DIPARTIMENTO DI
INGEGNERIA ELETTRICA
E DELL'INFORMAZIONE

Politecnico
di Bari

LabZERO
Zero Emission Research Option

DEI Doctoral Research Seminars

February 16th 2022, Bari

Studies to enable end-users to provide energy services to the power grid

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Seminar structure

First part

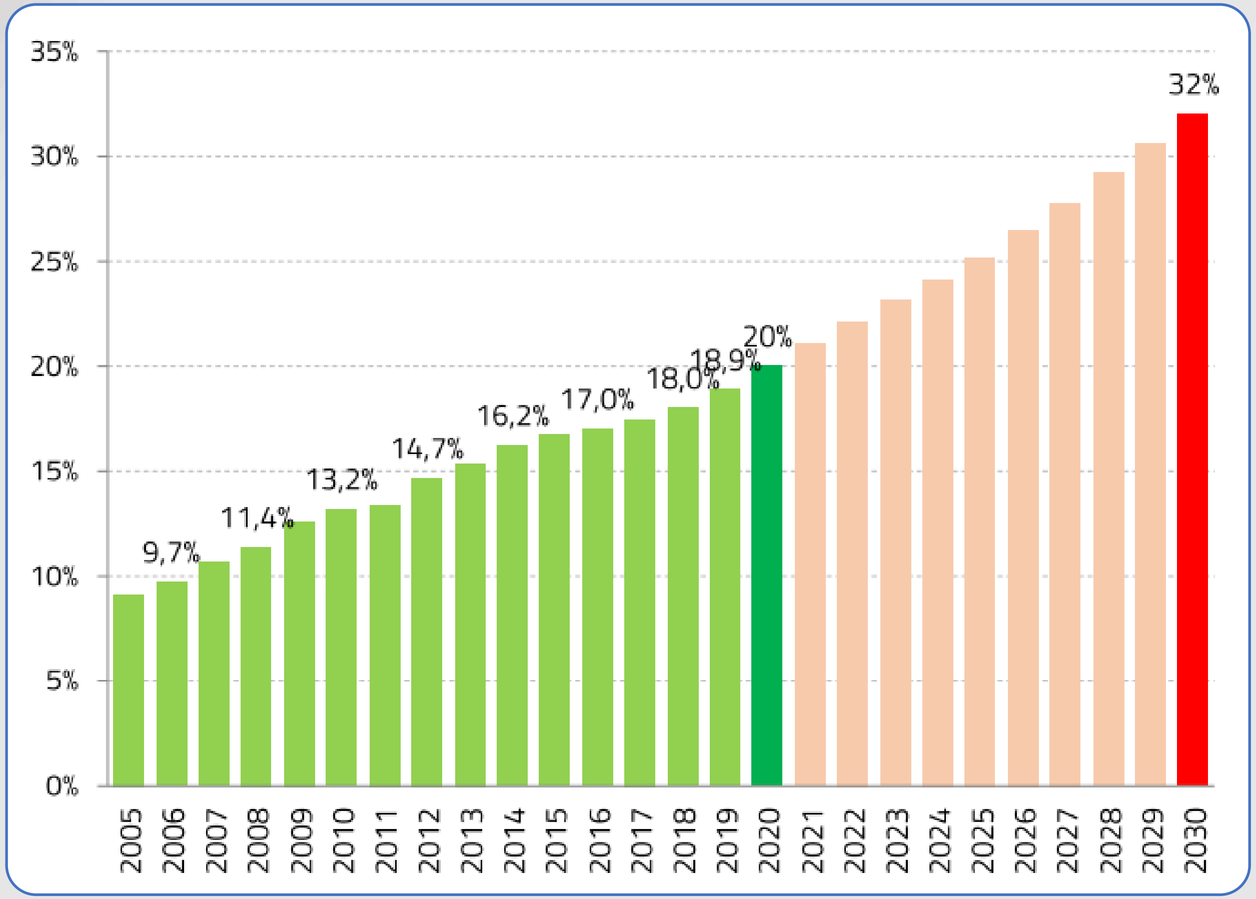
- *Decarbonization and power grid inertia reduction*
- *A study to provide frequency support to the power grid by hybrid energy storage systems*

Second part

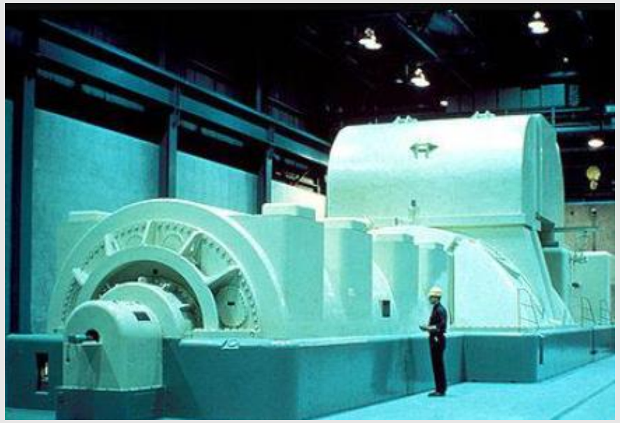
- *Italian small-islands and differences in frequency regulation*
- *A study to provide frequency support to a small-islanded microgrid by lightining systems*

RES evolution in the Italy power system

Trajectory of the portion of overall energy consumption covered by RES up to 2030 in EU (%)



increase in inverter-based installations



reduction of rotating generators

Reference: GSE – Fonti rinnovabili in Italia e in Europa 2019

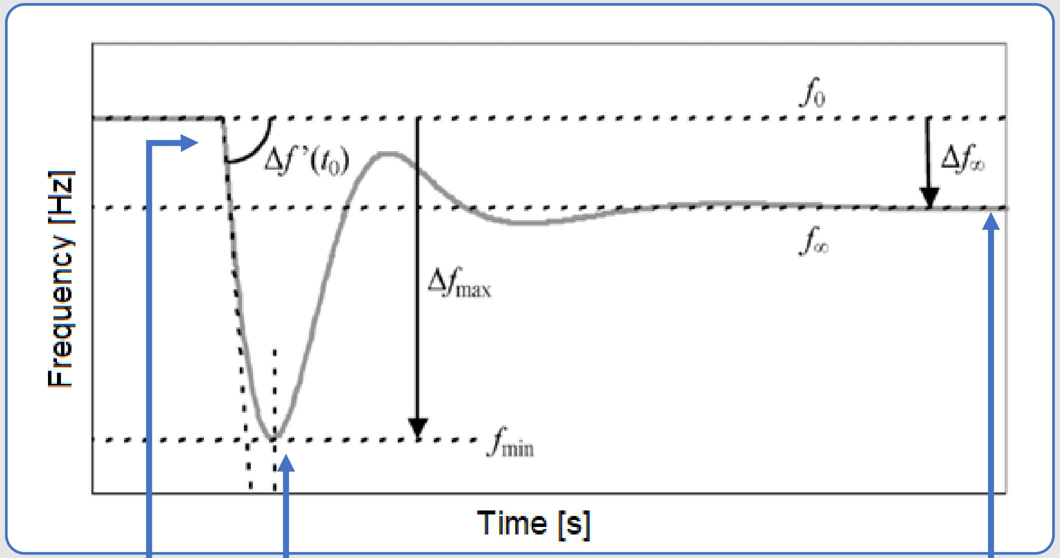
Frequency regulation in low inertia system

Reduction of rotating generator

Reduction of total system inertia

- *Higher frequency excursions for little power imbalance*
- *More oscillations during frequency transients*
    - *Higher RoCoF after a contingency*

$$RoCoF|_{t=0^+} = \frac{\Delta P_{imbalance}}{P_{LOAD}} \cdot \frac{f_0}{2 \cdot H}$$

