DEI DOCTORAL RESEARCH SEMINARS

Grid Services to Transmission and Distribution System Operators Through Distributed Energy Resources (DERs)

LabZERO
Zero Emission Research Option

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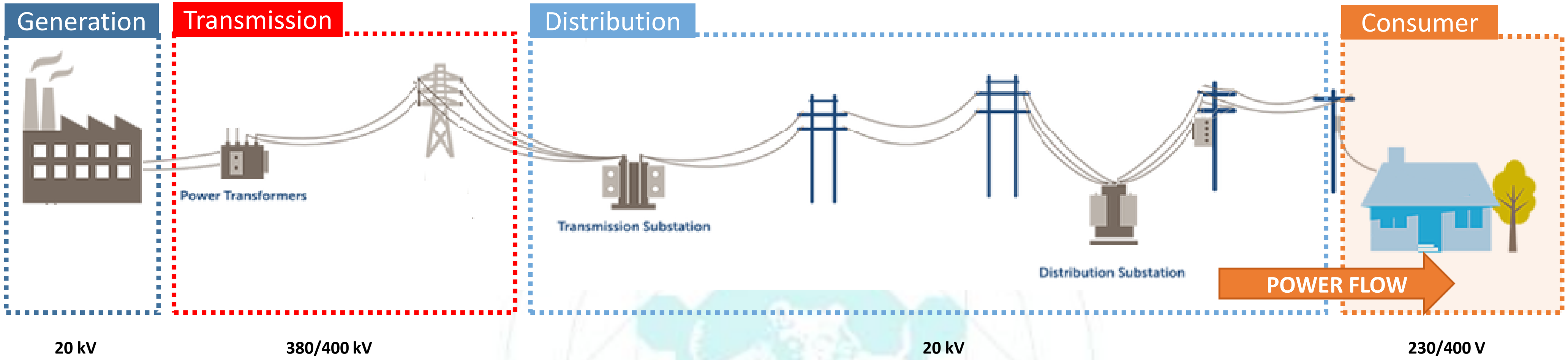
Summary

- ✓ *Introduction:* **How does a power system work?**
- ✓ ***Coordination between Transmission and Distribution System Operators***
- ✓ ***Flexibility resource to provide Ancillary Services***
- ✓ ***Need for Synthetic Inertia of Electrical Systems***
- ✓ ***A low-cost controller for DERs to provide SI: description and validation tests***
- ✓ ***Findings and final conclusions***

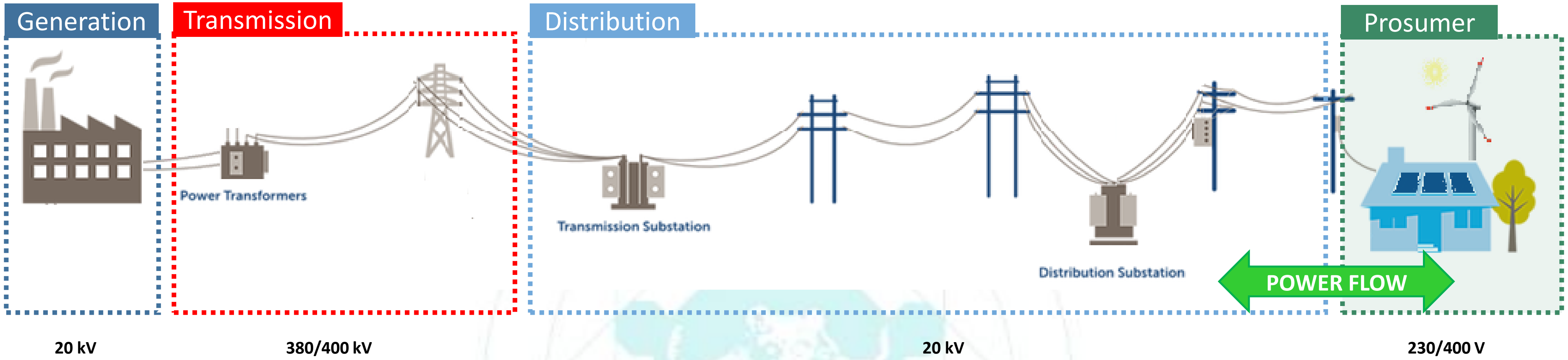
Introduction: How does a power system work?



CONSUMER

- Withdraws electricity from the distribution network.

Introduction: How does a power system work?



~~CONSUMER~~

- Withdraw electricity from the distribution network.

