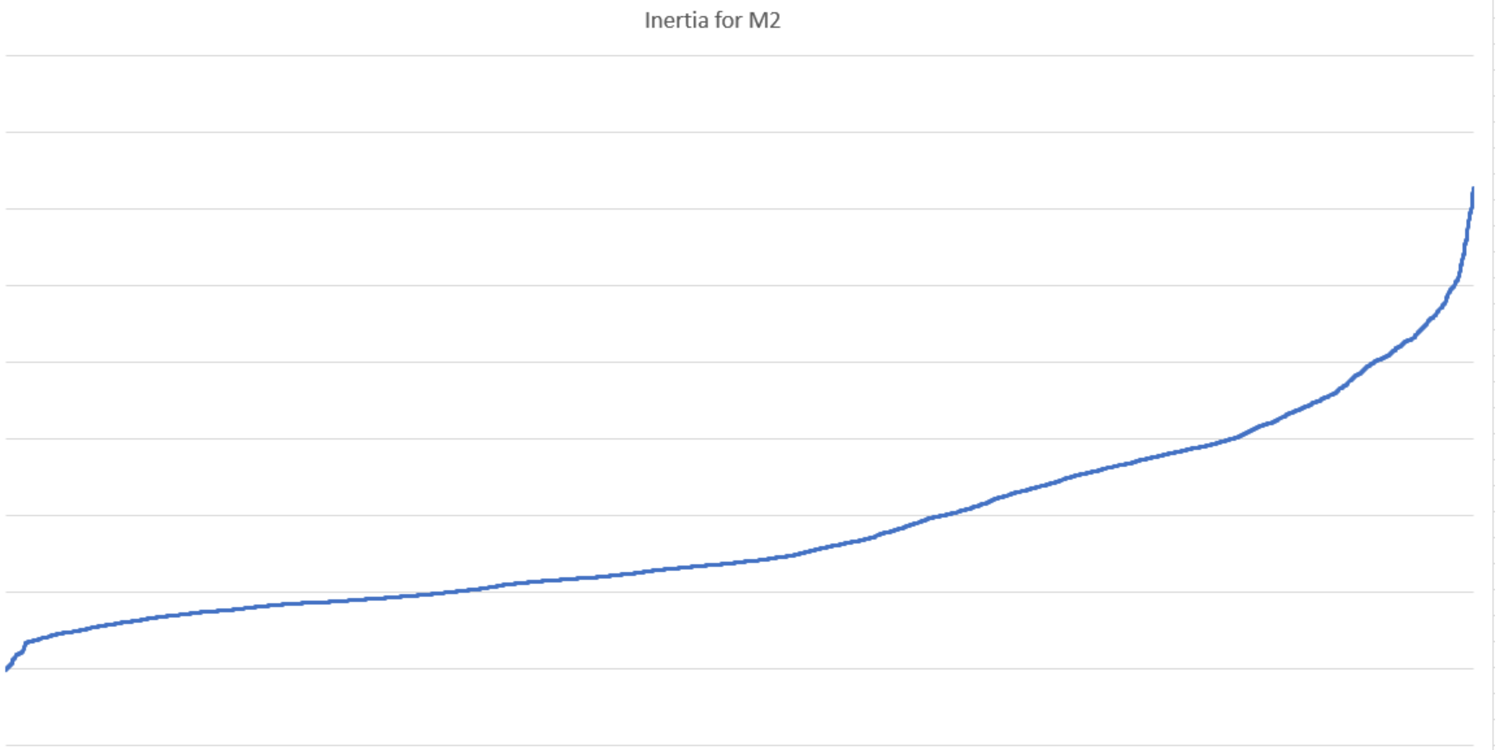


French system Evolution

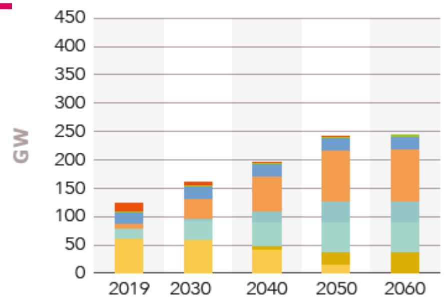
In the case with nuclear generation, the inertia level is higher.

BUT, there are still time of the year with very low inertia level.

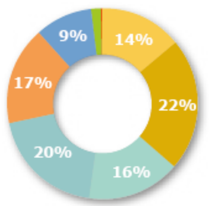
Scénario N2 : Énergies renouvelables + nouveau nucléaire 2

Sources de production d'électricité

Capacités installées par filière



Bilan énergétique annuel en 2050



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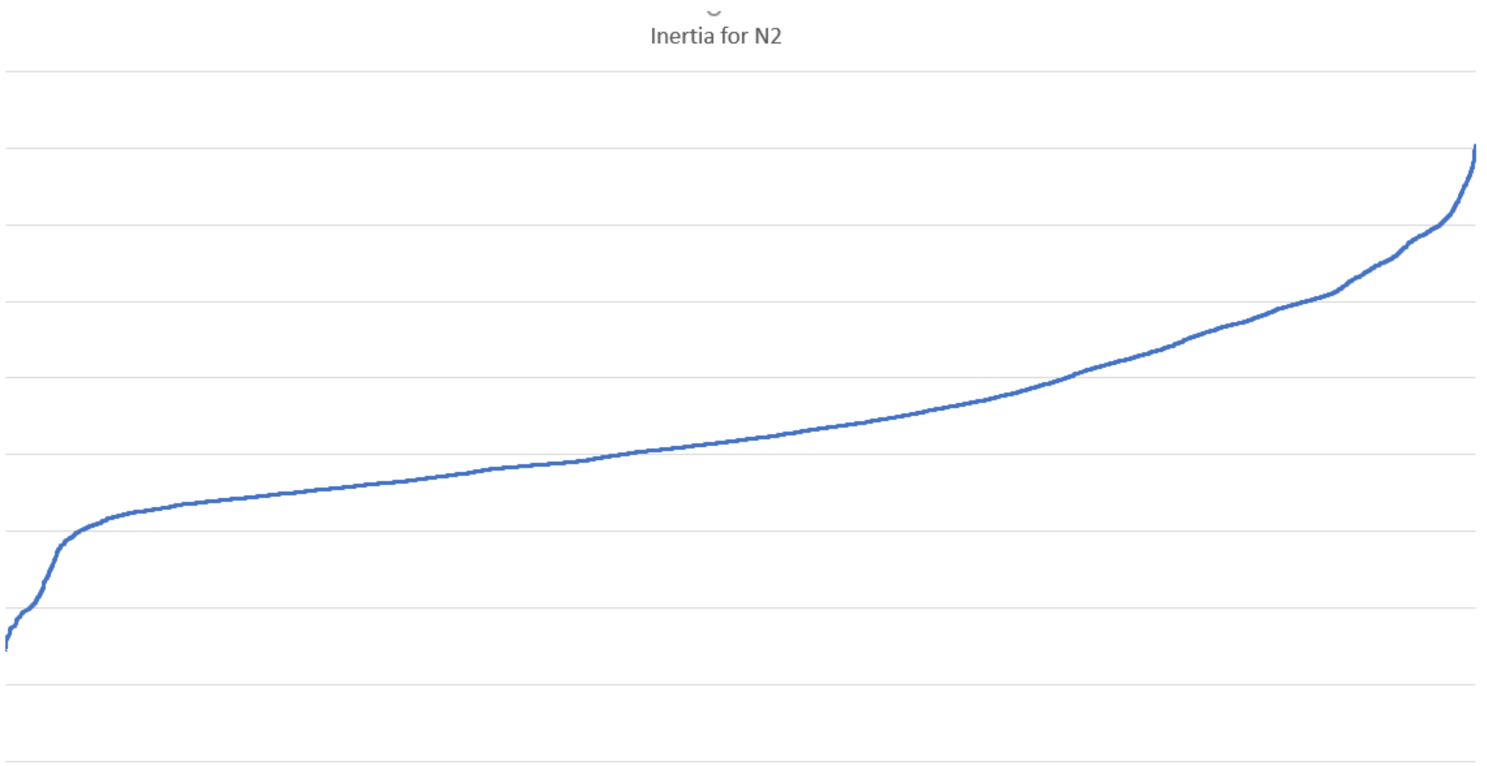
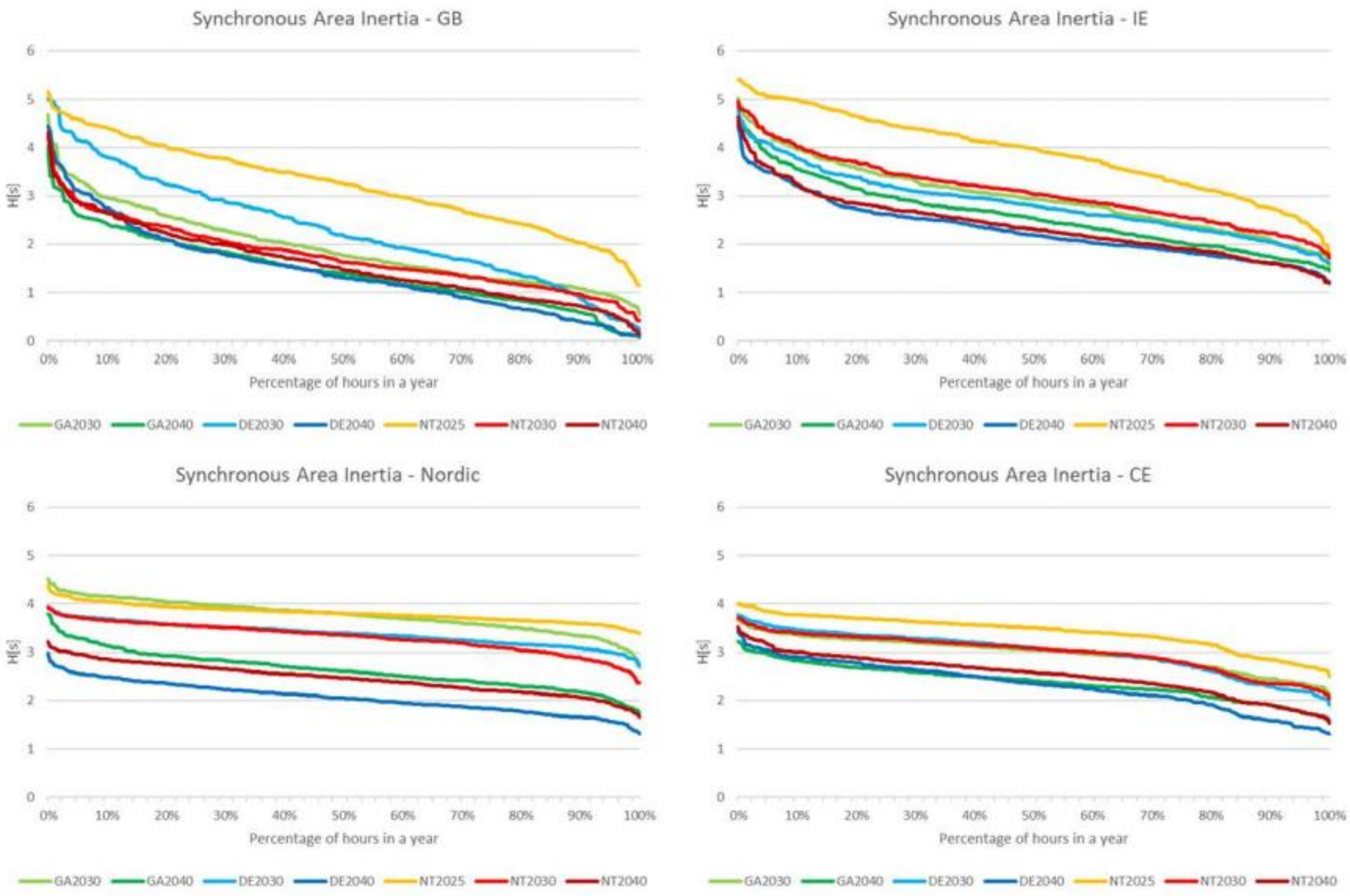