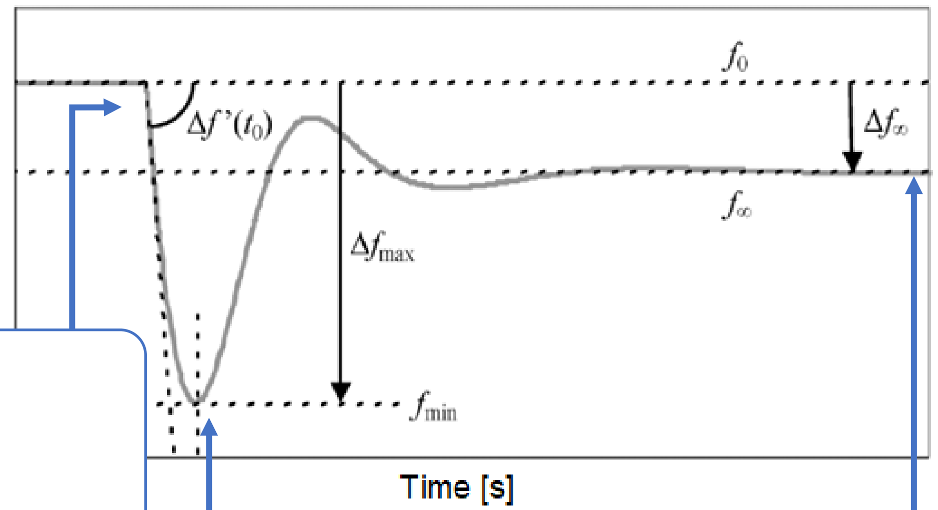


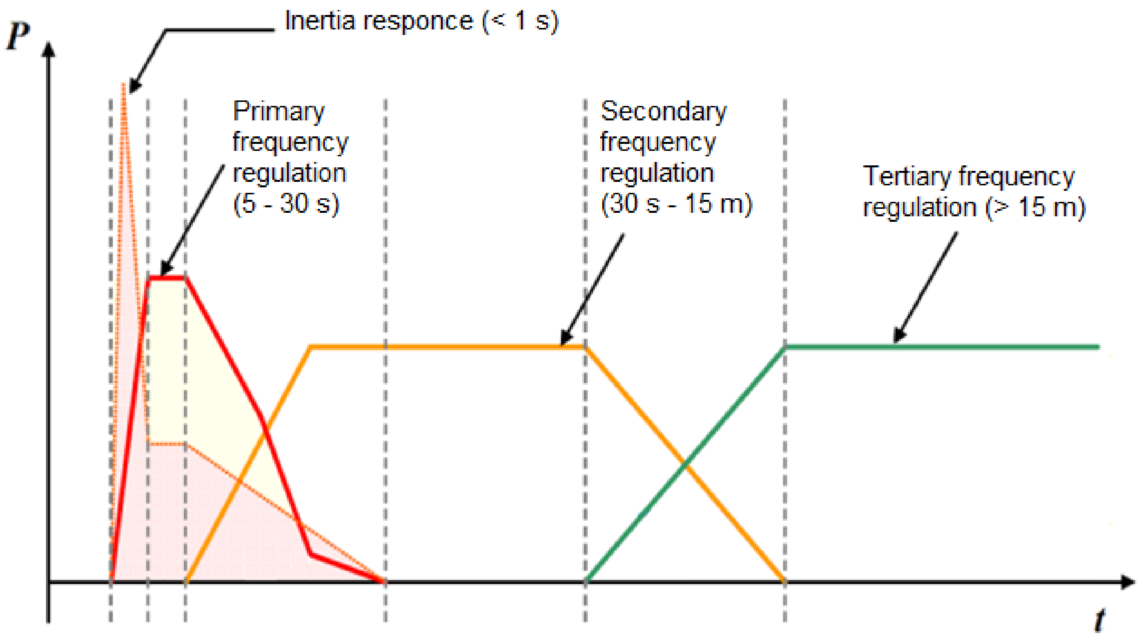
Frequency response indicators:

- *Nadir [Hz]*
- *RoCoF [Hz/s]*
- $f_{steady-state}$ *[Hz]*

Reference: ENTSO-E – Inertia and Rate of Change of Frequency (RoCoF), ver. 17, 16 Dec. 2020.

Frequency regulation in low inertia system





Frequency response indicators:

- *Nadir [Hz]*
- *RoCoF [Hz/s]*
- $f_{steady-state}$ *[Hz]*

Fast frequency support by inverter-based resources

Synchronous condensers can be installed to increase the total system inertia, but with the drawback of increasing system costs and complexity.
Another possibility is to provide fast frequency support with inverter-based resources.
The actions to counteract the effect of reduced system inertia are as following:

Synthetic Inertia

Synthetic inertia is defined as the controlled contribution of electrical power from a unit that is proportional to the RoCoF at the terminals of the unit.

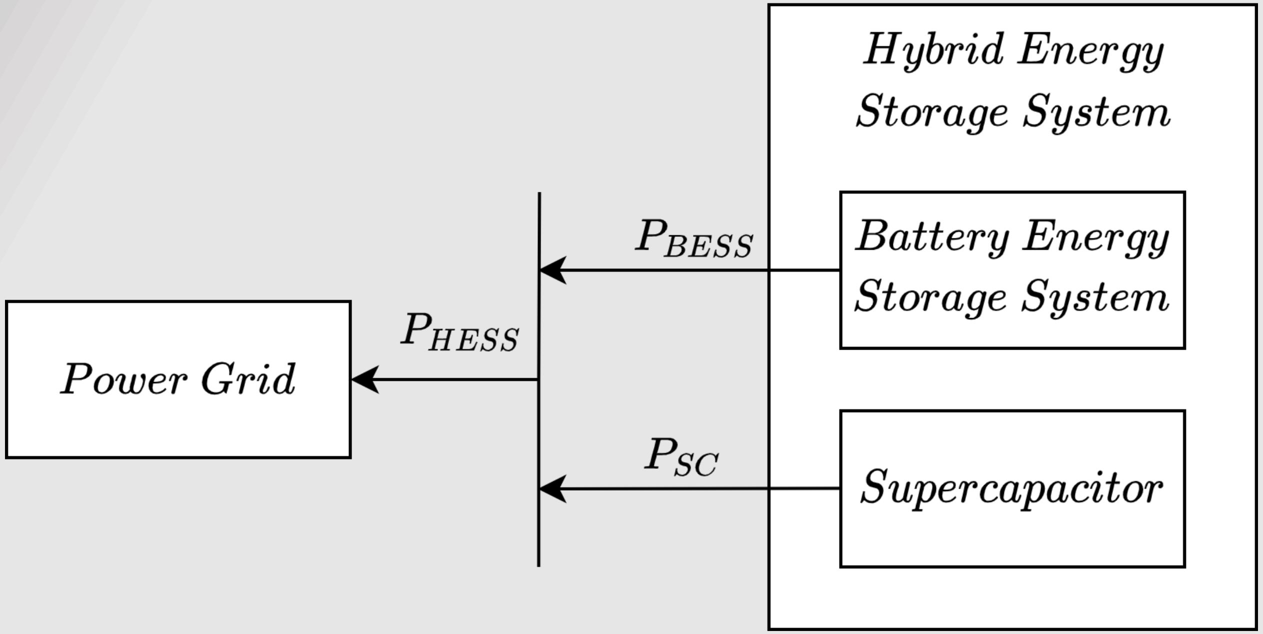
Fast Frequency Response

Fast frequency response is the controlled contribution of electrical power from a unit which responds quickly to changes in frequency in order to counteract the effect of reduced inertial response.

Reference: 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.

A study to provide fast frequency contribution to the power grid

A study has been done to provide to the power grid a mixed contribution of synthetic inertia and fast frequency response



Hybrid Energy Storage System

Battery Energy Storage System

Supercapacitor

Power Grid

P_{BESS}

P_{SC}

P_{HESS}

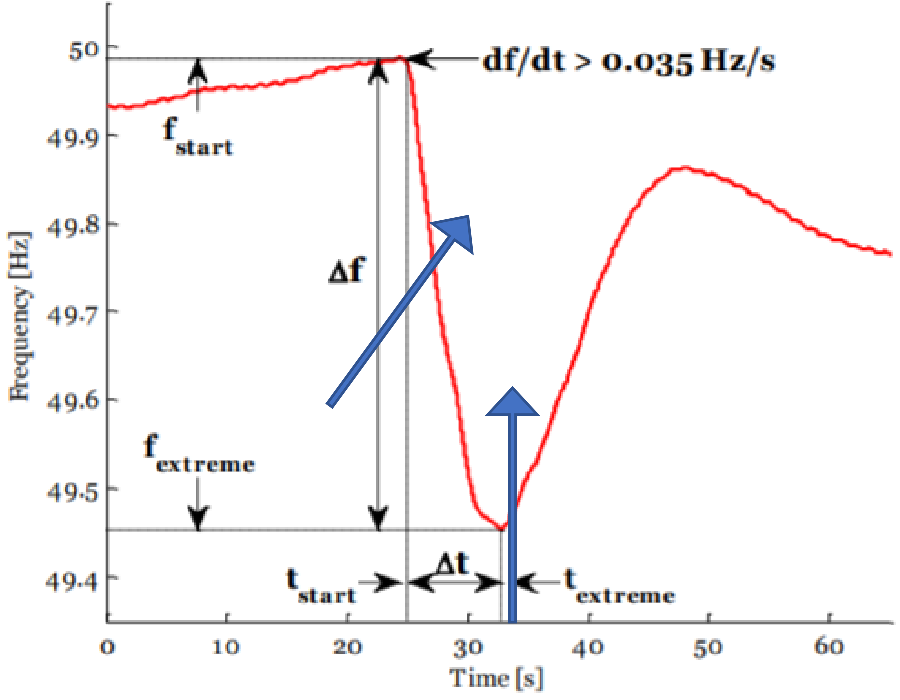
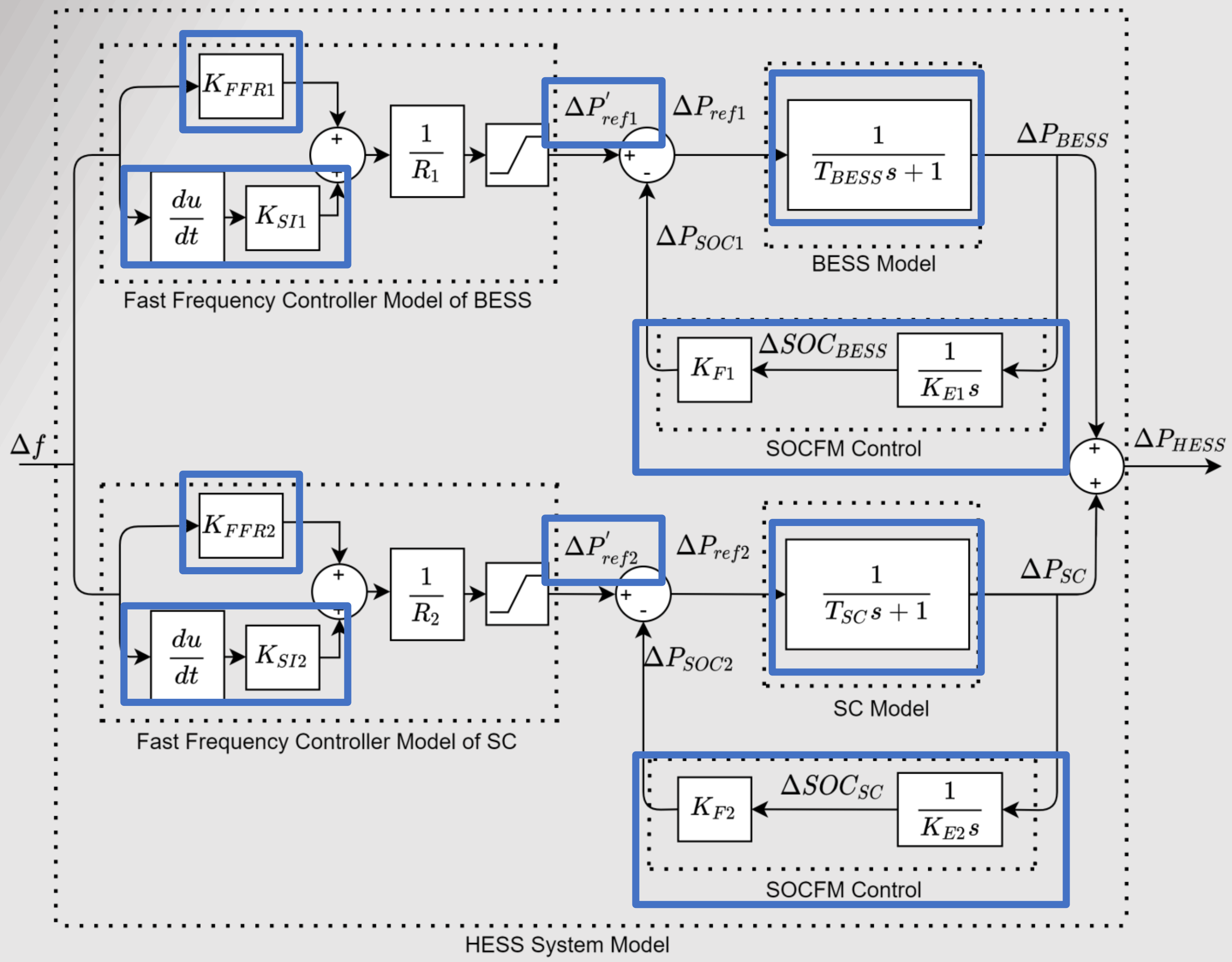