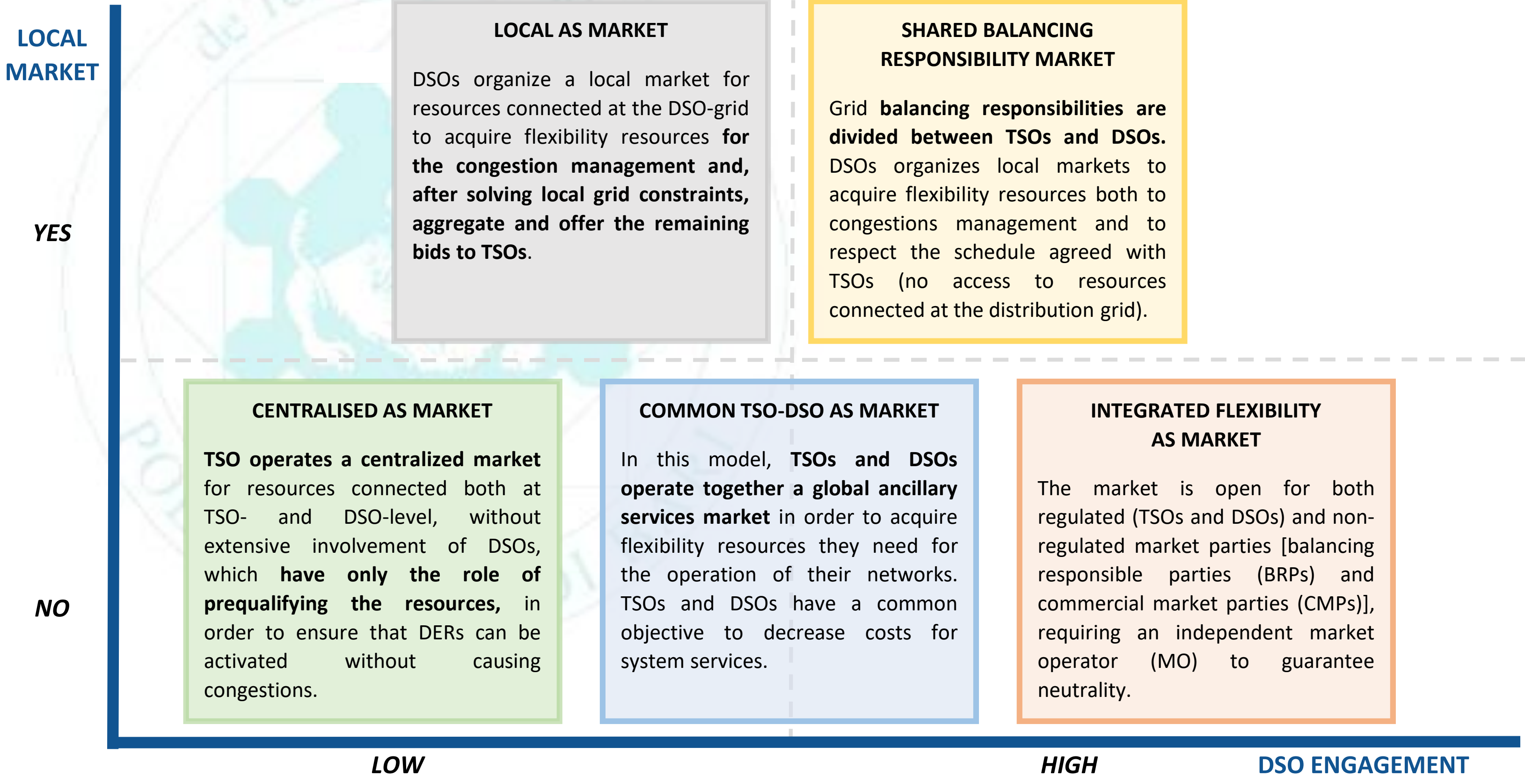
PROSUMER

- Produces energy from its own DERs.
- Injects excess production in the distribution grid.
- Withdraws electricity only when self-production is not sufficient to meet own needs.

Coordination between Transmission (TSOs) and Distribution (DSOs) System Operators [2]

In using DERs as flexibility resources for power system management, *TSOs, DSOs and aggregators* should be coordinated to optimize operational costs, maximize sustainability and guarantee power system security.

With this aim, **different TSO-DSO coordination schemes have been proposed in the literature** (*e.g. by SmartNet*), **each one characterized by specific roles of system operators and detailed AS markets**.



LOCAL AS MARKET

DSOs organize a local market for resources connected at the DSO-grid to acquire flexibility resources **for the congestion management and, after solving local grid constraints, aggregate and offer the remaining bids to TSOs**.

SHARED BALANCING RESPONSIBILITY MARKET

Grid **balancing responsibilities are divided between TSOs and DSOs.** DSOs organizes local markets to acquire flexibility resources both to congestions management and to respect the schedule agreed with TSOs (no access to resources connected at the distribution grid).

CENTRALISED AS MARKET

TSO operates a centralized market for resources connected both at TSO- and DSO-level, without extensive involvement of DSOs, which **have only the role of prequalifying the resources,** in order to ensure that DERs can be activated without causing congestions.

COMMON TSO-DSO AS MARKET

In this model, **TSOs and DSOs operate together a global ancillary services market** in order to acquire flexibility resources they need for the operation of their networks. TSOs and DSOs have a common objective to decrease costs for system services.

INTEGRATED FLEXIBILITY AS MARKET

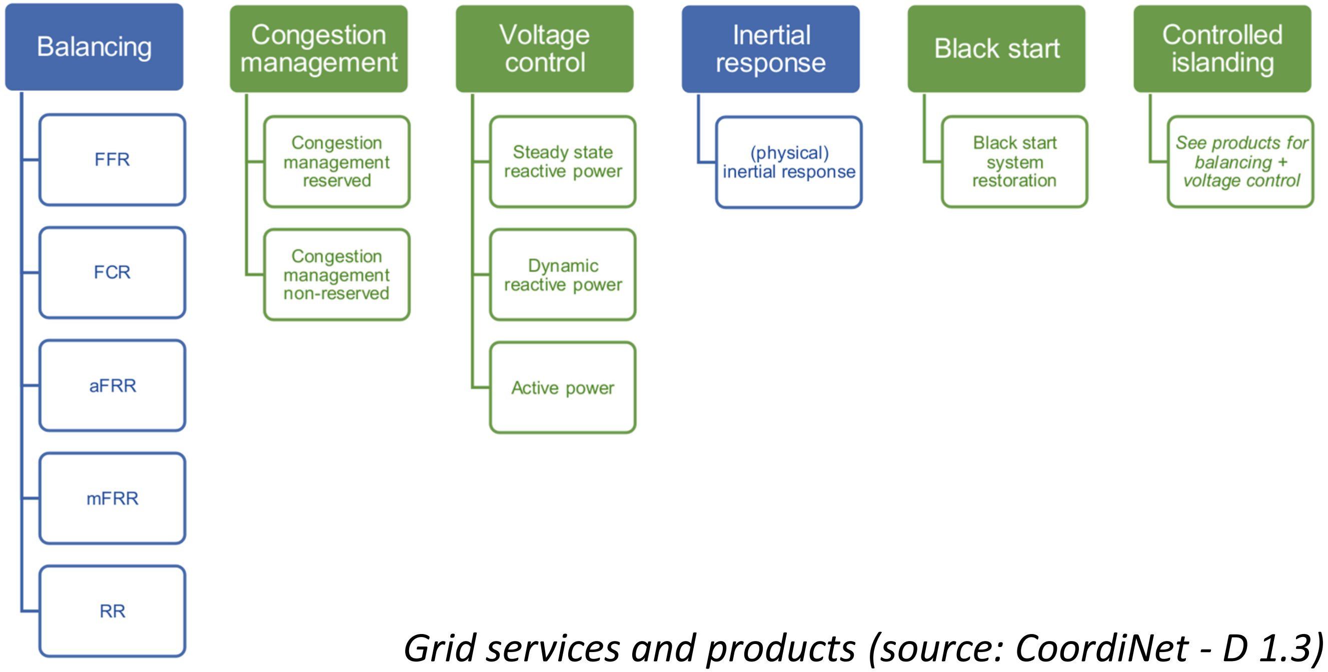
The market is open for both regulated (TSOs and DSOs) and non-regulated market parties [balancing responsible parties (BRPs) and commercial market parties (CMPs)], requiring an independent market operator (MO) to guarantee neutrality.

Flexibility resource to provide Ancillary Services (AS) [2-4]

Ancillary services are traditionally managed by TSOs through the control of traditional power plants, whereas usually DSOs play a limited passive role in power system management.

In the next years, both operators should benefit from employing these flexibility resources located at distribution level (*Directive 2019/944*):

- TSO for frequency/voltage regulation and congestions management.
- DSO to manage local congestions and voltage control.



