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sweet swiss energy research for the energy transition

PATHFNDR

The EPFL smart grid platform

Prof. Mario Paolone
EPFL Distributed Electrical Systems Laboratory

PATHFNDR lunch talk
03.02.2022

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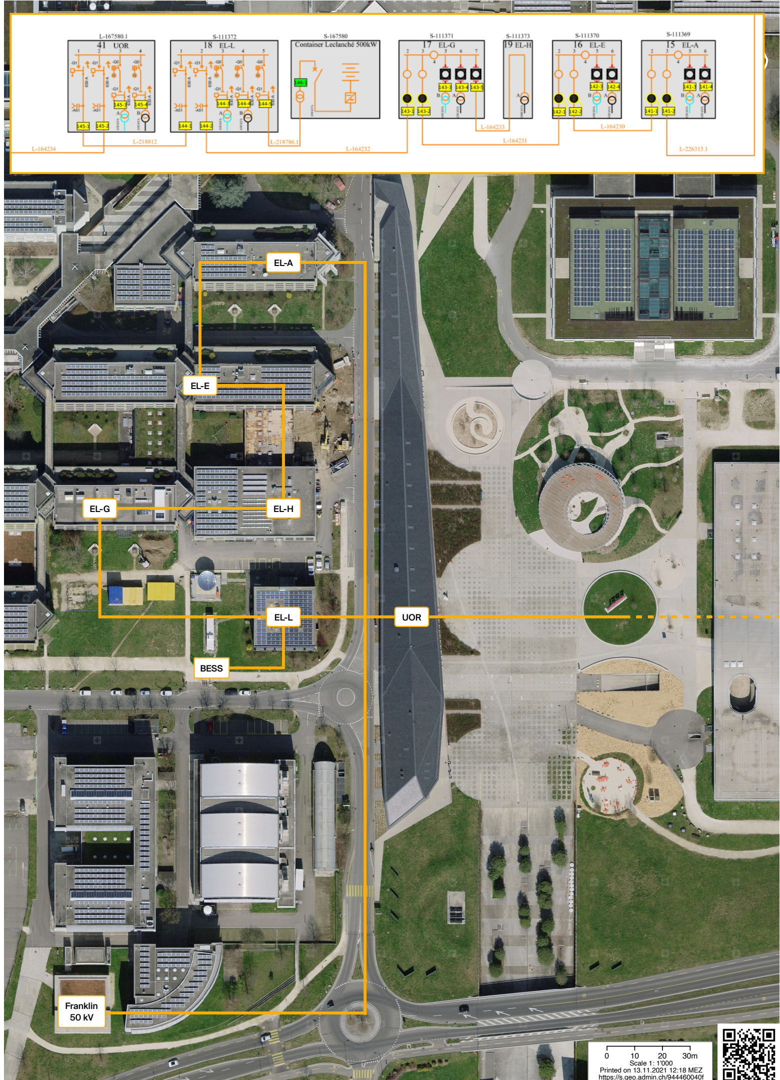
Research topics

- Real-time situational awareness
- Machine-learning forecasting of renewables
- Interaction of MW-class renewable energy sources and energy storage systems
- Centralized vs decentralized control schemes
- IoT schemes applied to power systems
- Demand side management
- Self-healing grids



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Overview of the infrastructure

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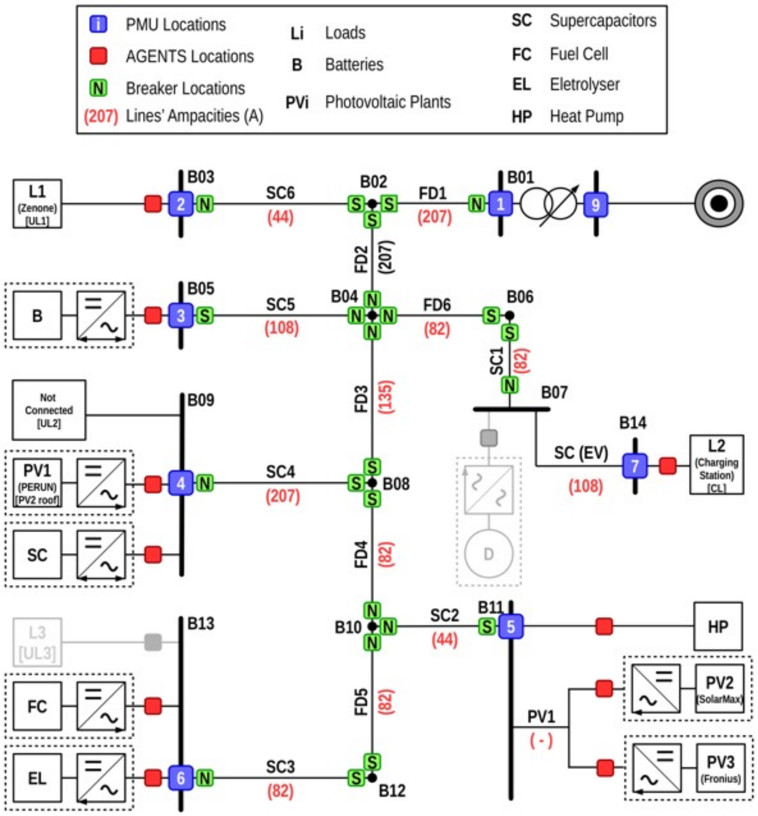
The medium-voltage infrastructure