FIGURE 2.5: GRAPHICAL REPRESENTATION OF FREQUENCY RESPONSE INDICATORS

Reference: S. Bruno, G. De Carne, C. Iurlaro, C. Rodio and M. Specchio, "A SOC-feedback Control Scheme for Fast Frequency Support with Hybrid Battery/Supercapacitor Storage System," 2021 6th IEEE Workshop on the Electronic Grid (eGRID), 2021, pp. 1-8, doi: 10.1109/eGRID52793.2021.9662149.

A study to provide fast frequency contribution to the power grid



BESS – higher energy capacity

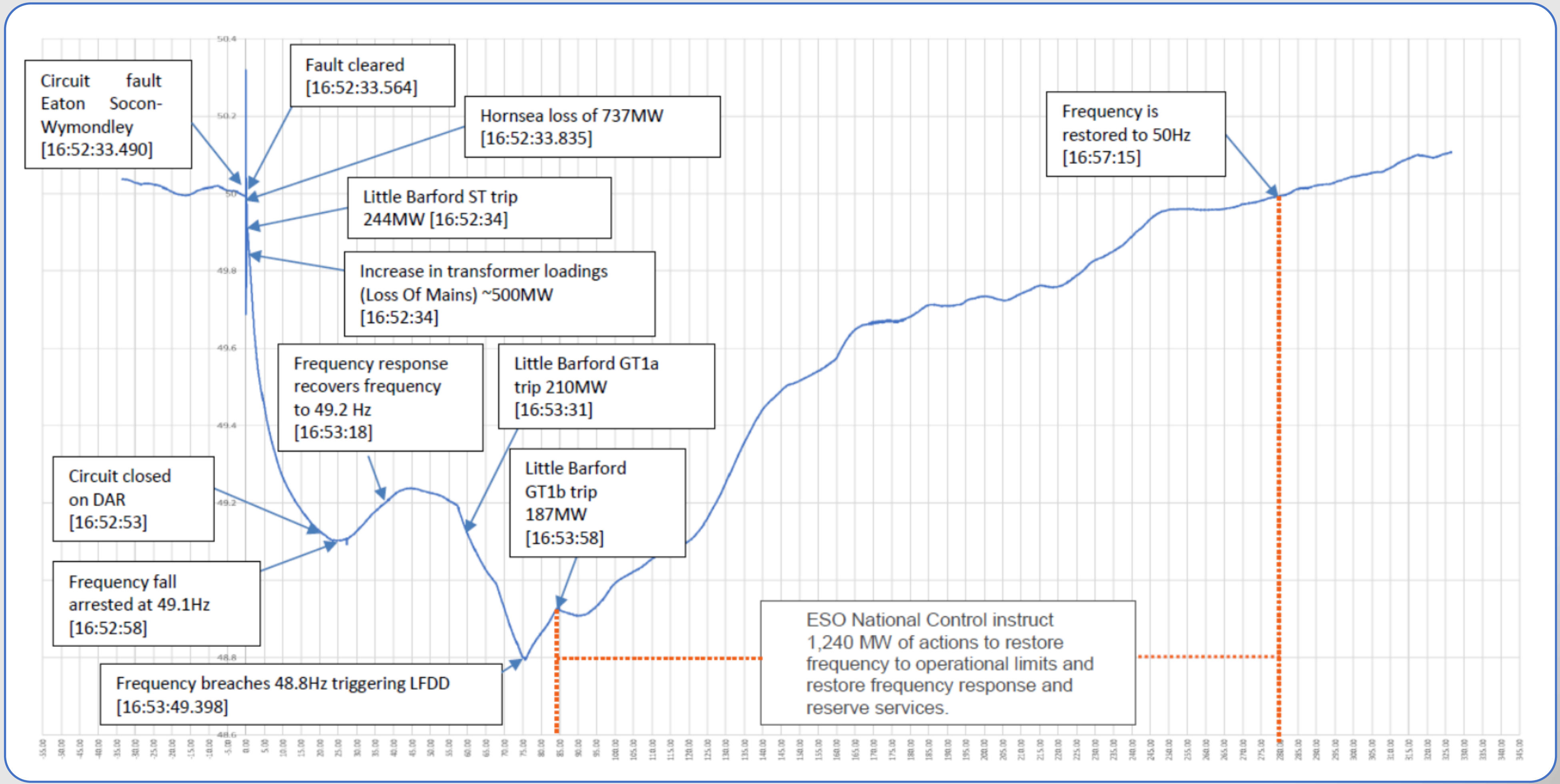
Higher $K_{FFR1} = 0.8$
Lower $K_{SI1} = 0.2$

SC – higher power density

Lower $K_{FFR2} = 0.2$
Higher $K_{SI2} = 0.8$

Open-loop Test of the Proposed Controller

Great Britain
Power System
Disruption
9th August 2019



Circuit fault Eaton Socon-Wymondley [16:52:33.490]

Fault cleared [16:52:33.564]

Hornsea loss of 737MW [16:52:33.835]

Little Barford ST trip 244MW [16:52:34]

Increase in transformer loadings (Loss Of Mains) ~500MW [16:52:34]

Frequency response recovers frequency to 49.2 Hz [16:53:18]

Little Barford GT1a trip 210MW [16:53:31]

Circuit closed on DAR [16:52:53]

Little Barford GT1b trip 187MW [16:53:58]

Frequency fall arrested at 49.1Hz [16:52:58]

Frequency breaches 48.8Hz triggering LFDD [16:53:49.398]

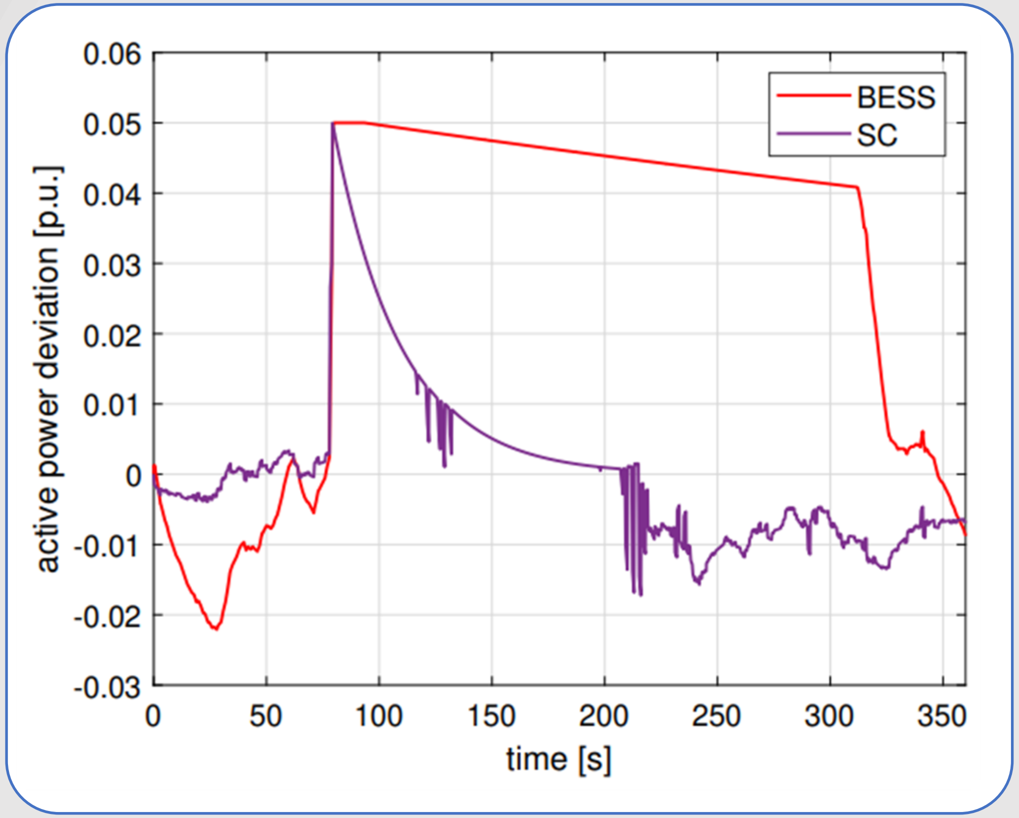
Frequency is restored to 50Hz [16:57:15]

ESO National Control instruct 1,240 MW of actions to restore frequency to operational limits and restore frequency response and reserve services.