- Balancing
  - FFR
  - FCR
  - aFRR
  - mFRR
  - RR
- Congestion management
  - Congestion management reserved
  - Congestion management non-reserved
- Voltage control
  - Steady state reactive power
  - Dynamic reactive power
  - Active power
- Inertial response
  - (physical) inertial response
- Black start
  - Black start system restoration
- Controlled islanding
  - *See products for balancing + voltage control*

Grid services and products (source: CoordiNet - D 1.3)

Need for Synthetic Inertia (SI) of Electrical Systems

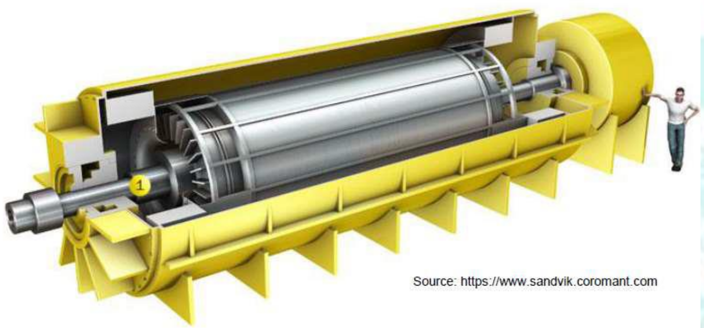
In a classic power plant, synchronous generators limiting the rate of change of frequency (ROCOF) in case of sudden frequency event, by releasing the stored kinetic energy,.

$$T_m \frac{dn}{dt} = m_m - m_{el}$$

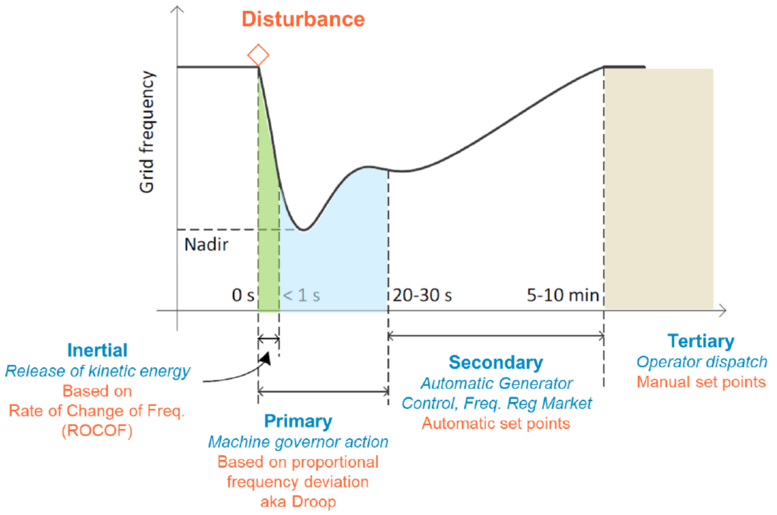
$$E_{rot} = \frac{1}{2} J \omega^2$$

$$P = \frac{dE_{rot}}{dt} = J\omega \frac{d\omega}{dt}$$

$$P_m - P_{el} = J\omega \frac{d\omega}{dt}$$



Source: https://www.sandvik.coromant.com



Source: EPIC Final Report | 2.05 Synthetic Inertia

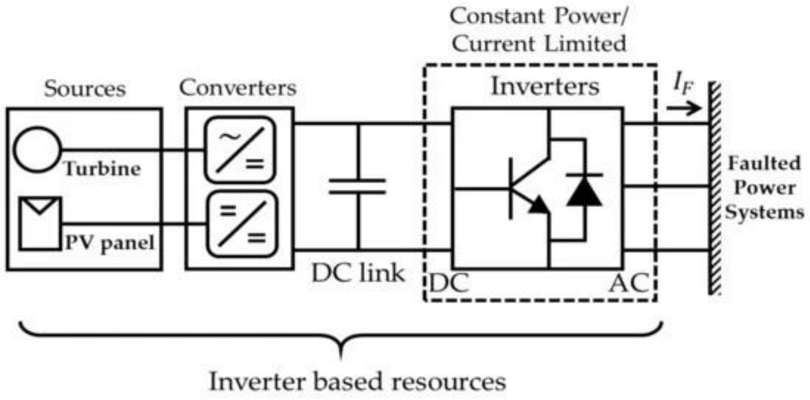
With reduced inertia conditions, sudden faults or system contingencies can generate wide frequency excursions, affecting the capability of the system to preserve grid integrity (undesired tripping of protections, generation/load units disconnection and instability).

Need for Synthetic Inertia (SI) of Electrical Systems [1], [4]

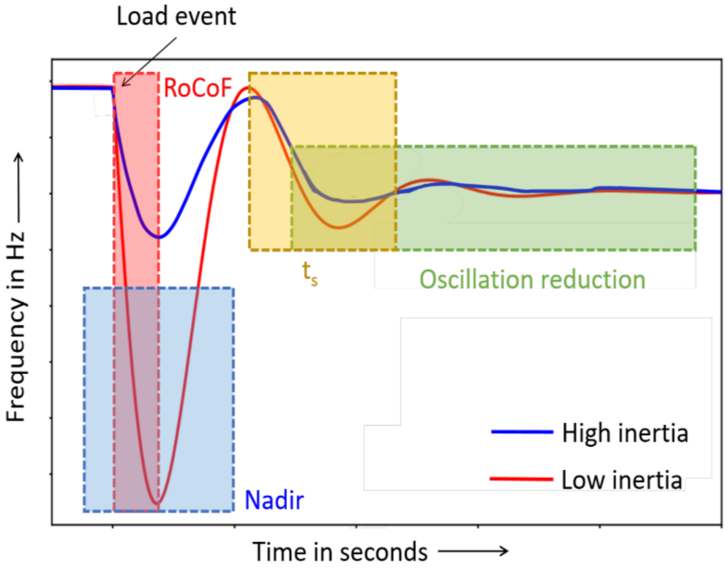
Total System Inertia is progressively decreasing!

DECARBONIZATION OF POWER GRIDS
Replacing of synchronous generators

EMPLOYMENT OF RENEWABLE ENERGY SOURCES (RES)
interfaced with networks by means of inverters (then lacking in inertia)



Source: MDPI (https://www.mdpi.com/2071-1050/11/4/1153)



Source: ENERGIES (https://www.mdpi.com/1996-1073/13/24/6485/htm)