The low-voltage infrastructure

Grid topology and devices (benchmark defined by the Cigré Task Force C6.04.02)



- Photovoltaic (PV) systems:
  30 kW, divided into three plants
- Load (L) emulators:
  30 kVA, three power electronic converters
- EV charging station: Chademo, DC charger, single/3-phase AC charger
- Supercapacitor (SC) storage system:
  75 kW / 2 kWh.
- Battery (B) storage system:
  25 kW / 25 kWh, Lithium-Titanate-based
- Fuel Cell (FC):
  20 kW, under refurbishment
- Electrolyzer (EL):
  5 kW
- H2/O2 storage (HOS):
  0.9 MWh @ 30 bar (200 bars max)

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The low-voltage infrastructure

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Functions
Time-deterministic sensing via PMUs

Functions – Situational awarenes

Needs

Evolution of the whole power systems infrastructure

- major changes in their **operational procedures (i.e. ctrl, protection)**;
- need of situational awareness tools to manage the increasing complexity of the grid;
- main involved aspect is the **network monitoring** by means of Phasor Measurement Units **(PMUs)**;

PMU definition (as stated in IEEE Std.C37.118-2011):
"A device that produces synchronized measurements of **phasor** *(i.e. its amplitude and phase),* **frequency**, **ROCOF** *(Rate of Change Of Frequency) from voltage and/or current signals based on a* ***common time source*** *that typically is the one provided by the* Global Positioning System UTC-GPS."

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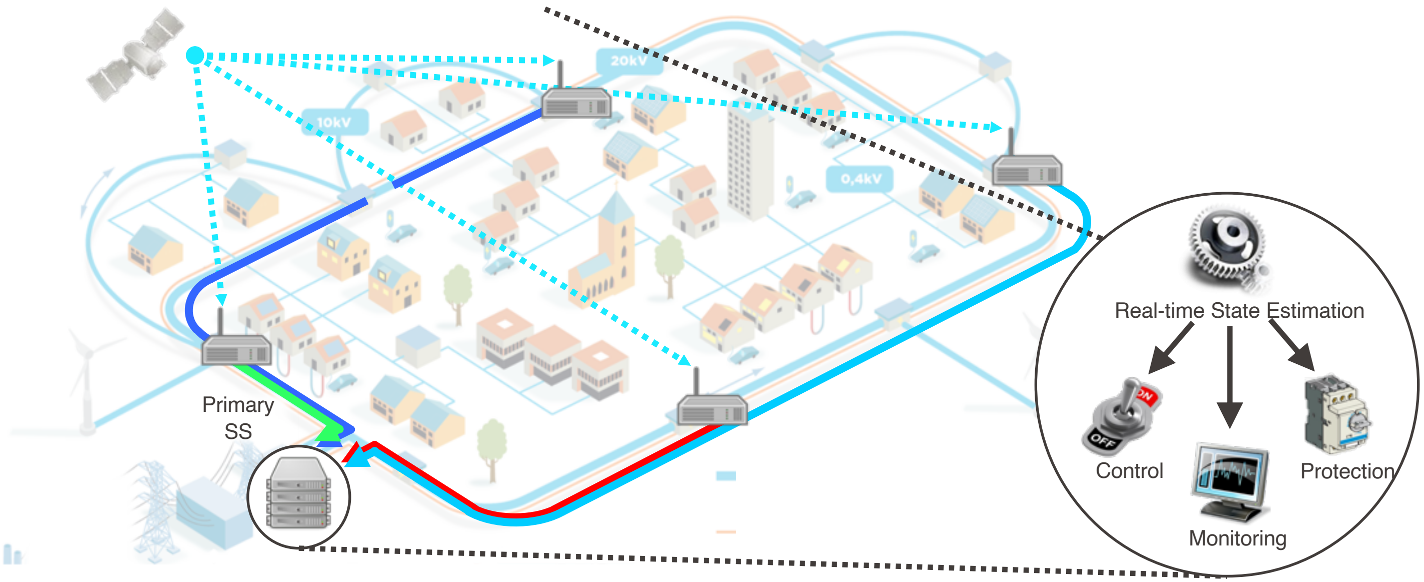
Functions – Situational awarenes

Drivers Availability of new technologies (e.g., precise time dissemination)