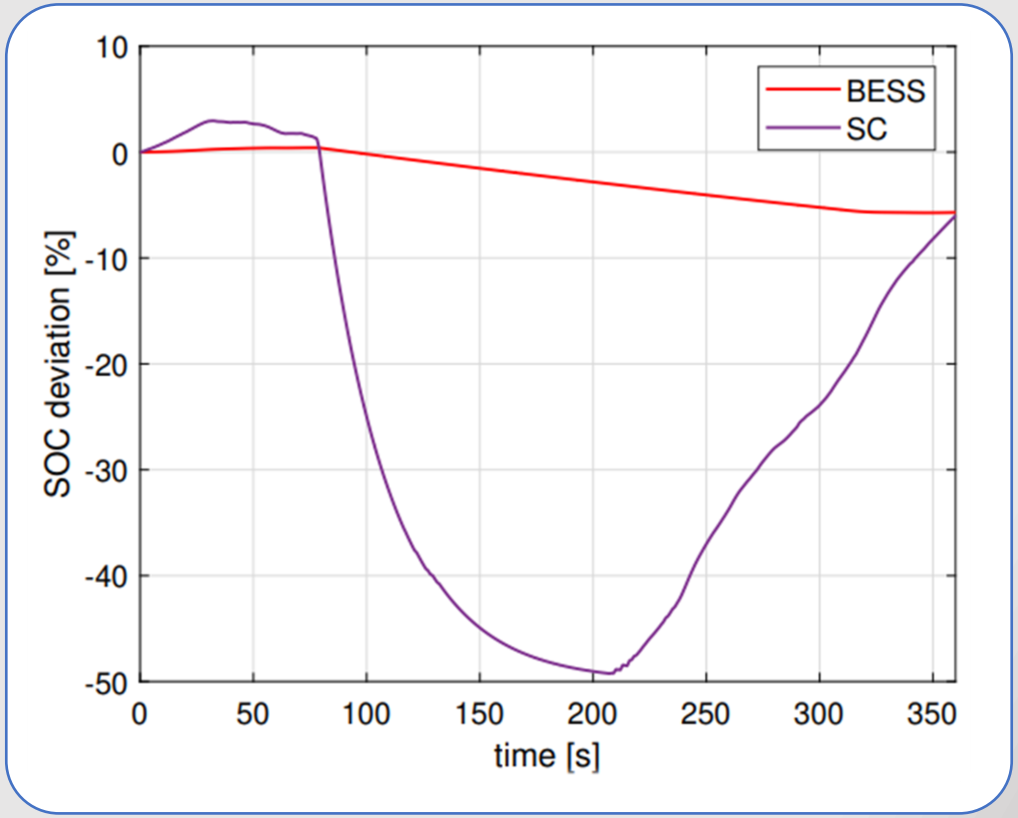
Reference: BEIS - Department for Business, Energy & Industrial Strategy, “GB Power System Disruption - 9 August 2019,” Tech. Rep., 2019.

Open-loop Test of the Proposed Controller

Active power exchanged by the devices

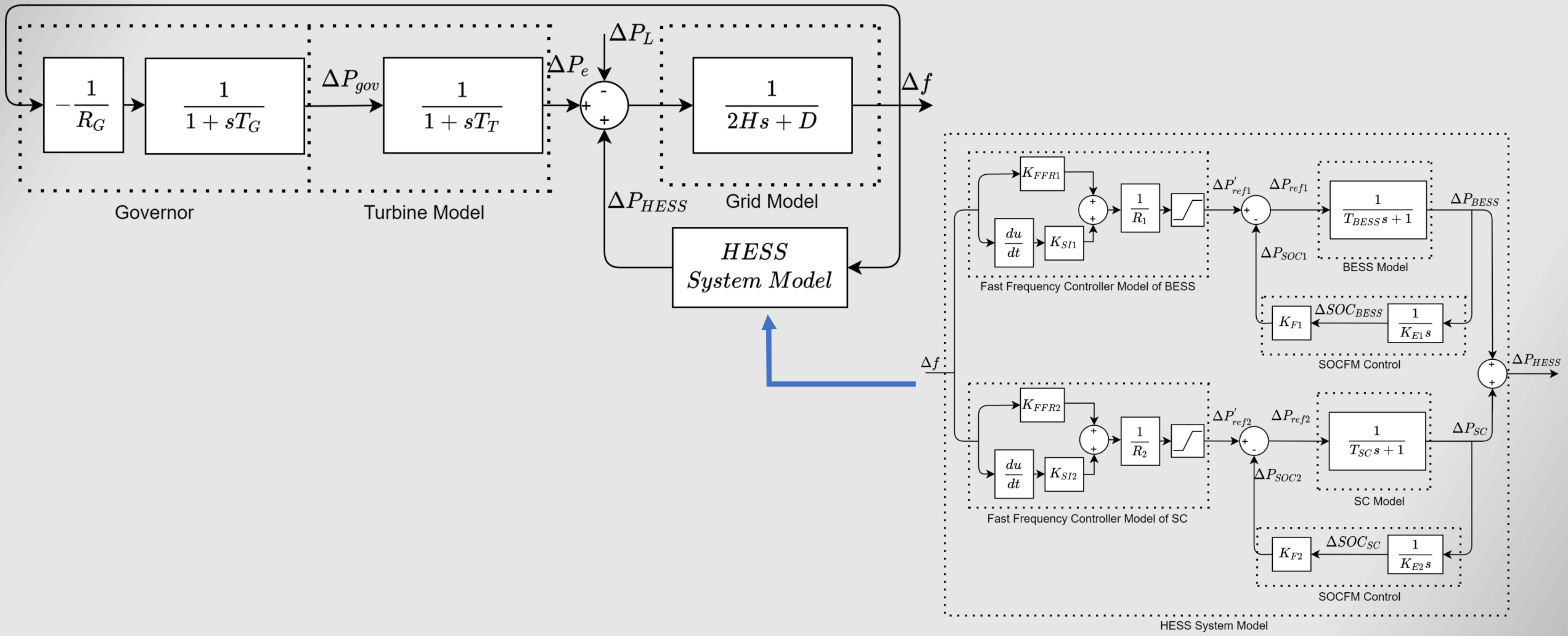


State of charge behaviours



Closed-loop Response Analysis and Controller Parameters Optimal Tuning

The overall power system model used.



Closed-loop Response Analysis and Controller Parameters Optimal Tuning

The fast frequency controllers gains and the gains of the additional control can be optimally tuned by means of a generic optimization algorithm.

The problem to be solved minimized a generically nonlinear function of all system variables:

$$\min_{\boldsymbol{u}} \int^{T} f(\boldsymbol{x}(t), \boldsymbol{u}, d) \cdot dt$$

subject to a differential set of equations

$$\mathbf{h}(\boldsymbol{x}(t), \boldsymbol{u}, d) = 0 \qquad \begin{matrix} \boldsymbol{x} \in \boldsymbol{X} \\ \boldsymbol{u} \in \boldsymbol{U} \end{matrix}$$

X *takes into account all physical constraints and* ***U*** *limits the control variables.*

that can be expressed in the form:

$$\dot{\boldsymbol{x}} = A(\boldsymbol{u}) \cdot \boldsymbol{x}(t) + B(\boldsymbol{u}) \cdot d$$

where:

- *the set of the state variable is:*

$$\boldsymbol{x}^T = [\Delta P_e(t), \Delta f(t), \Delta P_{gov}(t), \Delta P_{BESS}(t), \Delta P_{SC}(t), \Delta SOC_{BESS}(t), \Delta SOC_{SC}(t)]$$

- *the set of the control variables is:*

$$\boldsymbol{u}^T = [K_{FFR1}, K_{SI1}, K_{FFR2}, K_{SI2}, K_{F1}, K_{F2}]$$

- *d* represents the disturbance ΔPL applied at $t = 0$.

Through discretization, the dynamic problem formulated in the previous slide can be converted into a static nonlinear problem in the discrete time domain.

$$\min_{\boldsymbol{u}} F(\hat{\boldsymbol{x}}, \boldsymbol{u}, d)$$

subject to the set of discretized differential equations

$$\mathbf{H}(\hat{\boldsymbol{x}}, \boldsymbol{u}, d) = 0 \qquad \begin{matrix} \hat{\boldsymbol{x}} \in \boldsymbol{X} \\ \boldsymbol{u} \in \boldsymbol{U} \end{matrix}$$

the state variables at the *kth* time step

$$\hat{\boldsymbol{x}}_k^T = [\Delta P_e^k, \Delta f^k, \Delta P_{gov}^k, \Delta P_{BESS}^k, \Delta P_{SC}^k, \Delta SOC_{BESS}^k, \Delta SOC_{SC}^k]$$

the state variables' simulated trajectory

$$\hat{\boldsymbol{x}}^T = [\hat{\boldsymbol{x}}_1^T,\ \hat{\boldsymbol{x}}_2^T,\ \dots,\ \hat{\boldsymbol{x}}_{nstep}^T]$$

Closed-loop Response Analysis and Controller Parameters Optimal Tuning

The function F is a multi-objective function given by a weighted sum of six different objective functions

$$F(\hat{\boldsymbol{x}}, \boldsymbol{u}, d) = \sum_{i=1}^{6} \alpha_i J_i(\hat{\boldsymbol{x}}, \boldsymbol{u}, d)$$

- *J1 minimizes the sum of the frequency variations for each time step*
- *J2 minimizes the maximum variation in frequency from the initial value.*
- *J3 and J4 take into account the energy provided buy the components in relation to their maximum capacity and minimize that.*
- *J5 and J6 minimize the sum of the active power variation delivered by the components.*

$$J_1 = \frac{1}{nstep} \cdot \sum_{k=1}^{nstep} \left(\frac{f^k - f^{k-1}}{f_n} \right)^2 \qquad J_2 = \left(\frac{max|f^k - f_n|}{f_n} \right)^2$$

$$J_3 = \frac{1}{nstep} \cdot \sum_{k=1}^{nstep} \left(\frac{P_{BESS}^k \cdot \Delta t}{E_{BESS}} \right)^2 \qquad J_4 = \frac{1}{nstep} \cdot \sum_{k=1}^{nstep} \left(\frac{P_{SC}^k \cdot \Delta t}{E_{SC}} \right)^2$$

$$J_5 = \frac{1}{nstep} \cdot \sum_{k=1}^{nstep} \left(\frac{P_{BESS}^k - P_{BESS}^{k-1}}{P_{BESS}^{max}} \right)^2 \qquad J_6 = \frac{1}{nstep} \cdot \sum_{k=1}^{nstep} \left(\frac{P_{SC}^k - P_{SC}^{k-1}}{P_{SC}^{max}} \right)^2$$