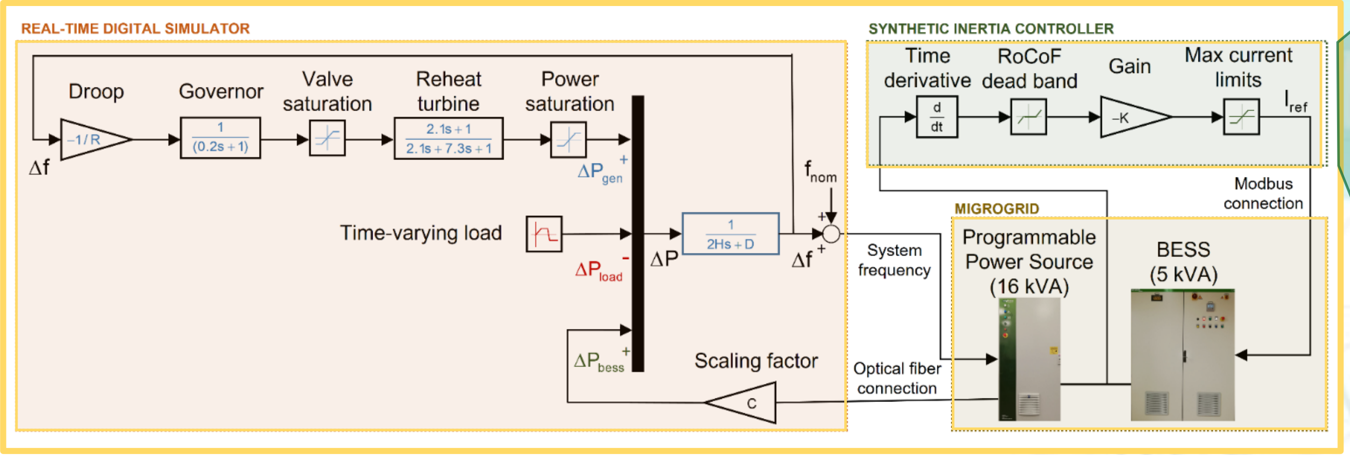
Need for Synthetic Inertia

- Synchronous condensers
- Virtual synchronous machines
- **Distributed energy resources - DERs**
  (load/generation/storage)

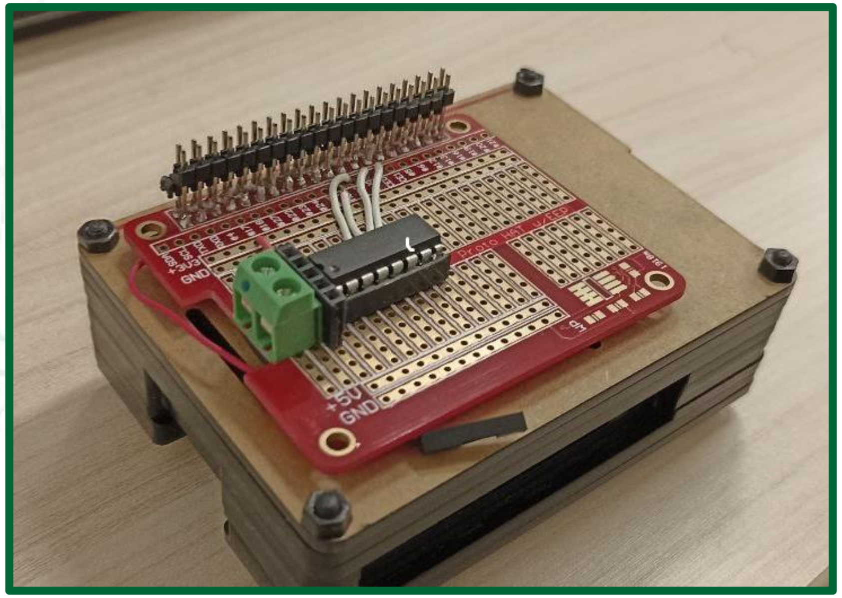
A low-cost controller for DERs to provide SI: description and validation tests [1]

Test bed architecture

Three experimental tests were carried out using the ***power-hardware-in-the-loop (PHIL) facility*** at LabZERO - Politecnico di Bari, in order to test the efficacy of the proposed controller to provide SI control actions through distributed energy resources



Source: [1]



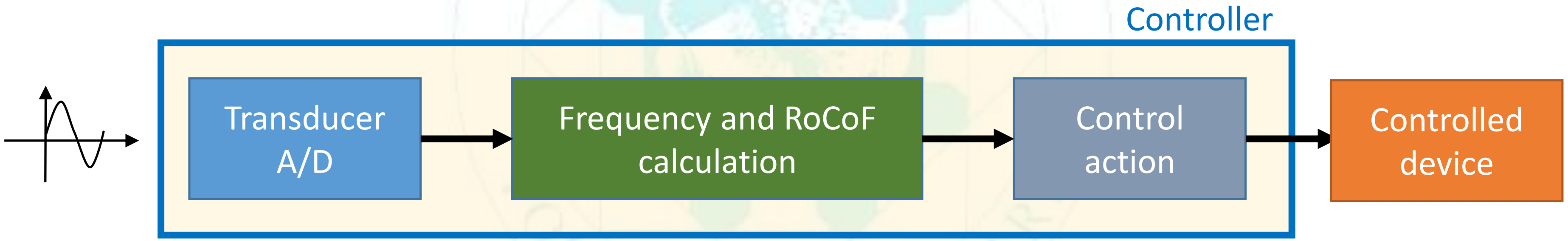
The proposed SI controller

A low-cost controller for DERs to provide SI: description and validation tests

SI controller: the proposed solution

An end-user low-cost controller (100 $) **able to measure frequency/RoCoF and generate a SI control law to manage legacy devices, without power converters reprogramming.**

It consists of a Raspberry Pi 4 Model B (single board computer) and an A/D converter directly mounted on a prototype shield.



The frequency calculation methodology is **based on a *signal autocorrelation algorithm* immune to noise, harmonic distortion and DC components**.

A low-cost controller for DERs to provide SI: description and validation tests

SI controller: frequency measurement algorithm

Considering a generic waveform x, with starting time t_0 and period $\tilde{\tau}$, the normalized function $\hat{A}(t,\tau)$ in eqn. (2) reaches the maximum in correspondence of $\tau = \tilde{\tau}$

$$A(t,\tau) = \int_{t_0}^{t_0+\tau} x(t)\cdot x(t+\tau)\,dt \quad (1) \qquad \longrightarrow \qquad \hat{A}(t,\tau) = \frac{A(t,\tau)}{C(t,\tau)} = \frac{\int_{t_0}^{t_0+\tau} x(t)\cdot x(t+\tau)\,dt}{0.5\cdot\int_{t_0}^{t_0+2\tau} x^2(t)\,dt} \quad (2)$$

Algorithm steps:

- voltage sampling (≃20 kHz) of about 2 cycles (46 ms);
- equally spacing and filtering of samples using interpolation/extrapolation rules:
- evaluation of $\hat{A}(t,\tau)$ for three subsequent candidates τ using a discretized expression of (2);
- period estimation considering previous candidates τ;

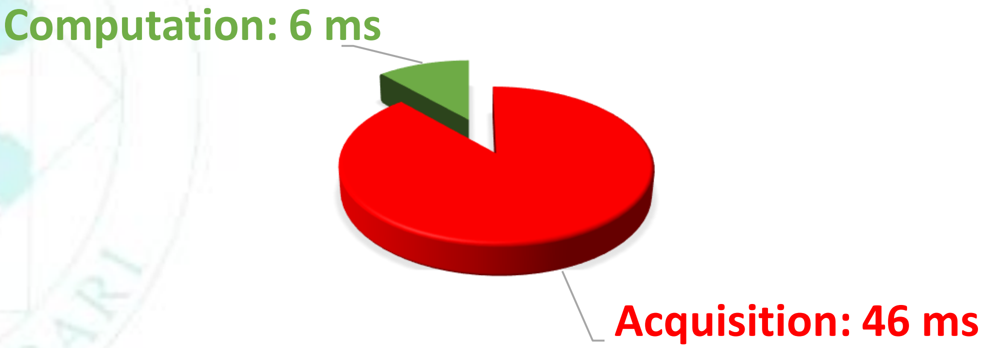
A low-cost controller for DERs to provide SI: description and validation tests

SI controller algorithm: accuracy and timing

To calculate the signal frequency, the proposed $\hat{A}(t,\tau)$ algorithm has been implemented on the device using Python language.