Inertia Evolution



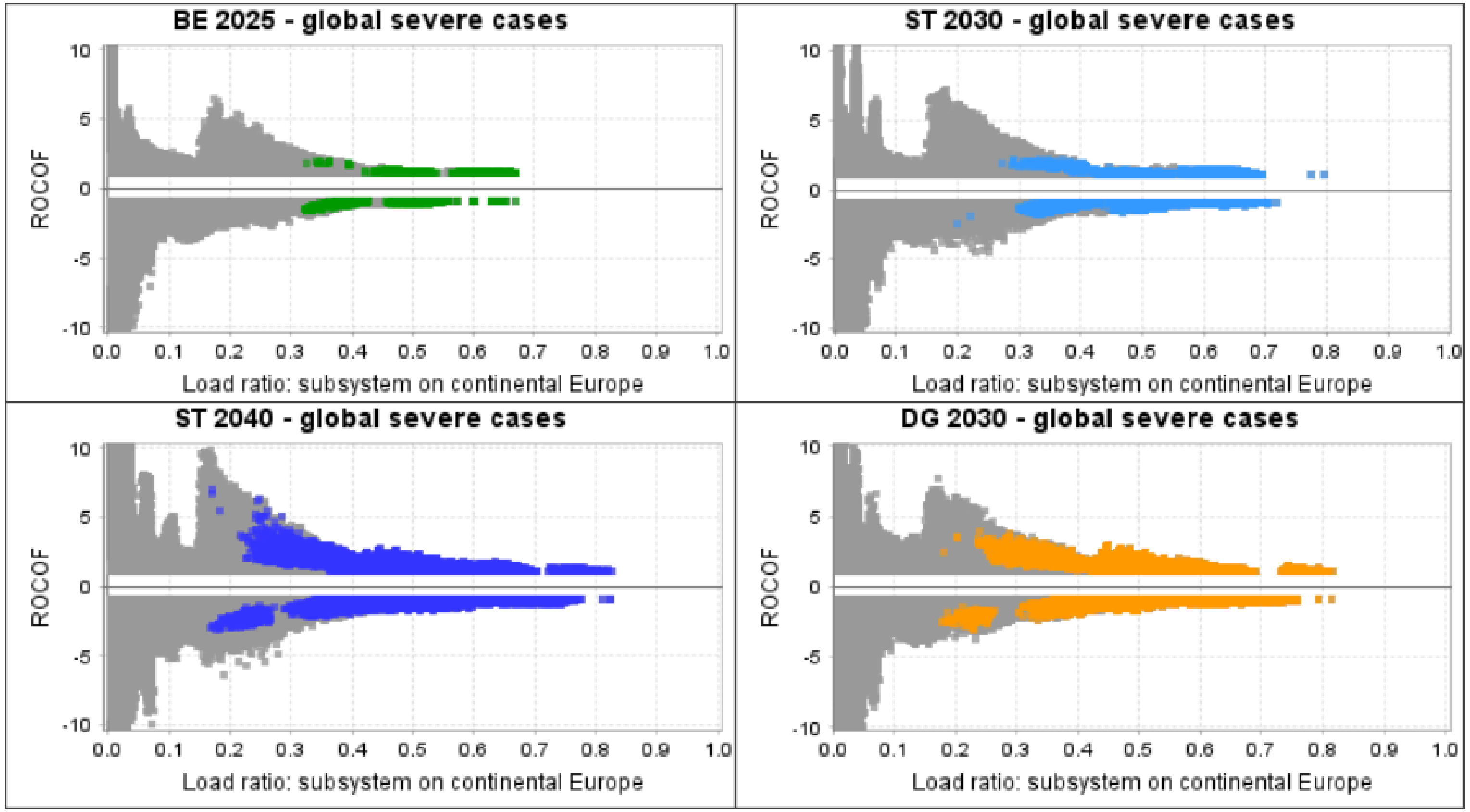
NT-National Transition;
DE-Distributed Energy;
GA-Global Ambition

Scenarios description available at:
https://www.entsos-tyndp2020-scenarios.eu/

https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/Foropinion/TYNDP2020_Insight_Report_Inertia.pdf

Inertia in Europe

A specific TF has been created in ENTSOE to address inertia issue:



Focus on system split

https://eepublicdownloads.azureedge.net/clean-documents/Publications/ENTSO-E%20general%20publications/211203_Long_term_frequency_stability_scenarios_for_publication.pdf

Inertia in Europe

Inertia and RoCoF issues :

One side of a bigger change: the operation of the grid with few synchronous machines

Have a look at DS3 study in Eirgrid and its new ancillary services, allowing for 70% IBR penetration

UK has grid code with grid forming capabilities embedded.

ENTSOE

Grid-Forming Capabilities: Towards System Level Integration

31 March 2021

- Grid-forming capabilities need to be defined in connection network codes (CNCs) to enable harmonised solutions
- Developing sufficient conditions for grid-forming capabilities via national level ancillary services
- HVDC, FACTs and SCs are the immediate candidates to explore the development of the grid-forming capabilities
- Storage and sector coupling facilities should be further explored in order to unlock their full potential of providing grid-forming capabilities

ENTSOE is presently working on the implementation of GFM in the connection code.

RDIC is working on the roadmap for future stability management.