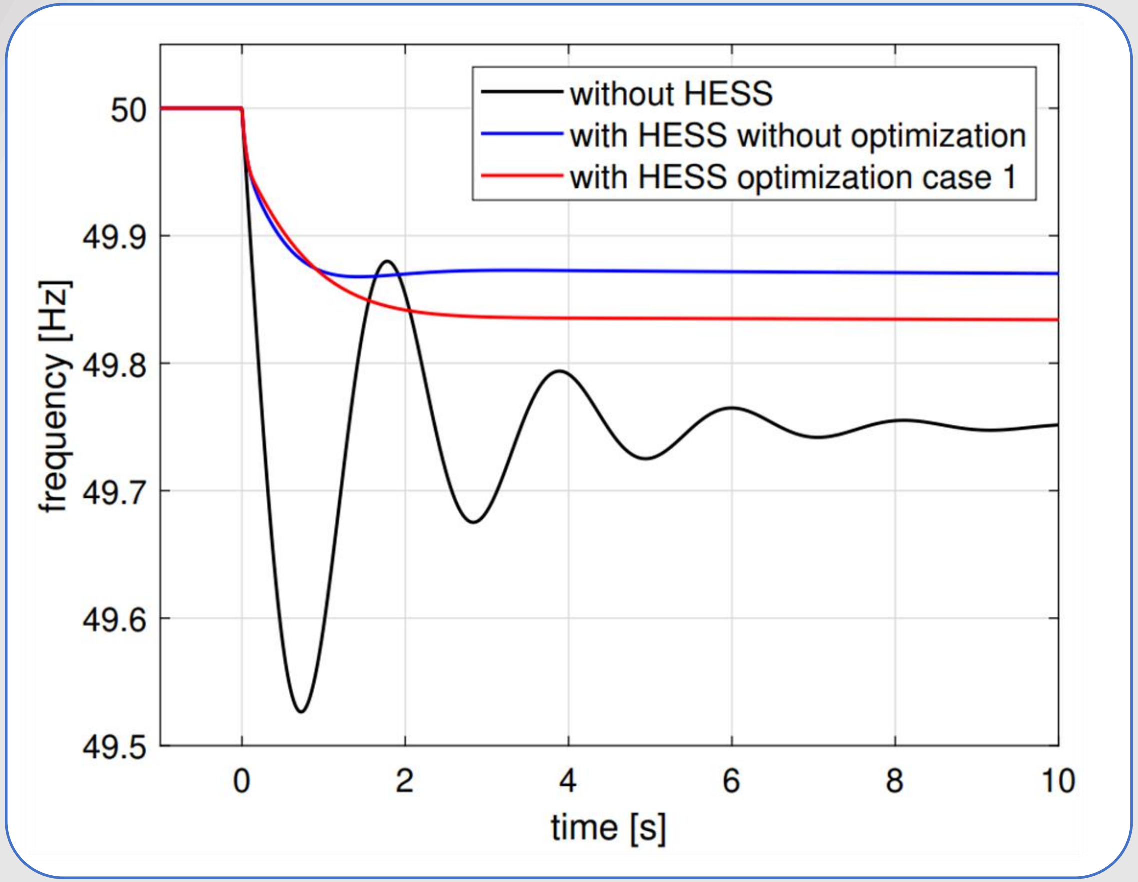
Genetic Algorithm (GA) method is used to solve the problem.

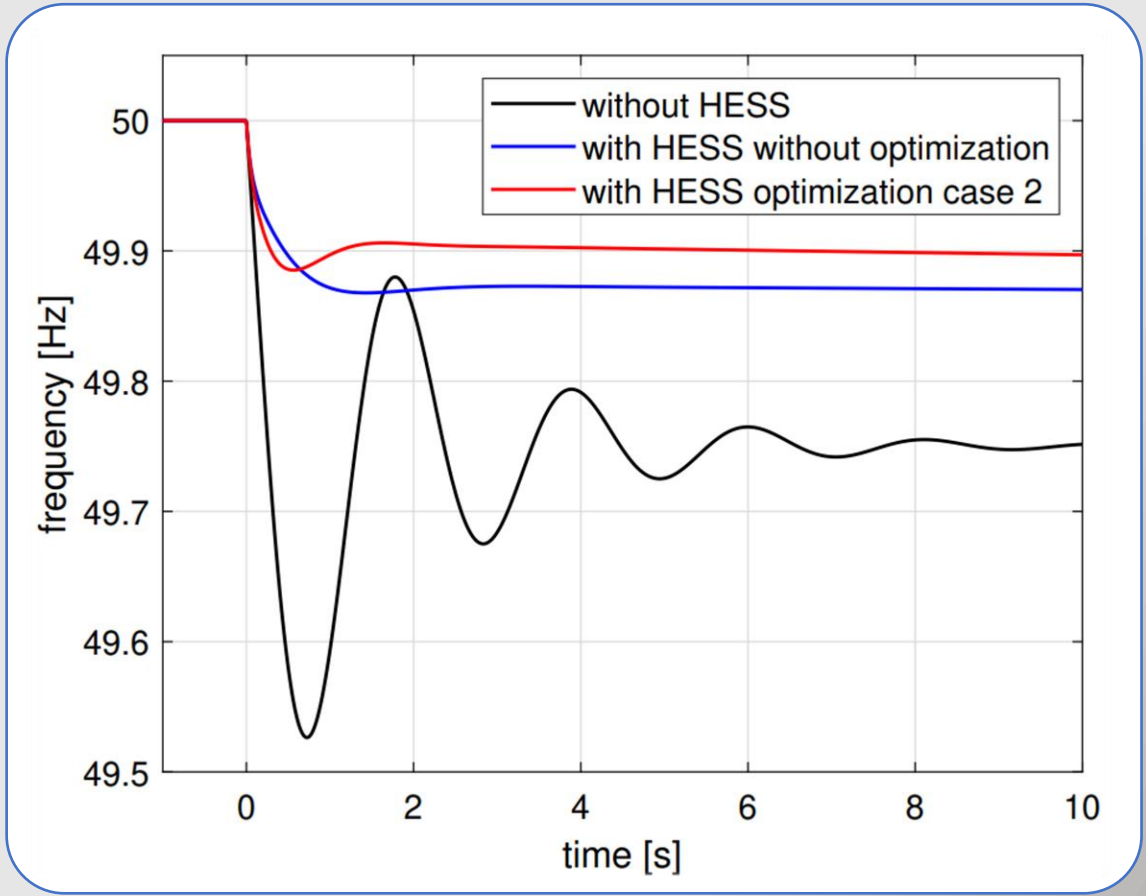
Test results

Have been studied 2 different cases provided by 2 different optimizations, changing the weights associated to the functions.

In Case 1: more importance has been attached to the minimization of J1.

In Case 2: more importance has been attached to the minimization of J5.

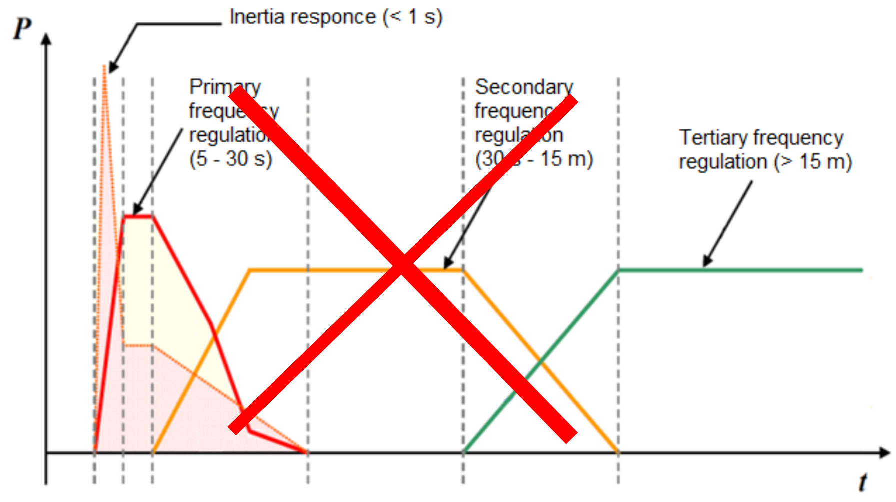




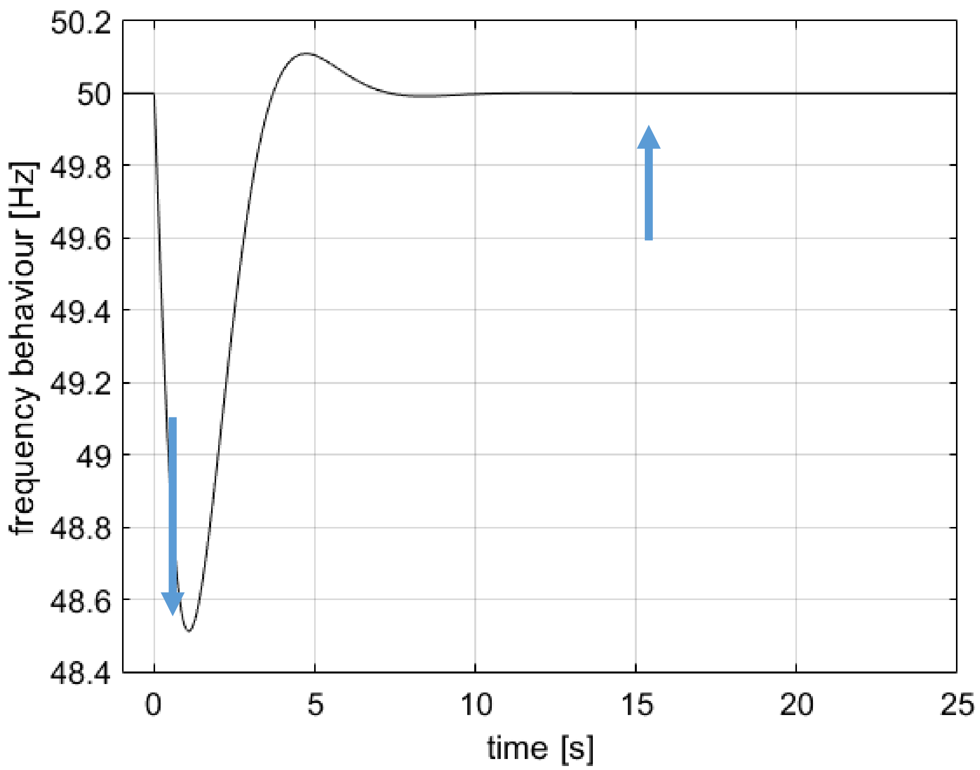
Italian Small-island

- Islanded systems
- Few generation plants with diesel generators: extremely low inertia system (about 0.3-0.5 seconds)
- High seasonal load variation

There is not a real differentiation between primary and secondary frequency regulation!