By means of preliminary tests, **the proposed method was tested through canonic waveforms from signal generators and voltage signals from universal relay testing machine**.

Mean Absolute Percentage Error [%]	*0.0023 - 0.0028*
Standard deviation [Hz]	*0.0014 - 0.0018*
Timing [ms]	*52*
Frequency measurement range [Hz]	*47.5 - 51.5*



Source: [1]

A slow reporting rate, acting as a low-pass filter, allows to reduce noise on RoCoF despite it adds delay in the overall control chain

A low-cost controller for DERs to provide SI: description and validation tests

Test bed architecture: simulated power system

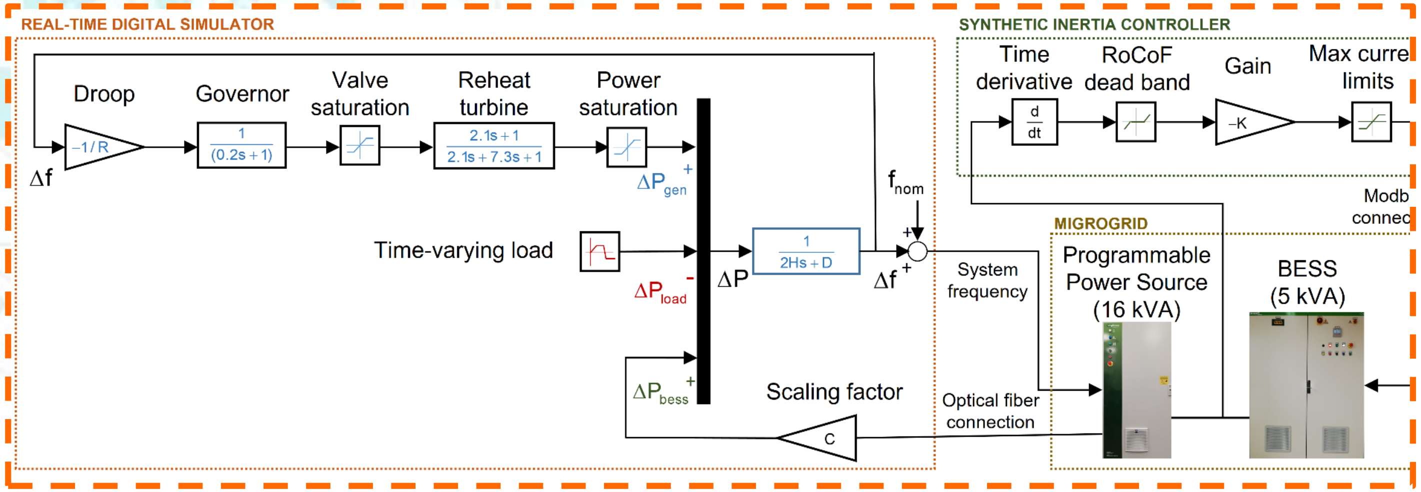
A real-time digital simulator (*"OPAL-RT"*) simulates the electromechanical response of a generic equivalent power system. It is able to interact with the following systems located in the microgrid:

- the ***programmable power source*** **(PSS)**, located in the microgrid, by means of a fiber-optics channel;
- the ***battery energy storage system*** **(BESS)**, through a Modbus TCP/IP communication.

$$\Delta f = \frac{1}{2Hs+D} \cdot \Delta P$$

$$\Delta P = \Delta P_{gen} + \Delta P_{load} + \Delta P_{bess} \quad \text{[p.u.]}$$

- ΔP_{gen}: primary frequency regulation response
- ΔP_{load}: load power fluctuations
- ΔP_{bess}: power exchange between BESS and PPS

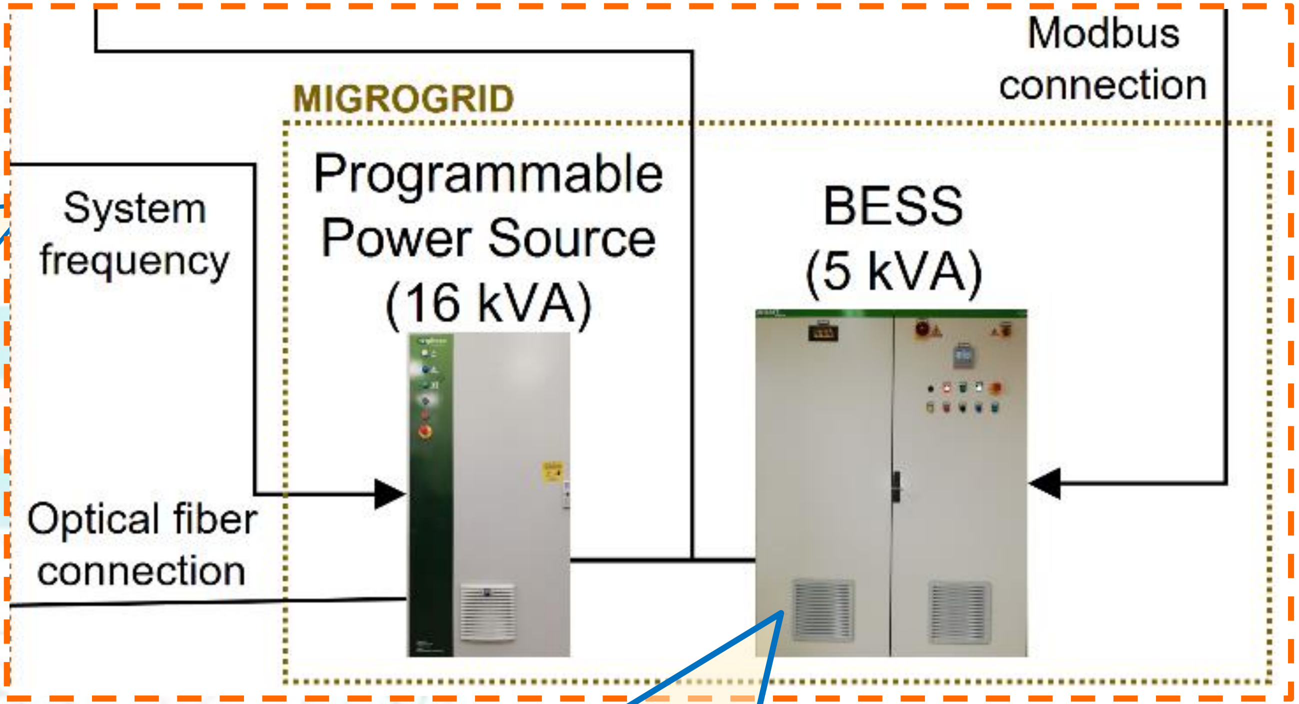


Source: [1]