OSMOSE
OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

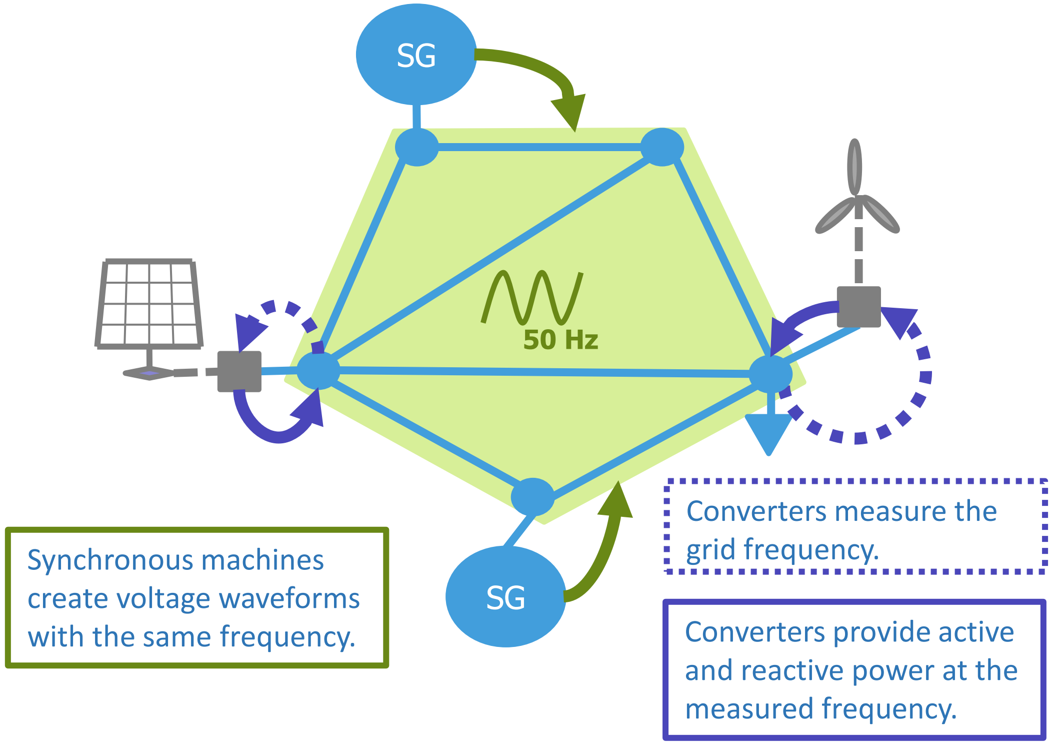
WP3 : Demonstration of grid forming control by energy storage systems

Thibault PREVOST & Carmen Cardozo (RTE)

The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 773406.

Context & backgrounds

- Inverter-based resources (IBR) currently connected to the grid are grid following:



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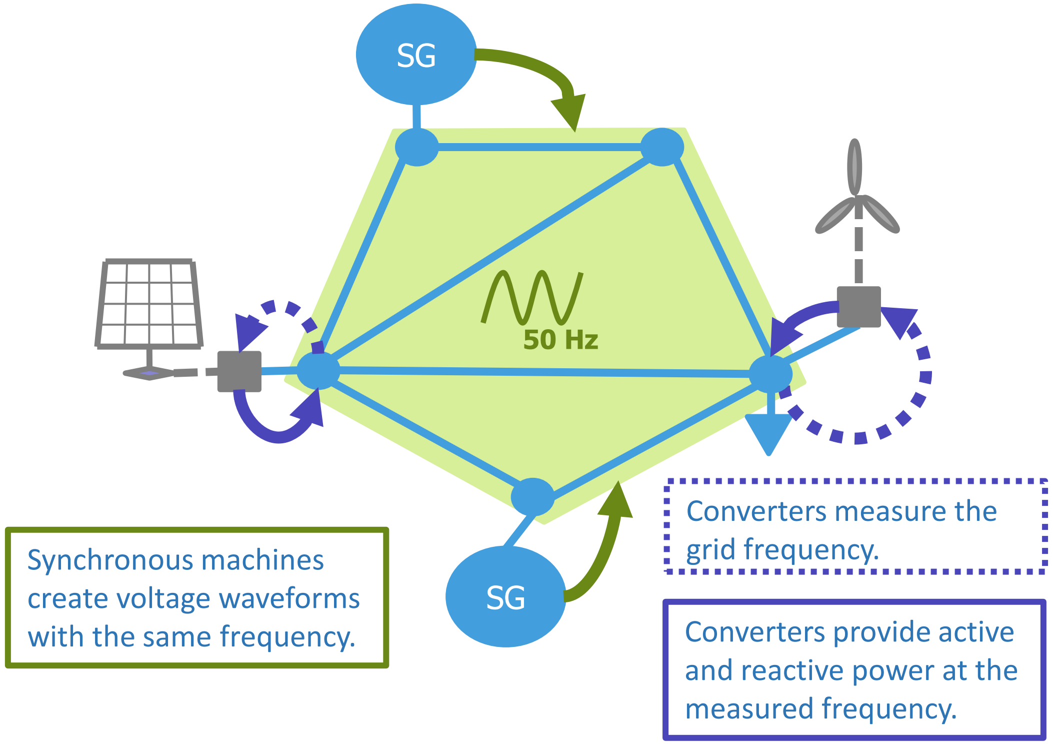
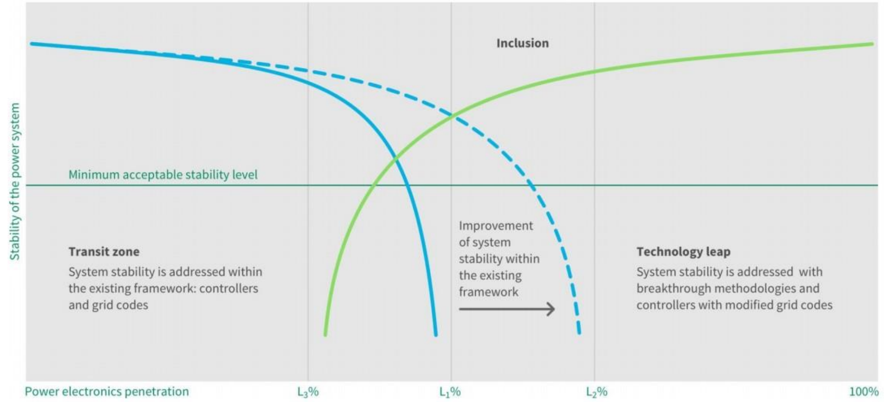


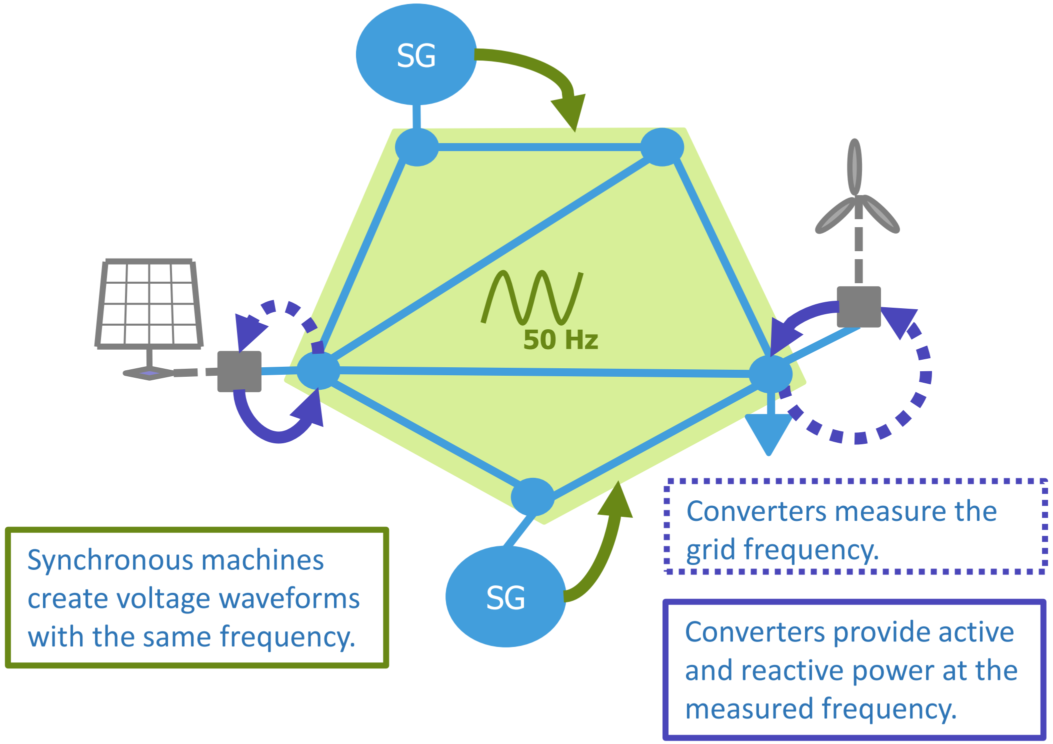
MIGRATE

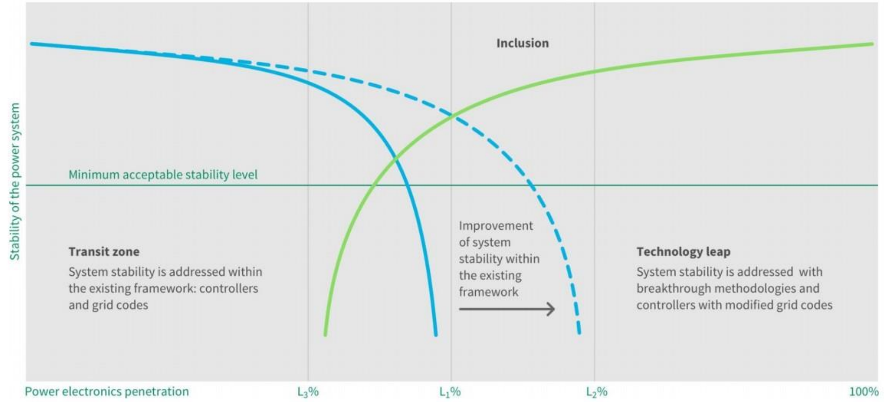


- How much IBR before unstable behavior?
- WP3: Can we operate a system 100% IBR?
  - Redefined system needs, and
  - proposed various grid forming (GFM) controls