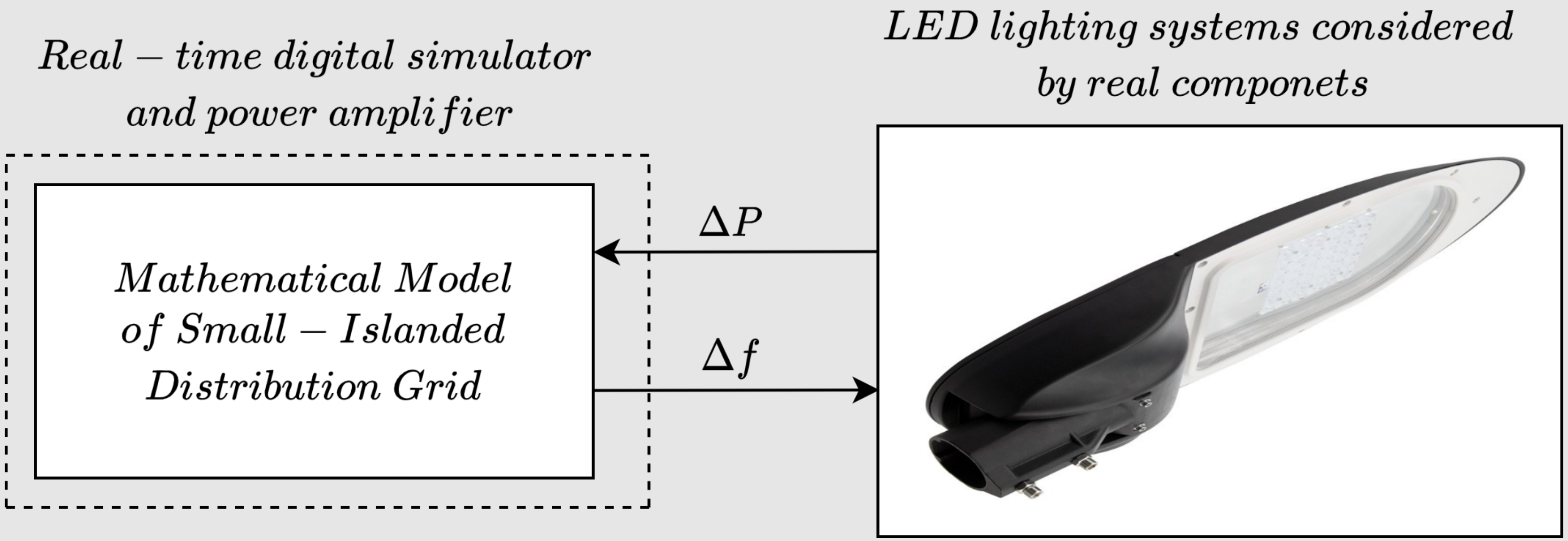


Usually, a merged frequency regulation is being implemented by the diesel governors.



A study to provide fast frequency contribution in a small-island grid

We wanted to test the contribution that a LED lighting systems can provide to an islanded microgrid to support the frequency transient. We did it modelling a frequency behaviour of an islanded microgrid and introduce in the model the measure of power consumption of a real street lighting LED lamp in a Power Hardware-in-the-Loop simulation.



Real – time digital simulator and power amplifier

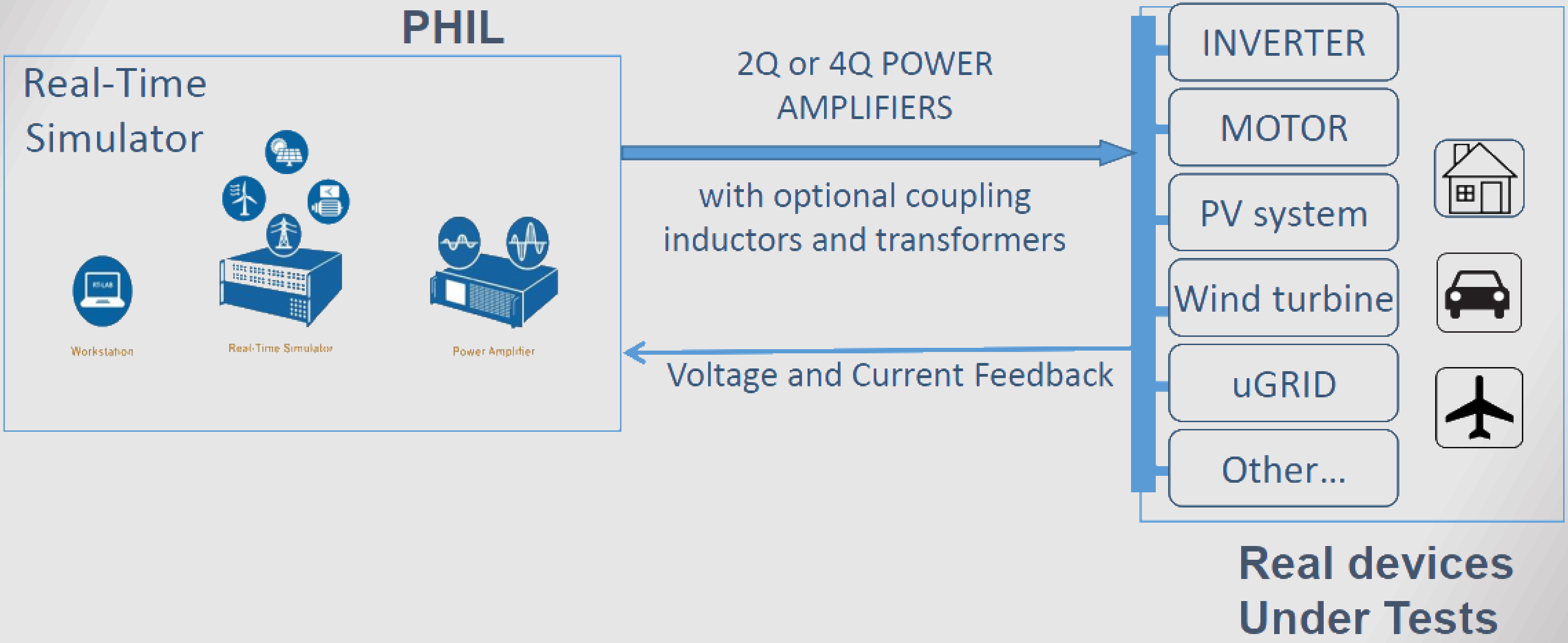
Mathematical Model of Small – Islanded Distribution Grid

ΔP

Δf

LED lighting systems considered by real componets

Power Hardware-in-the-Loop



PHIL

Real-Time Simulator

2Q or 4Q POWER AMPLIFIERS

with optional coupling inductors and transformers

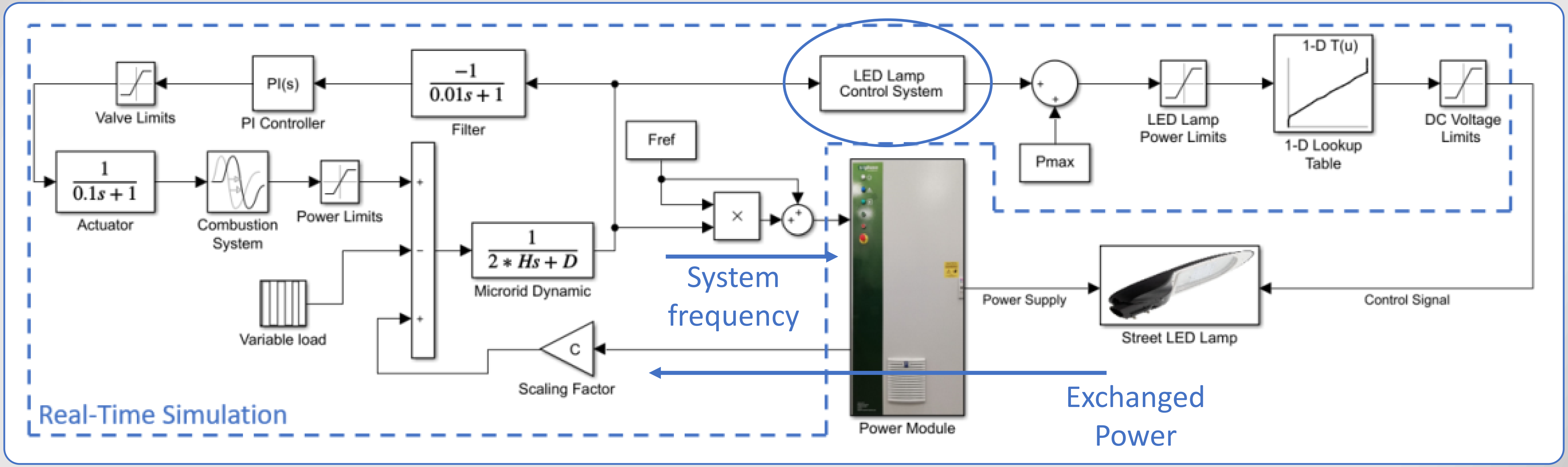
Voltage and Current Feedback

- INVERTER
- MOTOR
- PV system
- Wind turbine
- uGRID
- Other...