A low-cost controller for DERs to provide SI: description and validation tests

Test bed architecture: microgrid scheme

The power system frequency signal is sent from the digital simulator to the PSS, which imposes the simulated frequency on the **5 kVA LiFePO$_4$ BESS** operating in grid-forming mode.



Source: [1]

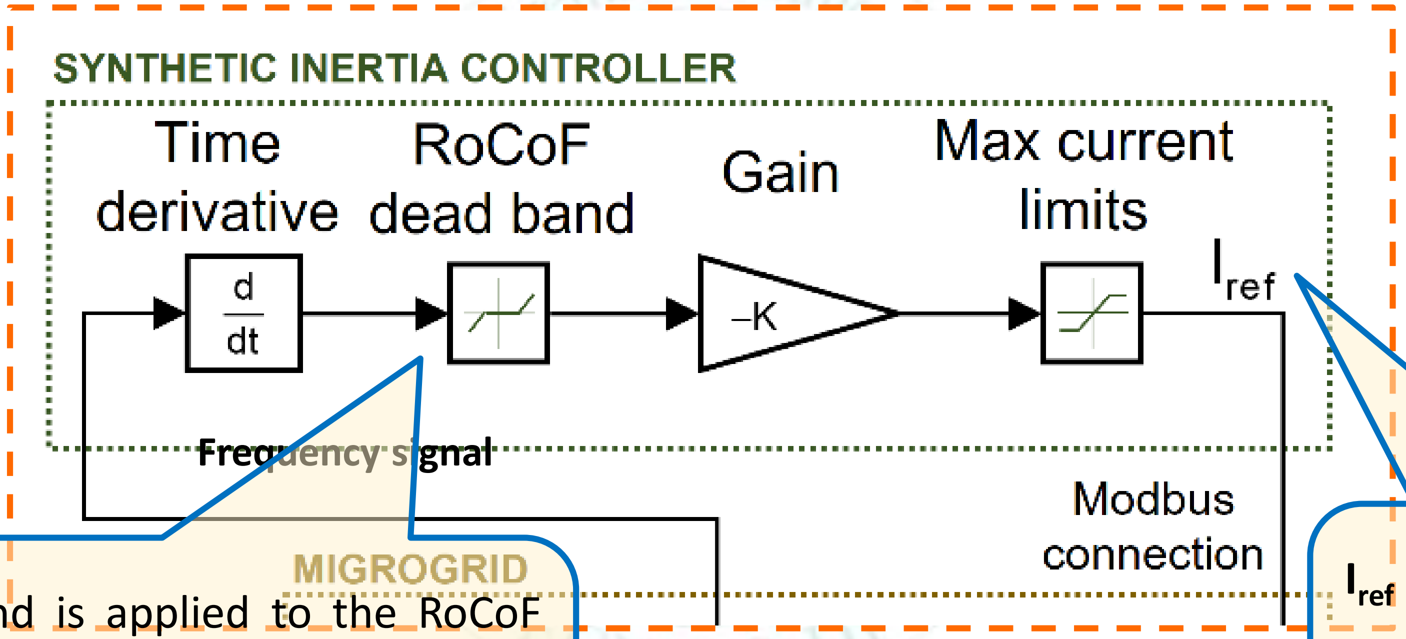
The value of power between BESS and PSS is measured and sent back to the digital simulator, giving a contribution to the power balance equation.

A low-cost controller for DERs to provide SI: description and validation tests

SI control algorithm: RoCoF measurement

The BESS power output is controlled according to a **current reference set-point I_{ref}**, which is proportional to values of *RoCoF* and established gain *K*.

$$\Delta f = \frac{1}{2Hs+D} \cdot \Delta P$$



Source: [1]

A suitable deadband is applied to the RoCoF signal in order to avoid excessive control activity of the BESS

I_{ref} is limited according to maximum charge and discharge power

A low-cost controller for DERs to provide SI: description and validation tests

Case 1: system response without synthetic inertia

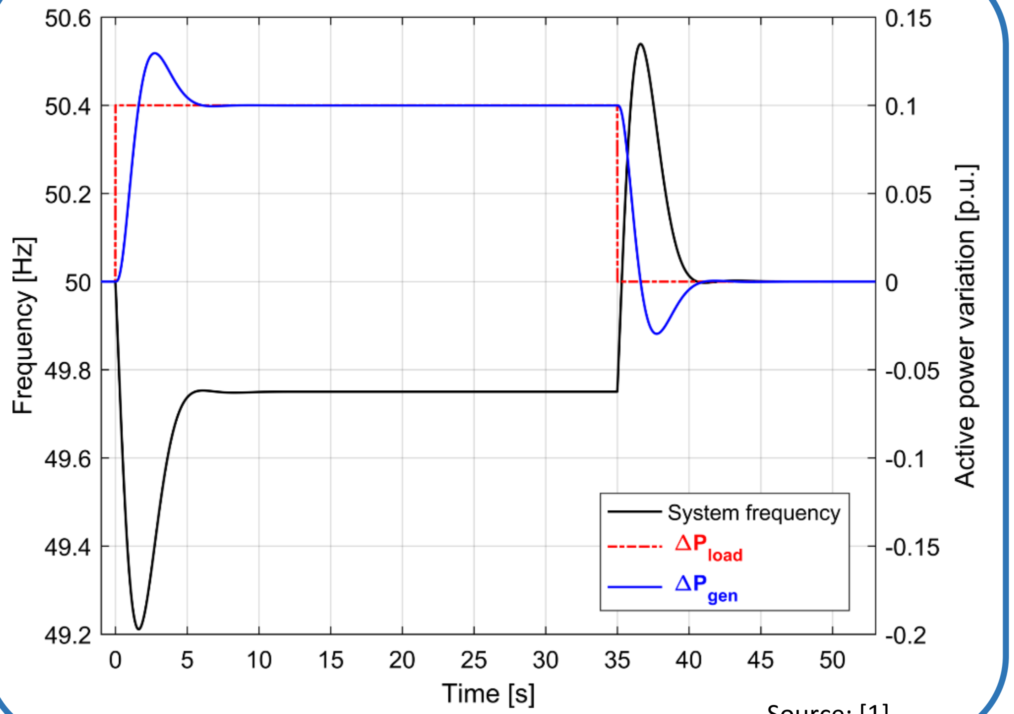
In the first test case, **primary frequency regulation only is provided** through the modelled thermo-electric plant, assuming:

- ***Droop R*** = 0.05 p.u.
- ***Damping D*** = 0.02 p.u.
- ***Inertia H*** = 3s (reduced TSI condition)

- t<0 s: **steady state condition**

- t=0 s: **upward load** step change (+0.1 p.u.)