Context & backgrounds

- Inverter-based resources (IBR) currently connected to the grid are grid following:





- How much IBR before unstable behavior?
- WP3: Can we operate a system 100% IBR?
  - Redefined system needs, and
  - proposed various grid forming (GFM) controls
- Many more now available in the literature
- 2 high power demonstration Siemens & ABB
- GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF)

WP3 objectives

- To progress on the common understanding, on the definition of the grid forming capability.

- To demonstrate:
  - the technical feasibility of providing grid forming capability with commercially available power-electronics interfaced energy storage systems (ESS),
  - that this solution can be industrially deployed in voltage source converter (VSC) without oversizing such that it is economically viable, and
  - that their contribution to power system stability can be quantified by means of external measurements without a detailed knowledge of specific low-level controls.

Demonstrators overview

[1] D3.2 Overall specification of the demos

Ingeteam / Rte

AC/DC	1000 kVA
Battery Li-ion	500 kW – 60 min
Supercapacitors	1000 kW – 10 s
Transformer	600 V – 20 kV

EPFL

AC/DC	720 kVA
Battery Li-Titan	720 kW – 45 min
Transformer	300 V – 21 kV

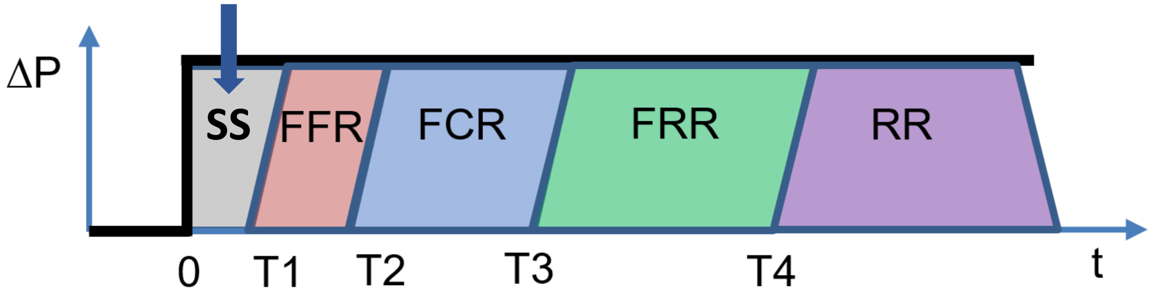
Figure 2.1: The 720kVA/500 kWh grid-connected BESS installed at the EPFL campus

WP 3 definition of grid forming capability

A GFM unit shall, within its rated power and current, be capable of self-synchronise, stand-alone and provide synchronization services.

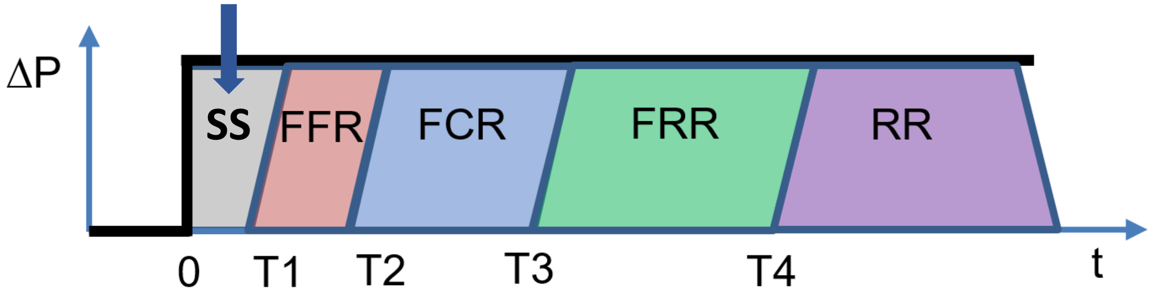
- By definition, a GFM does not rely on specific grid conditions to synchronise. It can operate at a wide range of short-circuit ratios and inertia levels.
- **Synchronization services** include a natural/ inherent/ immediate/ undelayed deployment of synchronising power, system strength, fault current and inertial response.
- Hence, a GFM unit will maintain and help others to maintain synchronism under stressful conditions, while still complying with the general requirements applying to the specific technology.
- No overload or capacity reservation is associated to the GFM capability, neither the provision of traditional ancillary services such as primary voltage and frequency regulation.

WP 3 definition of synchronisation services



T1= ~250ms-2s
T2=10-30s
T3= 5-15min
T4= 15-60 min

WP 3 definition of synchronisation services



T1= ~250ms-2s
T2=10-30s
T3= 5-15min
T4= 15-60 min

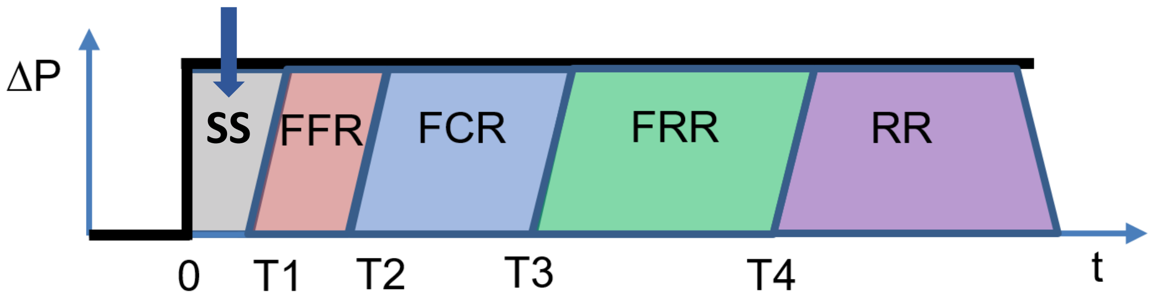
Non-frequency ancillary services

- Steady state voltage control (SSVC)
- Black start capability
- Island operation capability

- Fast reactive current injection (grid following)
- Short-circuit current (overload capability)

- Inertia for local grid stability

WP 3 definition of synchronisation services



T1= ~250ms-2s
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Non-frequency ancillary services

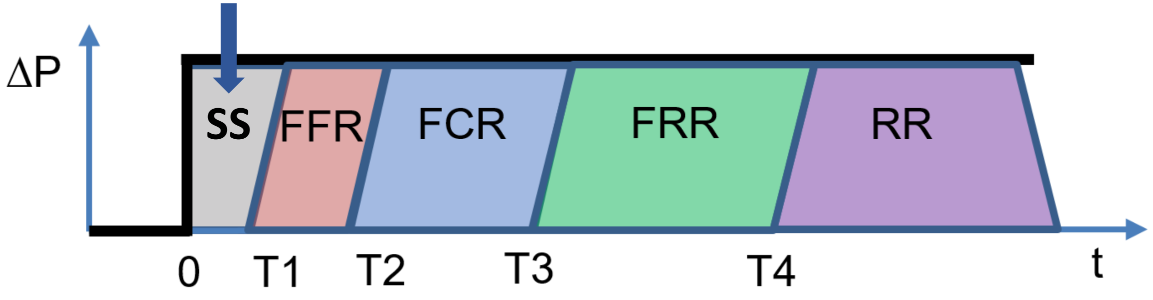
Steady-state (minutes-hours)

- Steady state voltage control (SSVC)
- Black start capability
- Island operation capability

Stability services (activation time <2s, variable sustained time depending on system needs seconds to minutes. Possible lower bound on activation time)

- Fast reactive current injection (grid following)
- Short-circuit current (overload capability)
- Fast voltage support (faster SSVC + capacity)
- Inertia for local grid stability

WP 3 definition of synchronisation services



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T2=10-30s
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Non-frequency ancillary services

Steady-state (minutes-hours)

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Stability services (activation time <2s, variable sustained time depending on system needs seconds to minutes. Possible lower bound on activation time)