Real devices Under Tests

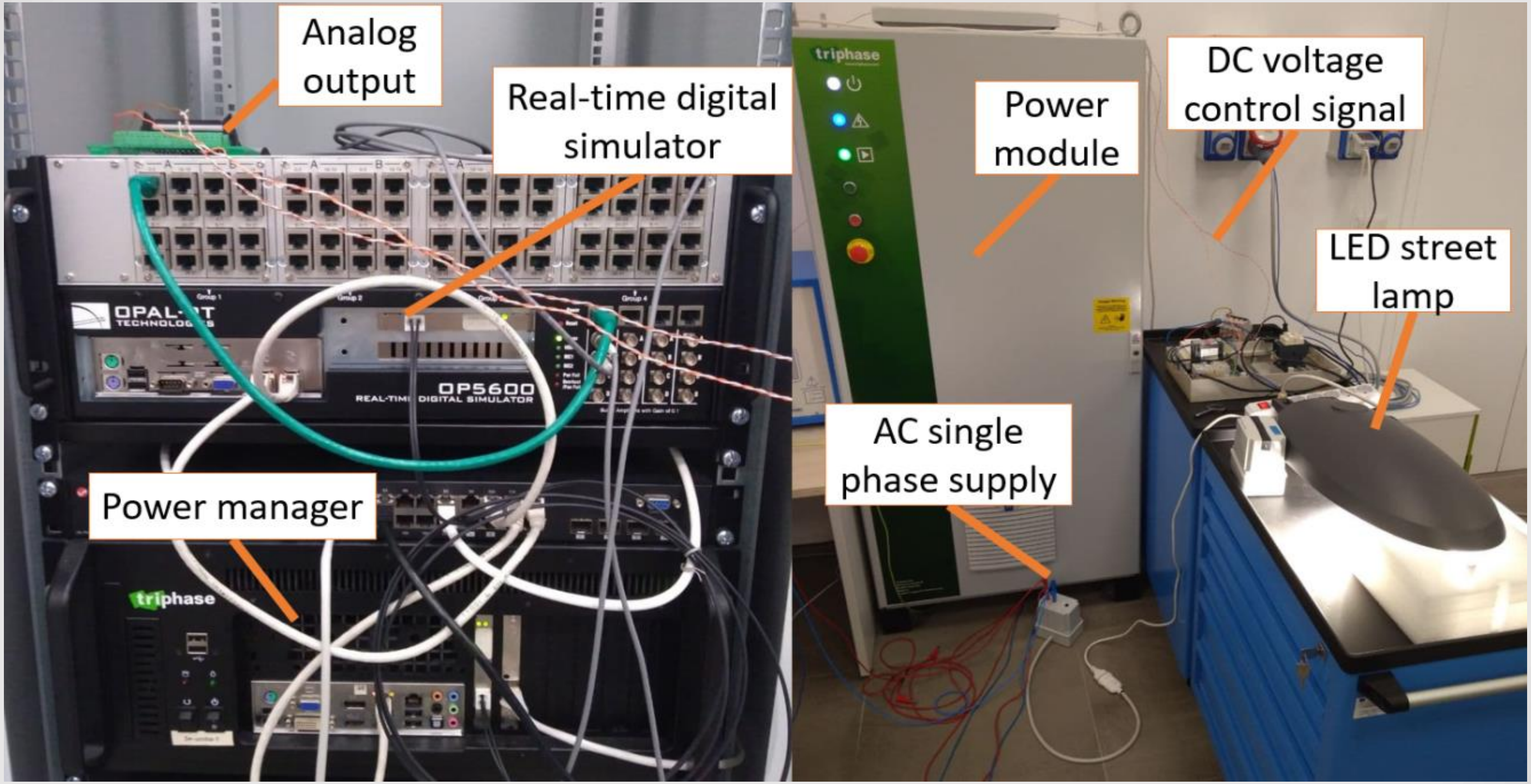
Reference: OPAL-RT - Power HIL (P-HIL): A Revolution in the Industry.

A study to provide fast frequency contribution in a small-island grid



Reference: 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.

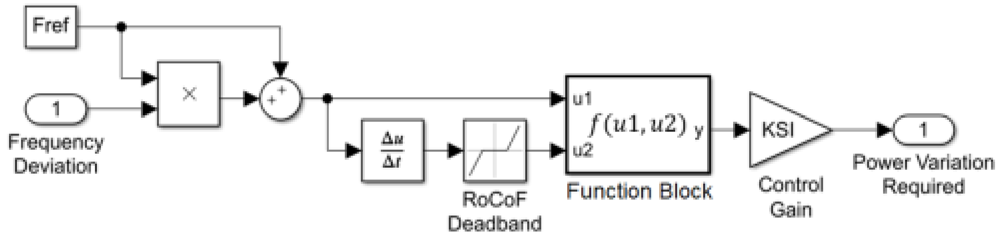
A study to provide fast frequency contribution in a small-island grid



A study to provide fast frequency contribution in a small-island grid

Two controllers have been studied:

Synthetic Inertia Controller

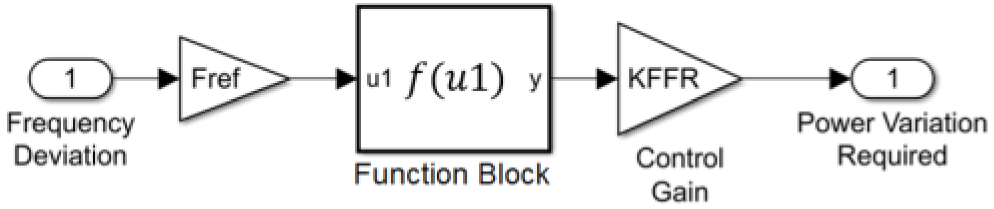


The *Function Block* applies RoCoF signals to the following gain block only if frequency deviations have the same sign of RoCoF itself.

A RoCoF deadband of ±10 mHz/s has been introduced.

The gain constant *KSI* was chosen so that the maximum power variation is applied for a RoCoF higher than 0.5 Hz/s.