- t=35 s: **downward load** step change (-0.1 p.u.)



Source: [1]

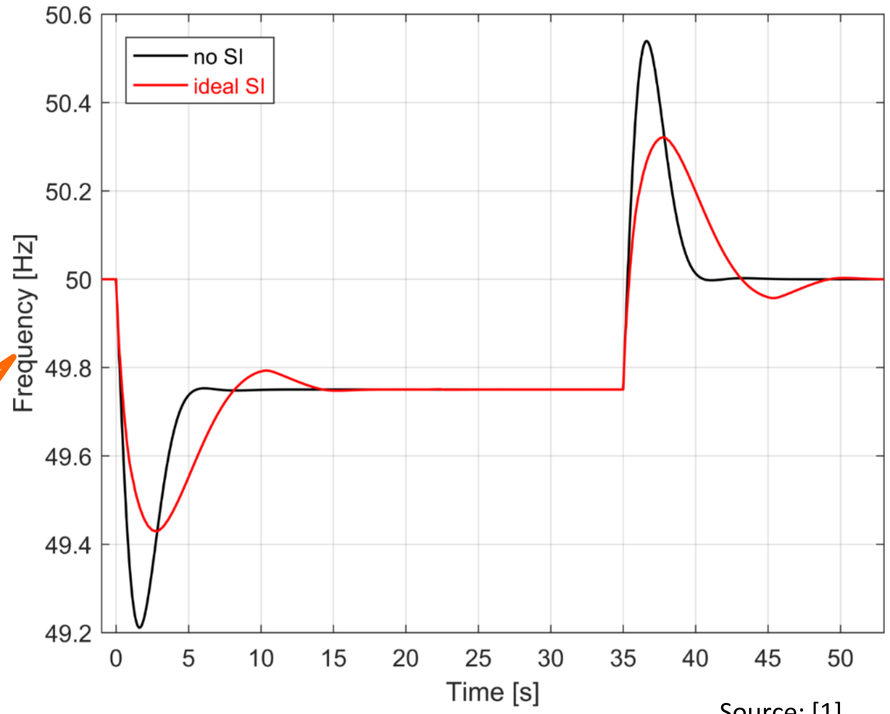
A low-cost controller for DERs to provide SI: description and validation tests

Case 2: ideal SI control action with simulated control – 1/2

SI controller functionalities are emulated by means of the digital real-time simulator and the BESS controlled in PHIL mode

Unfiltered RoCoF signal (not affected by measurement errors) was calculated and used to generate a SI control law to be applied on the BESS.

SI control action allowed to reduced frequency excursions with respect to the base case, having smaller overshoot and slopes, whereas settling time increased.



Source: [1]

A low-cost controller for DERs to provide SI: description and validation tests

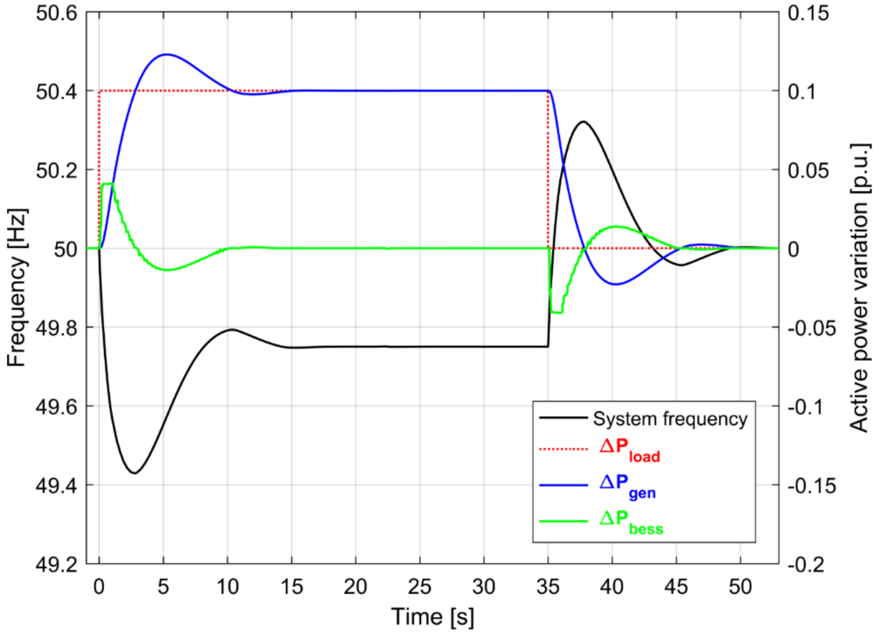
Case 2: ideal SI control action with simulated control – 2/2

In this test, **a *gain K* of 25 A/(Hz/s)** and a *factor C* (aimed to scale the BESS response) were applied.

The maximum BESS direct current output $\boldsymbol{I_{ref}}$ **of ± 5A corresponds to a power of 0.04 p.u.**

Due to the SI contribution, the response of the primary regulation is smoothed and delayed.

BESS power response is barely affected by delay, reaching a peak after 200 ms from the load step change variation (both downward and upward)



Source: [1]

A low-cost controller for DERs to provide SI: description and validation tests

Case 3: test of the SI controller – 1/3

SI control action is provided by the proposed controller: the device autonomously measured the frequency from the BESS busbar voltage, calculated the RoCoF and sent I_{ref} to the *Battery Management System* (BMS).

The real-time simulator provided the frequency reference to the programmable source

Since RoCoF estimation errors, the following exponential smoothing low-pass filter was applied:

$$s_t = \alpha \cdot f_t + (1 - \alpha) \cdot s_{t-1}$$

α is the set smoothing factor, $\mathrm{f_t}$ the frequency observation at time t, s_t and s_{t-1} the smoothed frequency values at current and previous time.

Higher values of α generated more effective SI control laws (higher nadir), but also more frequency fluctuations.