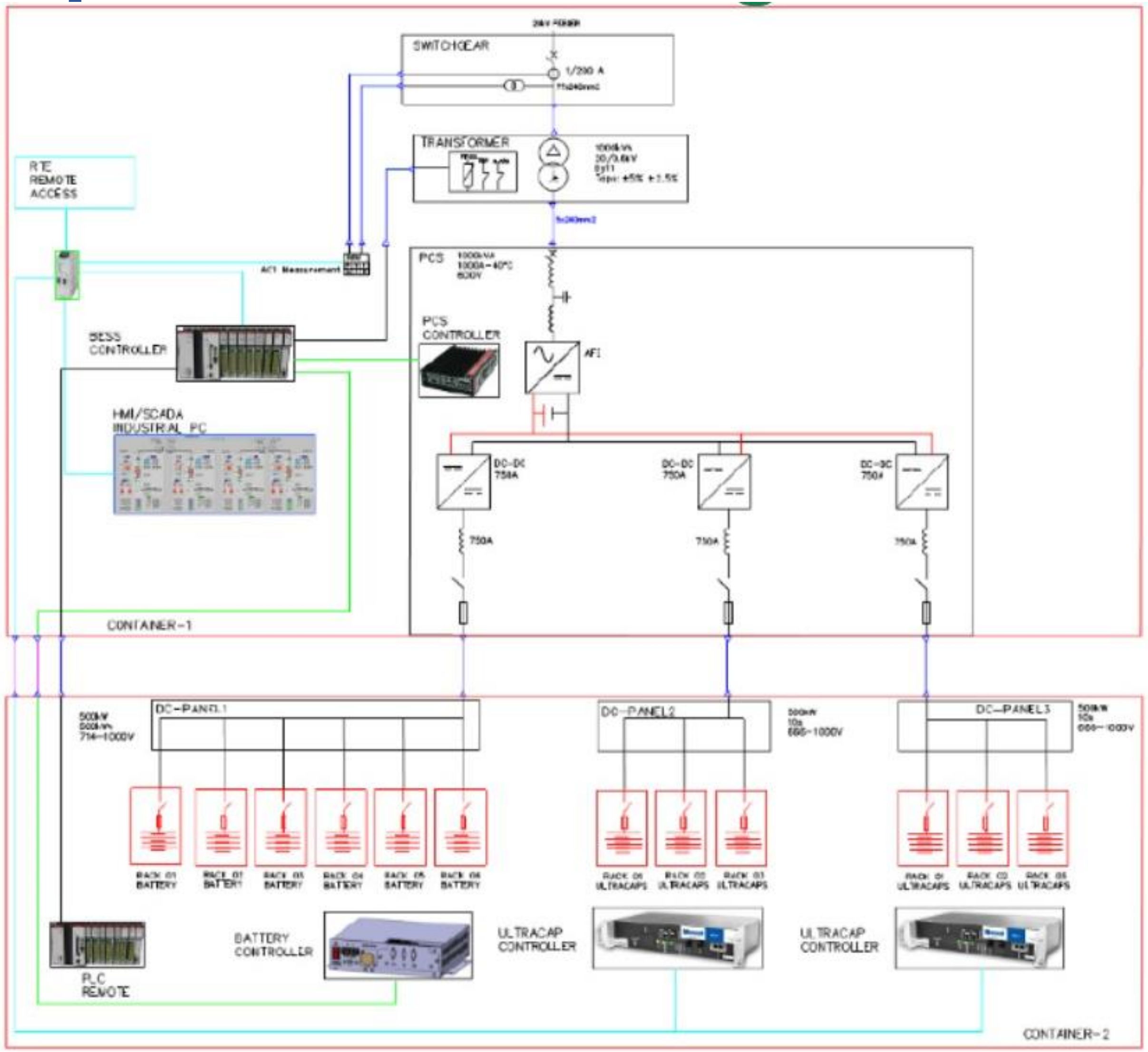
- Fast reactive current injection (grid following)
- Short-circuit current (overload capability)
- Fast voltage support (faster SSVC + capacity)

Synchronisation services (activation time <5ms, low sustained time)

- Fault current (immediate: grid forming)
- System strength
- Inertia for local grid stability
- Synchronising power
- Standalone capability

RTE-Ingeteam demo description

Ingeteam / Rte



A 1 MVA solution built for the project and connected to a 20 kV feeder in a RTE substation, including

four lithium-ion battery racks (0.5 MVA 60 min)

six ultra-capacitor (UC) racks (for a total of 1MW-10s).

An fire incident during commissioning prevent this Demo to ultimately be put into service.

RTE-Ingeteam: contributions in control design

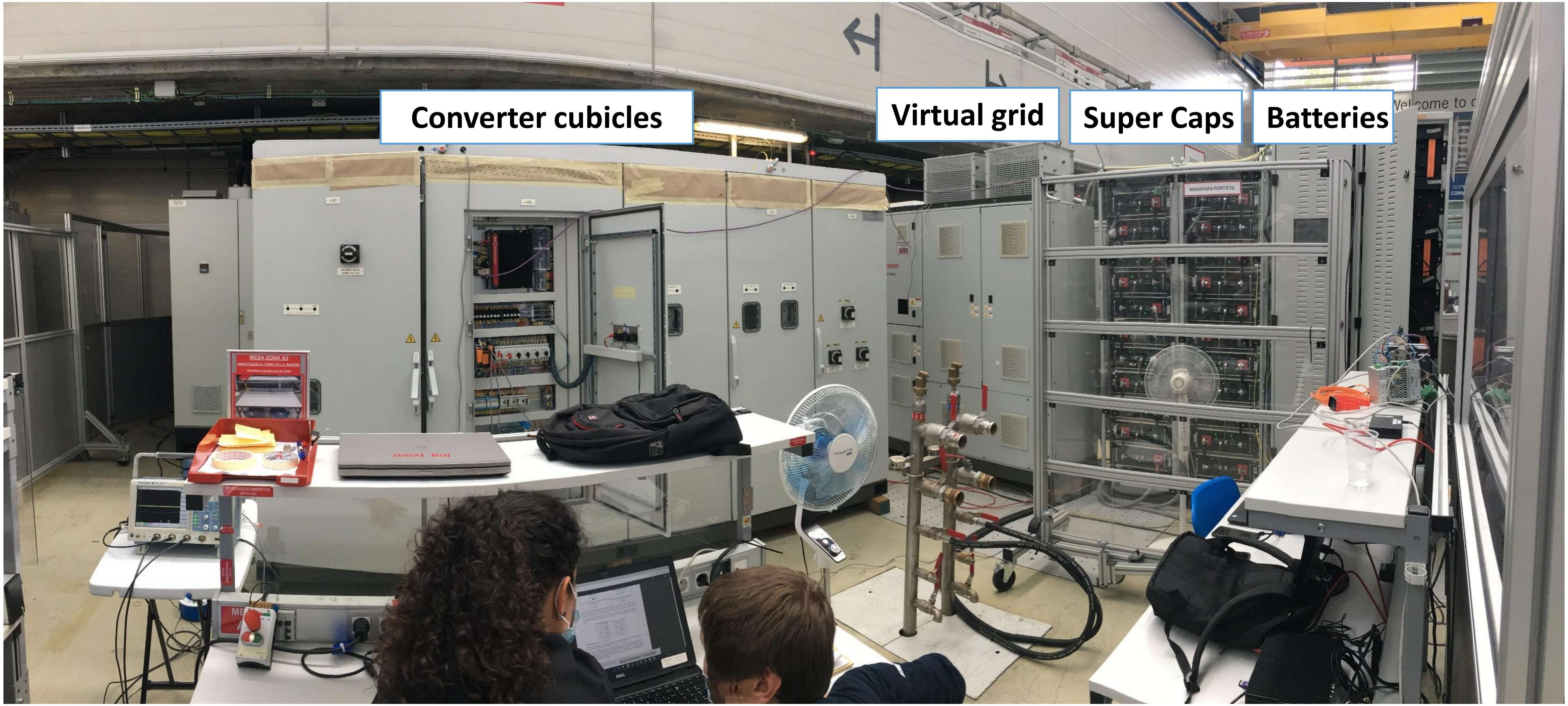
AC/DC grid forming control design

- Inclusion of a negative sequence (NS) component to the threshold virtual impedance (TVI) current limitation strategy to improve the grid forming control robustness to asymmetrical faults and define settable prioritisation between the positive and negative sequence.
- Decoupling between the synchronisation and the frequency-related services (FFR or FCR) at the AC/DC converter level (transient grid forming).