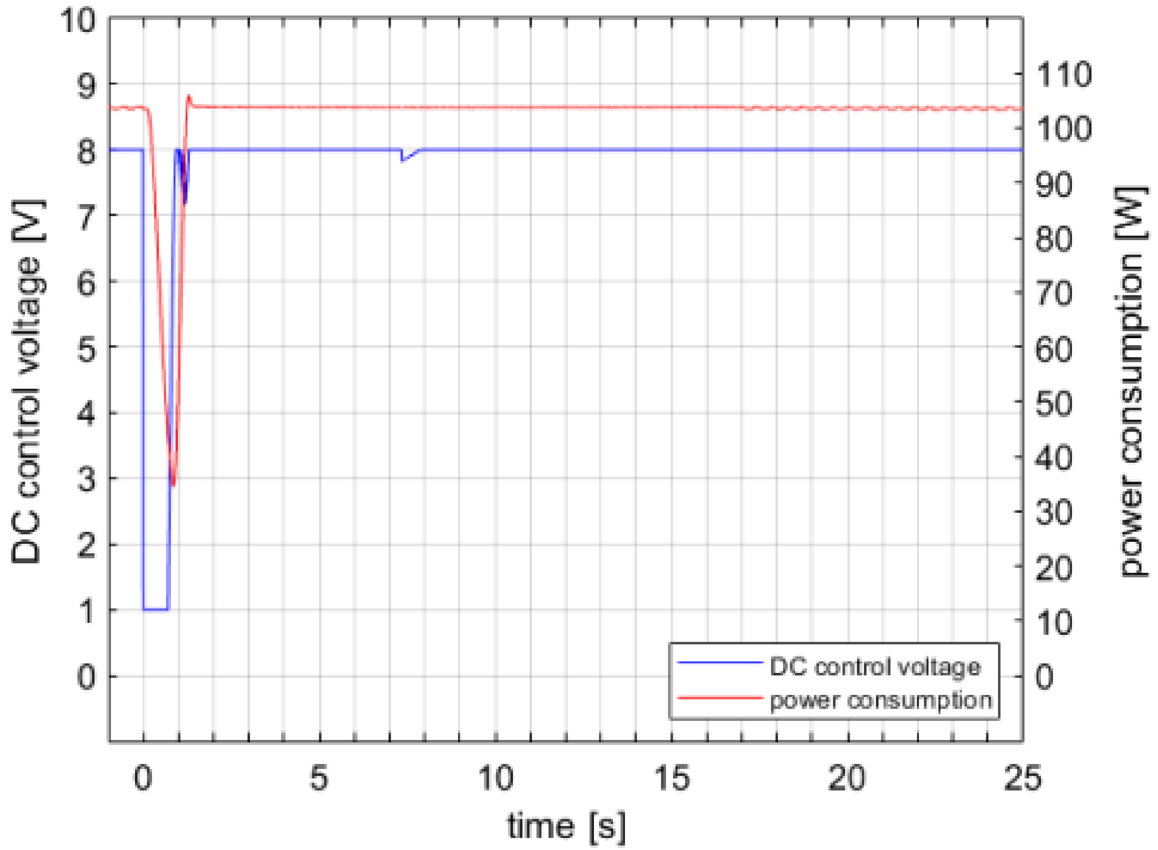
Fast Frequency Response Controller

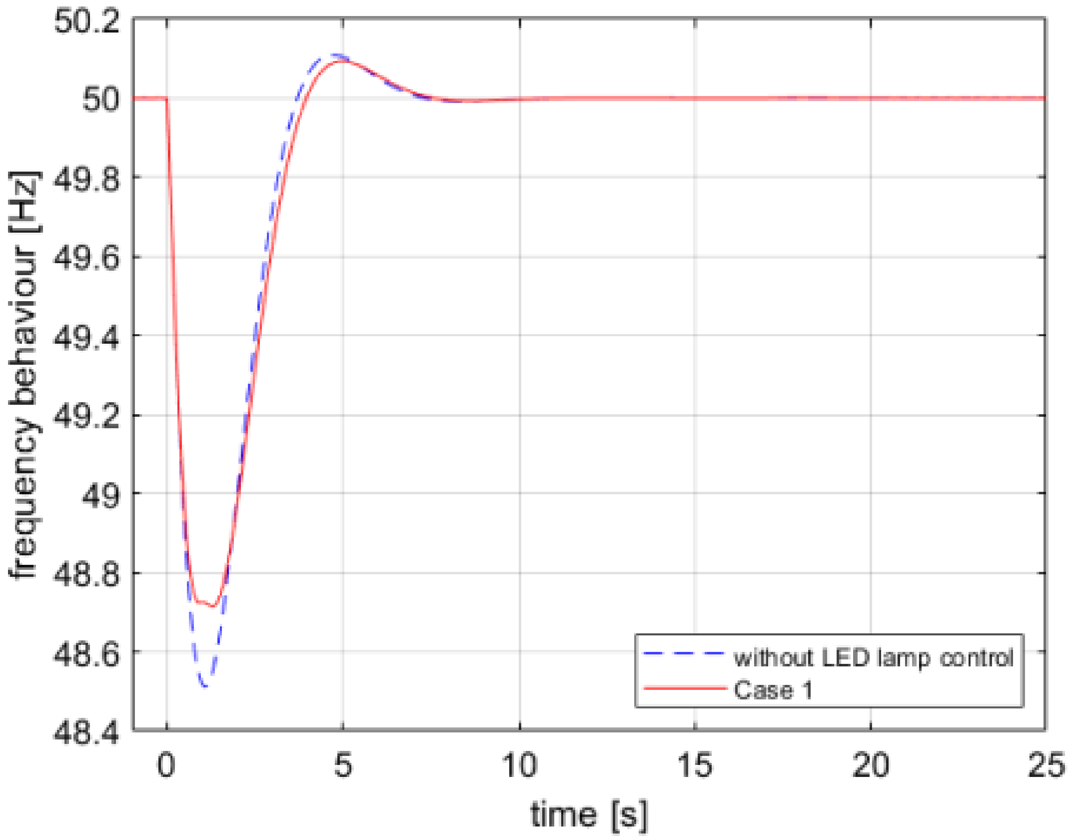


The *Function Block* applies a deadband of ±0.1 Hz around 50 Hz and gives to the following gain block the frequency deviation starting from 49.9 Hz (downward regulation) and 50.1 Hz (upward regulation).

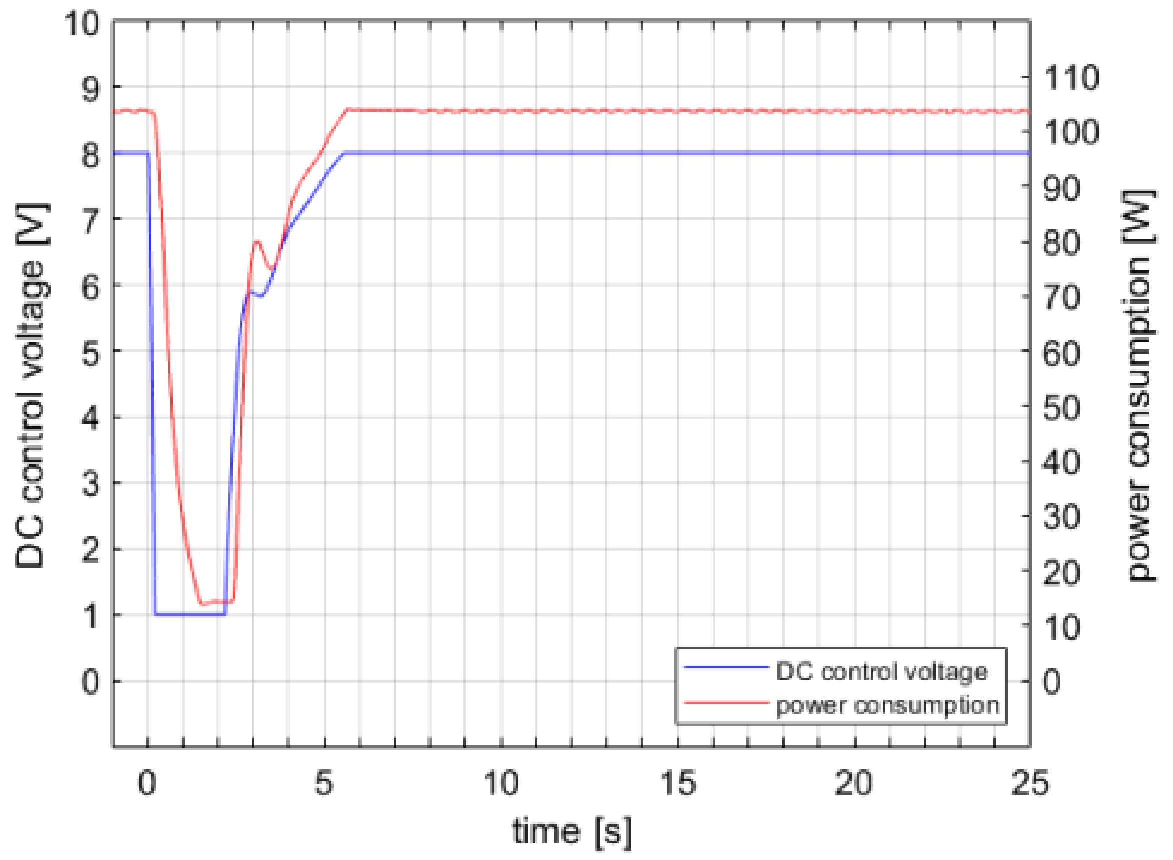
The gain constant *KFFR* was chosen so that the maximum power variation is applied for a frequency deviation higher than 0.5 Hz.

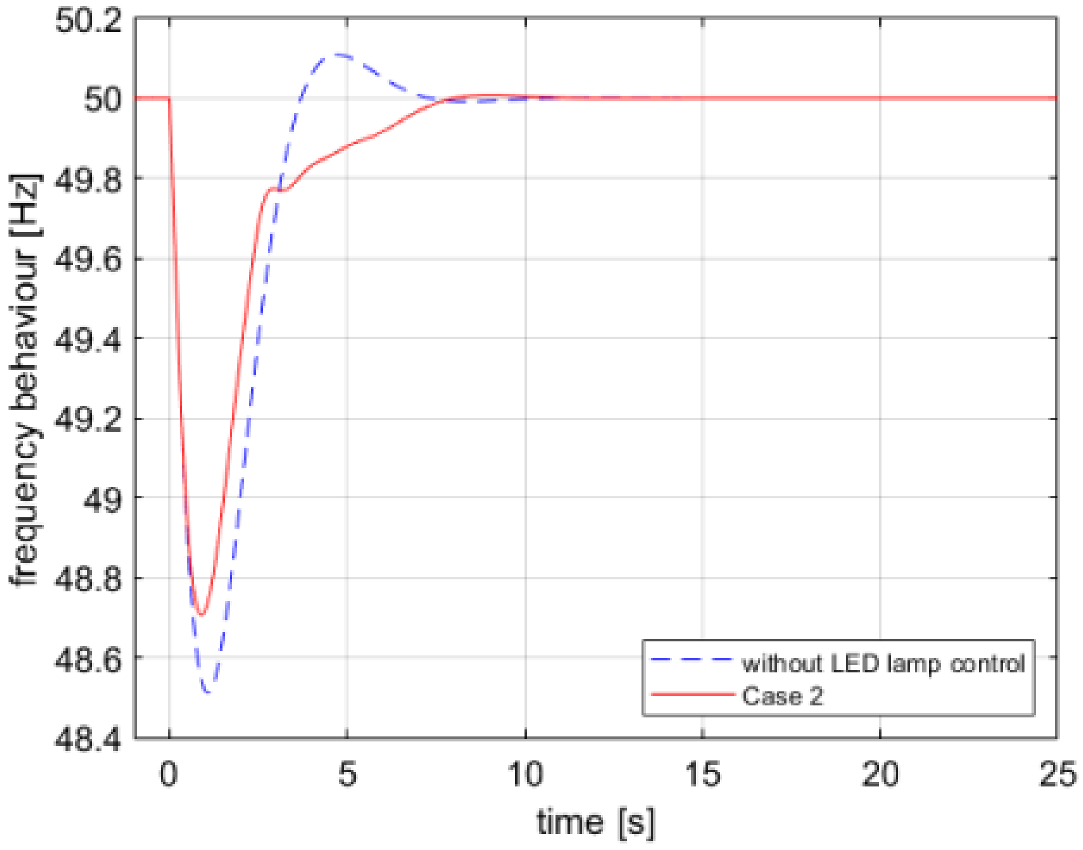
Test results





Test results





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DEI Doctoral Research Seminars - February 16th 2022, Bari

Test results

Synthetic Inertia Controller

Fast Frequency Response Controller

Conclusions

In the first study shown in this seminary has been demonstrated that an Hybrid Energy storage system, composed by battery and supercapacitor, can be exploited to improve power system frequency response.

It has been shown how, through targeted optimization of control parameters, it is possible to derive controller parameters in order to achieve an improvement in frequency response and/or avoid excessive component stress.

In the second study, the experimental tests, carried out through a Power Hardware-in-the-Loop set-up, showed the ability of LED lighting systems to provide fast frequency response.

The contribution made by these systems is small but not negligible and can be important in systems with few flexible resources.

Fast frequency response control is perfect for square, park and private lighting systems while the synthetic inertia control is perfect for street lighting system where the illumination flux must be over a certain value defined by safety standards.

Thanks for your attention