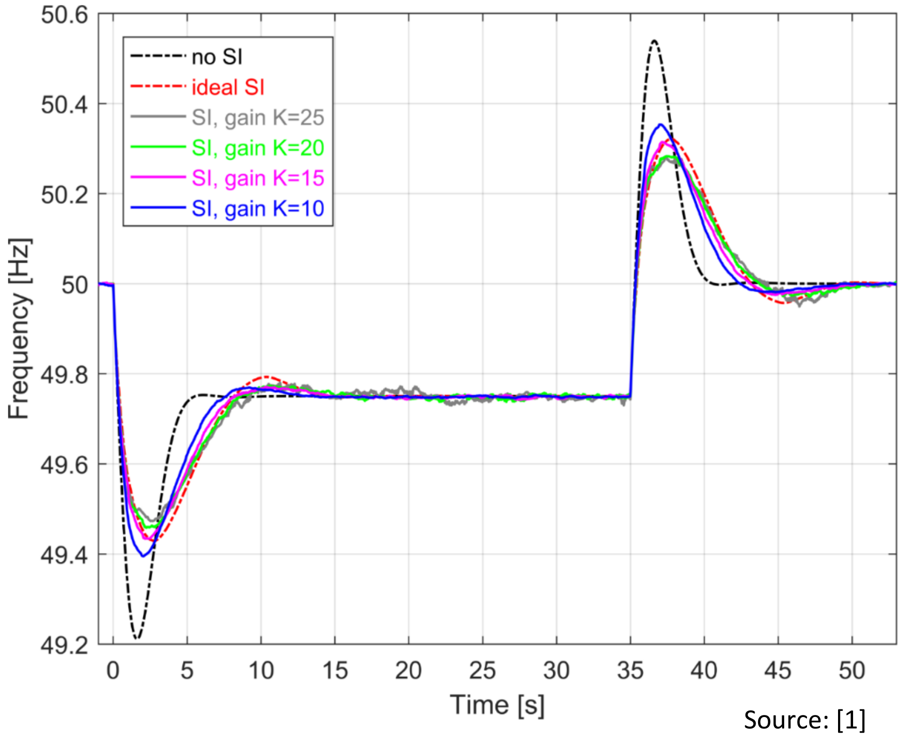
A low-cost controller for DERs to provide SI: description and validation tests

Case 3: test of the SI controller – 2/3

Synthetic inertia actions were performed applying:

- ***gain K*** **ranged from 10 to 25**.
- ***A smoothing factor α = 0.1*** (value suggested from empirical tests as suitable to filter the frequency signal.

Nadir and settling time raised with the gain increasing. Moreover, high gains introduced frequency fluctuations due to RoCoF errors amplification.



Source: [1]

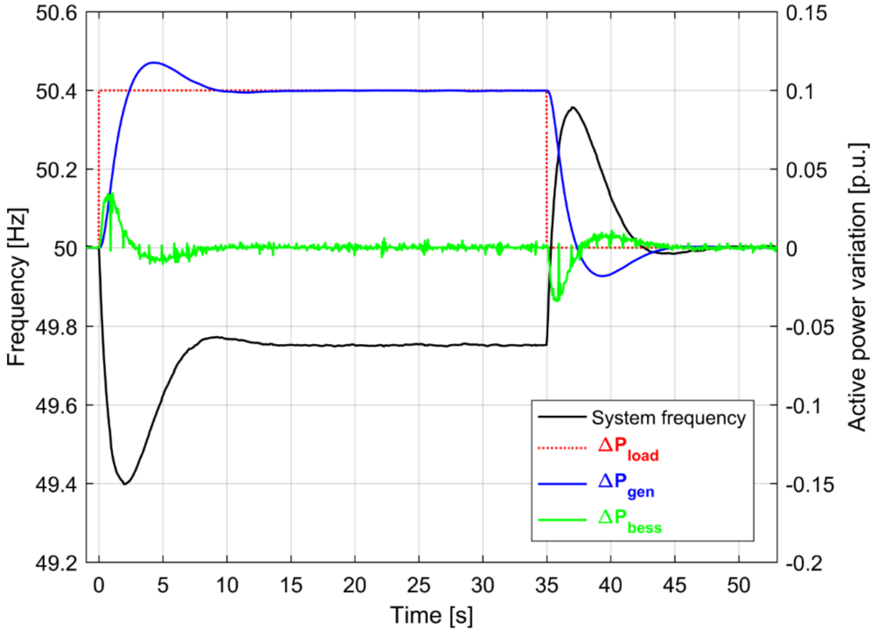
A low-cost controller for DERs to provide SI: description and validation tests

Case 3: test of the SI controller – 3/3

Fluctuations of the power response **ΔP_{bess} errors can be controlled by either reducing the gain K or introducing a suitable deadband on RoCoF** (large deadbands reduce RoCoF sensitivity).

ΔP_{bess} first reaction was observed after about 100 ms with respect to the frequency derivative due RoCoF filter.

The BESS response ΔP_{bess} reached its peak about 600 ms after the step change (due to the presence of the filter).



Source: [1]

Findings and final conclusions

- ✓ **The controller (100 $) is able to measure RoCoF and control legacy components**, whose management system cannot be easily reprogrammed, in order to provide **SI actions**.
- ✓ **PHIL tests shown the effectiveness of the SI control actions performed through a BESS**, with an accurate and fast enough response during transients.
- ✓ **The actual implementation requires careful tuning of a *low-pass filter* and *control gain***, in order to avoid undesired frequency fluctuations.
- ✓ **Further tests will be aimed at coordinating *gain* with both *frequency and RoCoF deadbands*** to reduce stress of controlled components and identify minimum requirements for distributed SI controllers.

References

[1] S. Bruno, G. Giannoccaro, C. Iurlaro, M. L. Scala and C. Rodio, ***"A Low-cost Controller to Enable Synthetic Inertia Response of Distributed Energy Resources,"*** 2020 EEEIC / I&CPS Europe, 2020, pp. 1-6, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160813.

[2] C. Rodio, G. Giannoccaro, S. Bruno, M. Bronzini and M. La Scala, ***"Optimal Dispatch of Distributed Resources in a TSO-DSO Coordination Framework,"*** 2020 AEIT International Annual Conference (AEIT), 2020, pp. 1-6, doi: 10.23919/AEIT50178.2020.9241175.

[3] S. Bruno, G. Giannoccaro, C. Iurlaro, M. L. Scala, L. Notaristefano and C. Rodio, ***"Mapping Flexibility Region through Three-phase Distribution Optimal Power Flow at TSO-DSO Point of Interconnection,"*** 2021 AEIT International Annual Conference (AEIT), 2021, pp. 1-6, doi: 10.23919/AEIT53387.2021.9627050.

[4] S. Bruno, G. Giannoccaro, C. Iurlaro, M. L. Scala, C. Rodio and R. Sbrizzai, ***"Fast Frequency Regulation Support by LED Street Lighting Control,"*** 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2021, pp. 1-6, doi: 10.1109/EEEIC/ICPSEurope51590.2021.9584577.

Grid services to transmission and distribution system operators through distributed energy resources (DERs)

THANK YOU FOR YOUR ATTENTION!

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