DC/DC control design

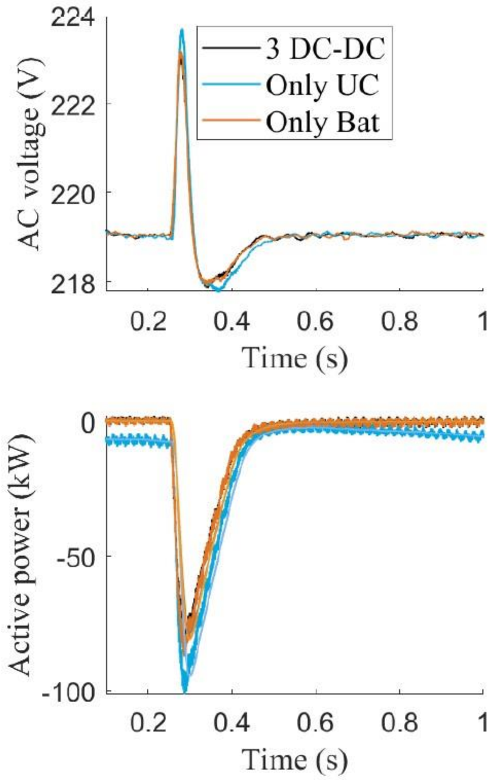
- Decoupling of the balancing and synchronisation services at device level through DC power sharing strategies: fast transients are fed by the UC, smoothing the battery power output. Energy intensive ancillary and flexibility services are provided by the battery.

RTE-Ingeteam: power hardware in the loop FAT



RTE-Ingeteam PHIL FAT results

Synchronising power



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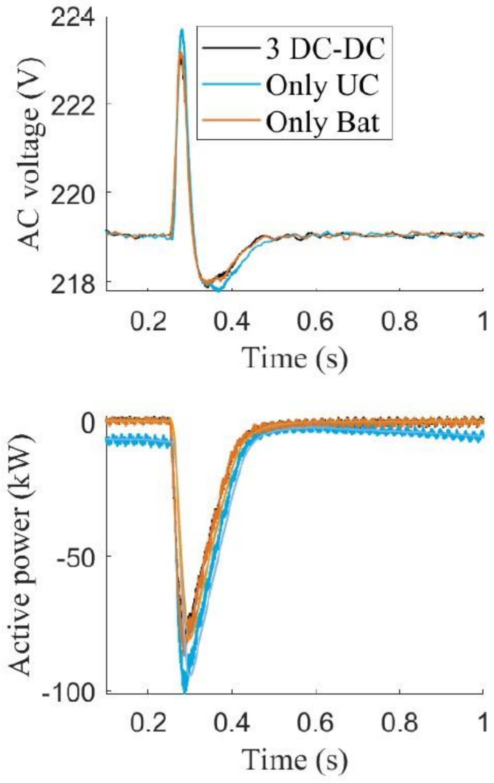
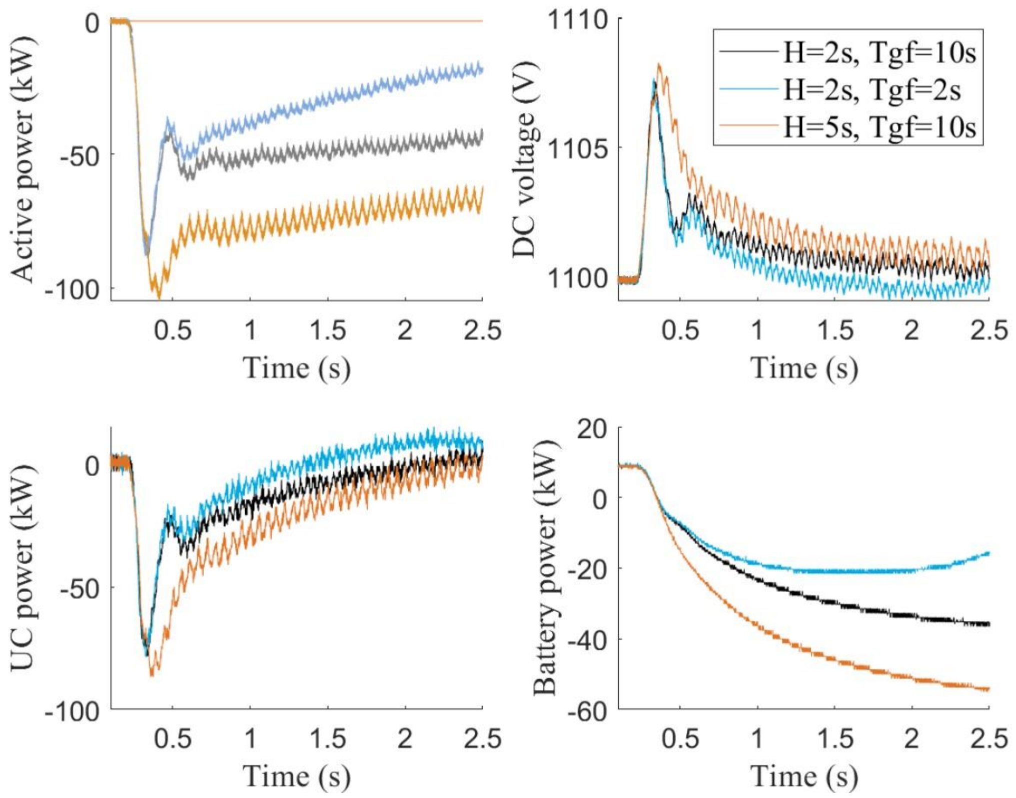


Inertial response



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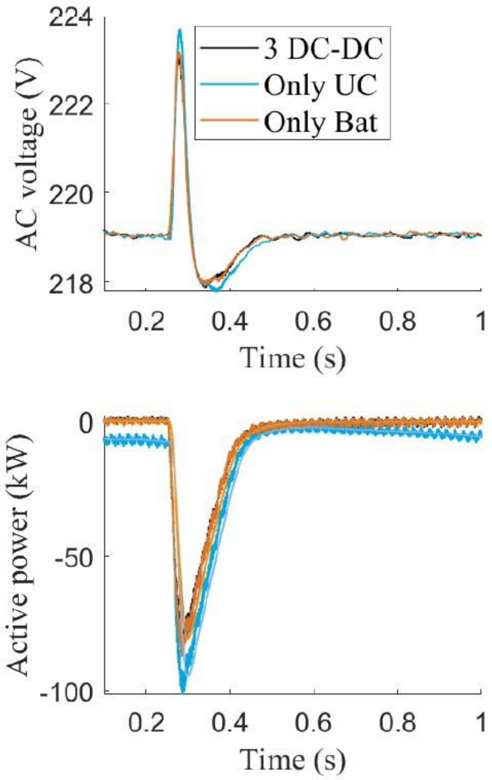

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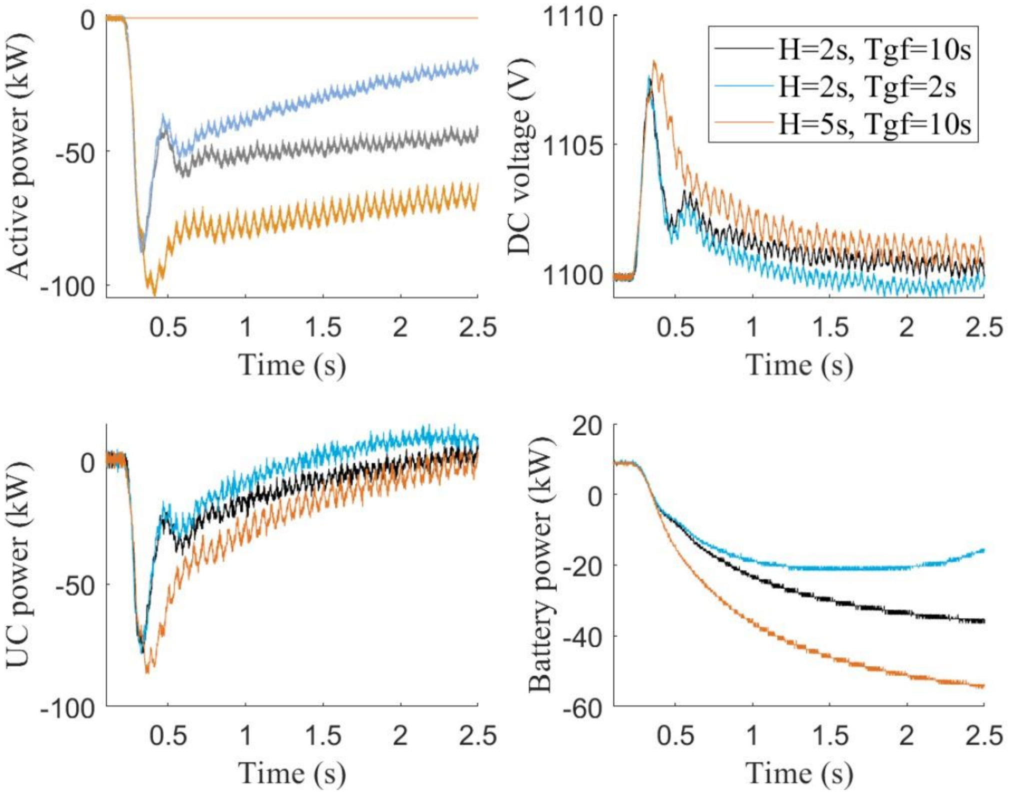
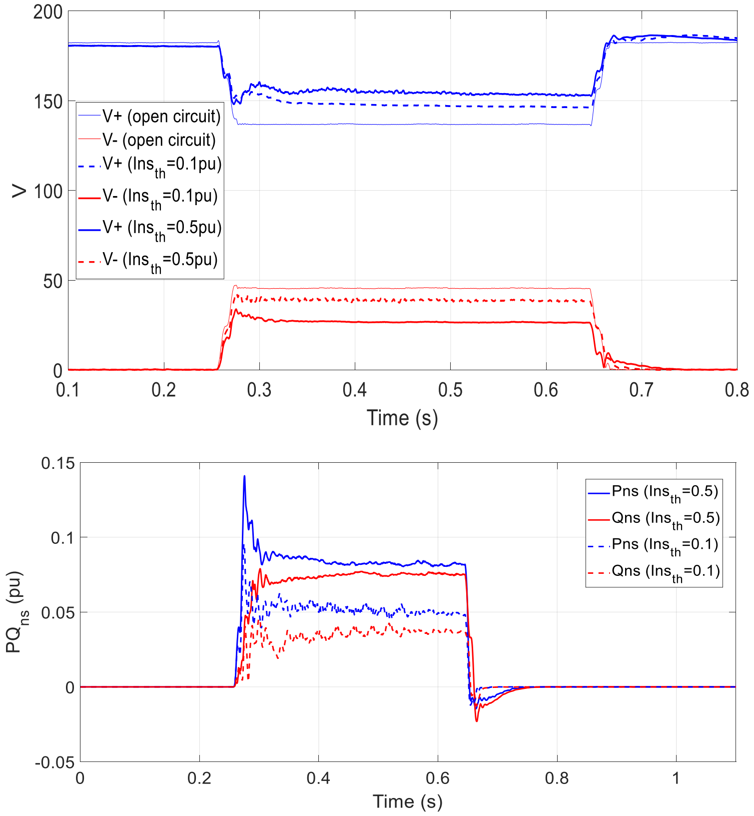


Unbalanced fault

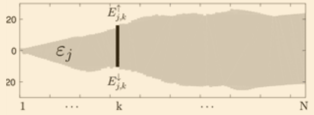


EPFL demo multiservice control framework

$$P = P_{ref} + \sigma_f \cdot (f - f_{ref})$$
$$Q = Q_{ref} + \sigma_v \cdot (v - v_{ref})$$

Day-Ahead[1]

$$x^o = \arg\max_x \; \lambda_1\left[w\left(\mathscr{E}_{disp} + \mathscr{E}_{fcr}\right)\right] + \lambda_2\left[w\left(\mathscr{Q}_{vc}\right)\right]$$

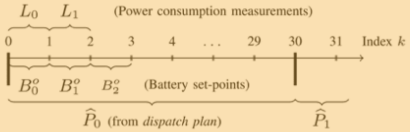


$\sigma_f, \sigma_v, \hat{P}_d$

[1]E. Namor, "Control of Battery Storage Systems for the Simultaneous Provision of Multiple Services," in IEEE Transactions on Smart Grid

Dispatch Tracking[2]

Model Predictive Control (MPC) for dispatch tracking

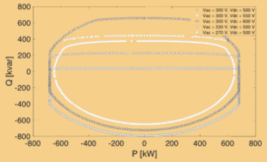


P_{ref}, Q_{ref}

[2] F. Sossan, "Achieving the Dispatchability of Distribution Feeders Through Prosumers Data Driven Forecasting and Model Predictive Control of Electrochemical Storage," in *IEEE Transactions on Sustainable Energy*

Real Time[3]

Check capability curve



f_{ref}, v_{ref}

[3] Real-time Control of Battery Energy Storage Systems to Provide Ancillary Services Considering Dynamic Capability of DC-AC Converters

Long term prediction of prosumption

Frequency time series

Voltage time series

Short term prediction of prosumption

TTC model

Capability curve

TTC model

Measured values (AC voltage, etc.)

Figure 2.1: The 720kVA/500 kWh grid-connected BESS installed at the EPFL campus

EPFL demo: key performance indicators

- **Relative Phase Angle Difference Deviation (rPADD)**

$$rPADD = \left|\frac{\Delta\theta_k - \Delta\theta_0}{\Delta P_k}\right|$$

quantifying the change in the phase-to-neutral voltage angle difference $\Delta\theta_k$, measured by two PMUs installed on nodes at different voltage level of the local feeder, versus the case with null delivered active power $\Delta\theta_0$,

$$\begin{cases}\Delta\theta_k = \theta_{k,PMU1} - \theta_{k,PMU2} \\ \Delta\theta_0 = \theta_{0,PMU1} - \theta_{0,PMU2}\end{cases}$$

- **Relative Rate-of-Change of Frequency (rRoCoF)**

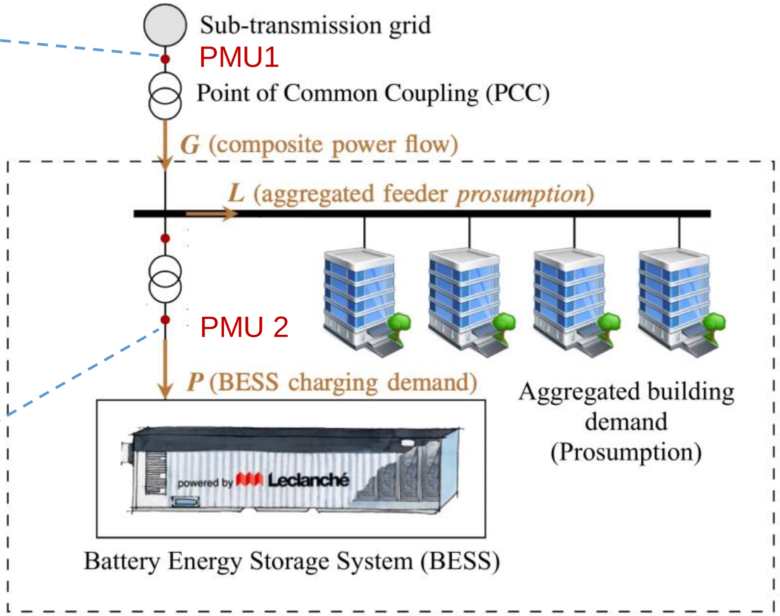
$$rRoCoF = \frac{\Delta f_{pcc}/\Delta t}{\Delta P_{BESS}}$$

where:

- Δf_{pcc} is the difference between one grid frequency sample and the next at the PCC.
- ΔP_{BESS} is the once-differentiated BESS active power.
- Δt is the sampling interval.

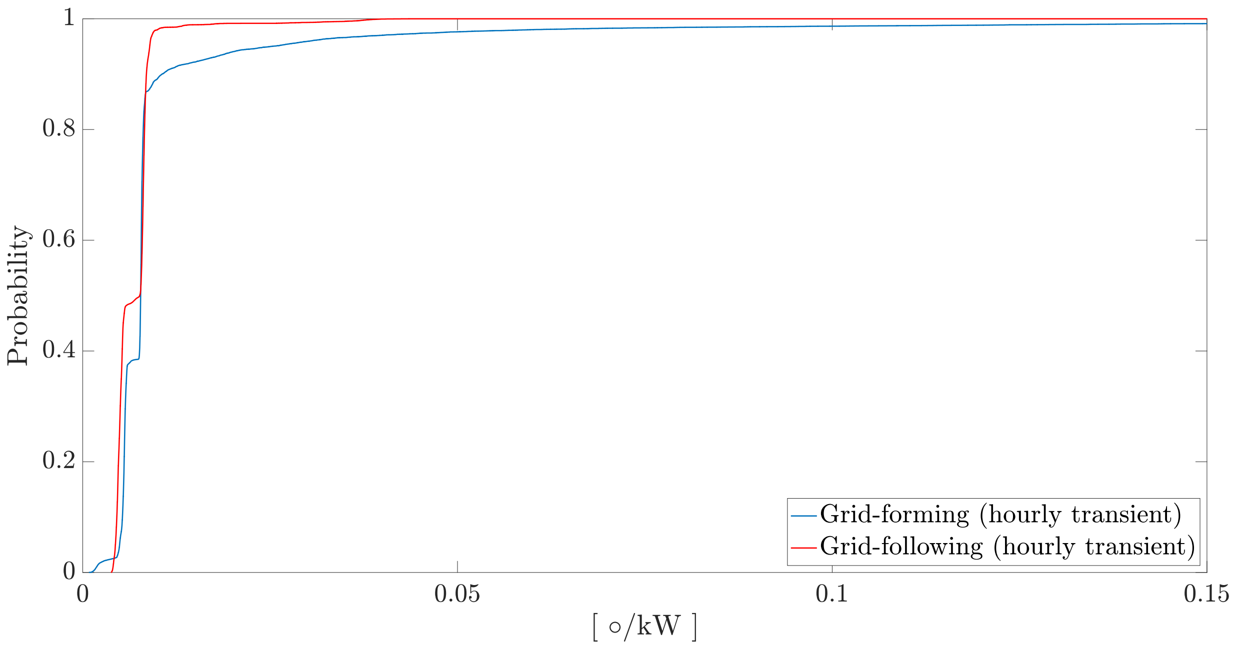
FPGA-based PMU

- Synchrophasor Estimation
- Enhanced Interpolated-DFT
- Accuracy in terms of 1 std deviation σ: 0.001 deg – 18 µrad
- Frequency Error < 0.4 mHz
- Reporting time 20 ms
- GPS Time synchronization (100 ns)

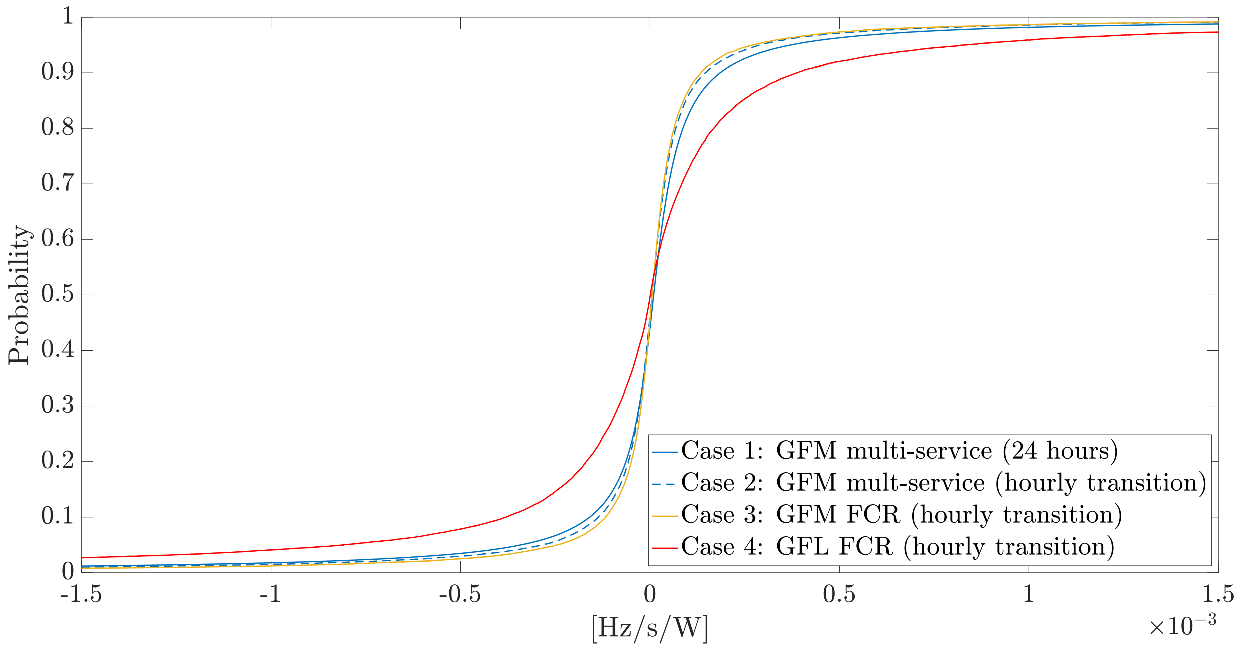


EPFL demo results: local Effects of BESS in GFM

rPADD Cumulative Density Function



rRoCoF Cumulative Density Function



rPADD is computed with PMU measurements during hourly transient at night when the prosumption of the dispatchable feeder has minor variations, such that the $\Delta\theta_0 \approx$ constant.

THANK YOU

- For further reading:
- https://www.osmose-h2020.eu/resource-center/

- For further questions

- Thibault.prevost@rte-france.com

&

- Carmen.Cardozo@rte-france.com

Read more on RTE-Ingeteam Demo

1. Enhanced TVI for Grid Forming VSC under Unbalanced Faults. Published on Energies. Available on: https://www.mdpi.com/1996-1073/14/19/6168
2. OSMOSE WP3: Factory Acceptance Test of the grid forming demonstrator. Presented in SIW 2020. Available on: https://www.researchgate.net/publication/348818638_OSMOSE_WP3_Factory_Acceptance_Test_of_the_grid_forming_demonstrator
3. OSMOSE Grid-Forming performance assessment within multiservice storage connected to the transmission grid. Presented in Cigre 2020. Available on: https://www.researchgate.net/publication/348818490_OSMOSE_Grid-forming_performance_assessment_within_multiservice_storage_connected_to_the_transmission_grid
4. Upgrade of a grid-connected storage solution with grid-forming function. Presented in SIW 2019. Available on: https://www.researchgate.net/publication/337561687_Upgrade_of_a_grid-connected_storage_solution_with_grid-forming_function
5. Performance assessment of Synchronous Condensers vs Voltage Source Converters providing grid-forming functions. Presented in PowerTech 2021. Available on: https://arxiv.org/abs/2106.03536

Read more on EPFL Demo

1. Optimal Grid-Forming Control of Battery Energy Storage Systems Providing Multiple Services: Modeling and Experiment Validation. Submitted to PSCC 2022. Available on: http://arxiv.org/abs/2110.10052.
2. Z. Yuan, A. Zecchino, R. Cherkaoui and M. Paolone, "Real-Time Control of Battery Energy Storage Systems to Provide Ancillary Services Considering Voltage-Dependent Capability of DC-AC Converters," in IEEE Transactions on Smart Grid, vol. 12, no. 5, pp. 4164-4175, Sept. 2021, doi: 10.1109/TSG.2021.3077696.
3. A. Zecchino, Z. Yuan, F. Sossan, R. Cherkaoui, M. Paolone, Optimal provision of concurrent primary frequency and local voltage control from a BESS considering variable capability curves: Modelling and experimental assessment, Electric Power Systems Research, Volume 190, 2021, https://doi.org/10.1016/j.epsr.2020.106643.
4. Local Effects of Grid-Forming Converters Providing Frequency Regulation to Bulk Power Grids. Accepted by 2021 IEEE PES ISGT Asia. Available on: https://arxiv.org/abs/2110.05392
5. Y. Zuo, Z. Yuan, F. Sossan, A. Zecchino, R. Cherkaoui, M. Paolone, Performance assessment of grid-forming and grid-following converter-interfaced battery energy storage systems on frequency regulation in low-inertia power grids, Sustainable Energy, Grids and Networks, Volume 27, 2021, https://doi.org/10.1016/j.segan.2021.100496.
6. Y. Zuo, F. Sossan, M. Paolone, Effect of Voltage Source Converters with Electrochemical Storage Systems on Dynamics of Reduced-inertia Bulk Power Grids. Electric Power Systems Research,vVolume 189, 2020, https://doi.org/10.1016/j.epsr.2020.106766.
7. E. Namor, F. Sossan, R. Cherkaoui and M. Paolone, "Control of Battery Storage Systems for the Simultaneous Provision of Multiple Services," in IEEE Transactions on Smart Grid, vol. 10, no. 3, pp. 2799-2808, May 2019, doi: 10.1109/TSG.2018.2810781.

WP 3 proposed types of grid forming units

Depending on the provided subset of synchronisation services we propose 4 types of GFM units

Type 4

- Services provided: Type 3 + “High” fault current (more than 2 times Nominal)
- Criticality: if protections fail to detect faults
- Cost: high for converters since they have to be oversized, null for synchronous machines

Type 3

- Services provided: Type 2 + Inertial response
- Criticality: When system inertia decreases globally
- Cost: limited due to the need of an energy buffer from a few seconds to 1min

Type 2

- Services provided: Type 1 + Synchronising power profile
- Criticality: When system inertia decreases locally
- Cost: very limited due to the need of an energy buffer <1 s.
  Other FFR resource are supposed to be available elsewhere to take over.

Type 1

- Service provided: Stand alone + System strength + “Low” fault current (within ratings, usually equal or close to nominal). Operate wide range of SCR
- Criticality: When system strength decreases locally
- Cost: null, only software

WP 3 proposed types of grid forming units

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- Criticality: if protections fail to detect faults
- Cost: high for converters since they have to be oversized, null for synchronous machines

Synchronous Machine

Type 3

- Services provided: Type 2 + Inertial response
- Criticality: When system inertia decreases globally
- Cost: limited due to the need of an energy buffer from a few seconds to 1min

VSC - ESS

Type 2

- Services provided: Type 1 + Synchronising power profile
- Criticality: When system inertia decreases locally
- Cost: very limited due to the need of an energy buffer <1 s.
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- Service provided: Stand alone + System strength + “Low” fault current (within ratings, usually equal or close to nominal). Operate wide range of SCR
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