→ Join situational-awareness, protection and control schemes in power distribution grids



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Functions – Situational awarenes

Synchrophasors estimation in power distribution systems

Window based Synchrophasor Estimation Algorithms

Class	Typical algorithms	Advantages	Drawbacks
DFT based	Fourier analysis Interpolated DFT	Low computational complexity, harmonic rejection	Spectral leakage, Harmonic interference, Off-nominal freq.
Wavelet based	Recursive wavelet	Harmonic rejection	Computational complexity
Optimization based	WLS Kalman Filter	They usually provide accurate estimates in combination with other methods	Non deterministic: driven by optimality criteria
Taylor series based	Dynamic Phasor	It intrinsically reflects the dynamic behaviors of power systems	Computational complexity

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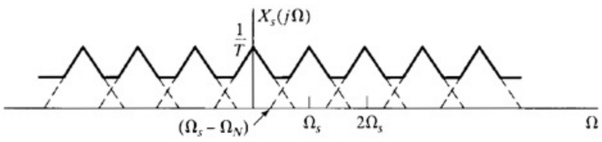
Functions – Situational awarenes

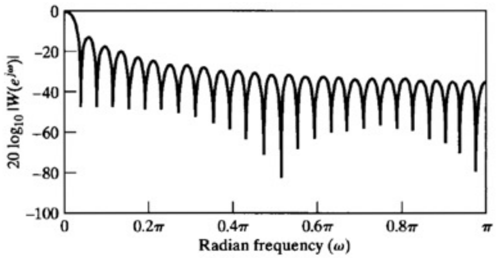
Synchrophasors estimation in power distribution systems

Main sources of errors in DFT-based synchrophasor's estimation

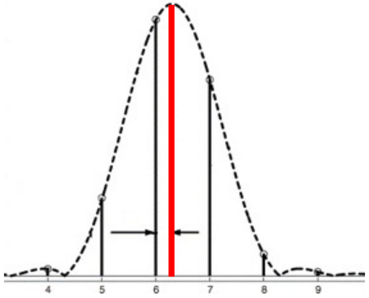
1. Aliasing



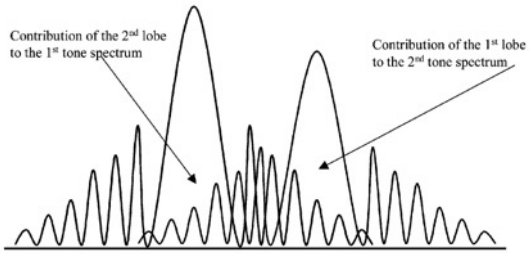
2. Long range leakage



3. Short range leakage



4. Harmonic interference



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Functions – Situational awarenes

Synchrophasors estimation in power distribution systems

Possible corrections

1. Aliasing

- Introduction of adequate anti-aliasing filters
- Increasing of the sampling frequency

2. Long range leakage

- Use of appropriate windowing functions

3. Short range leakage

- Interpolated DFT methods

4. Harmonic interference

- Iterative compensation of the self-interaction

Functions – Situational awarenes

Synchrophasors estimation in power distribution systems

Joint P+M class synchrophasor estimation – IpDFT solution for $\cos^{\alpha}$ windows

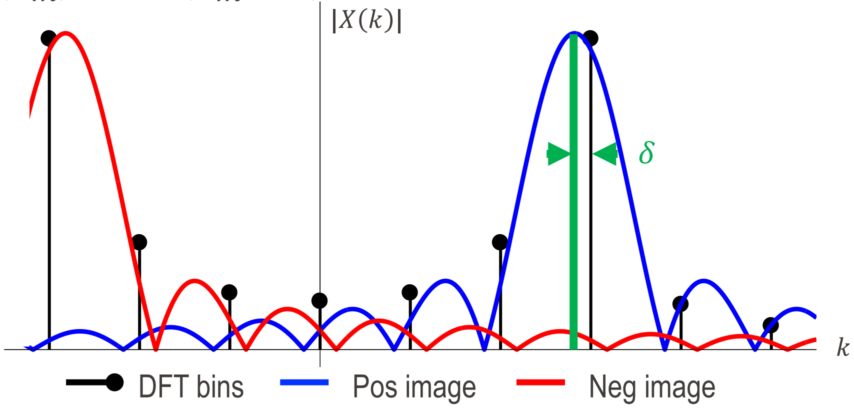
The IpDFT is a technique to extract the parameters f_0, A_0 and φ_0 of a sinusoidal waveform by interpolating the highest DFT bins of the signal spectrum. It mitigates the effects of incoherent sampling ($f_0/\Delta f \notin \mathbb{N}$):

- Interpolating the highest DFT bins ➔ minimize spectral sampling

$$\delta = a \cdot \varepsilon \frac{|X(k_m+\varepsilon)| - |X(k_m-\varepsilon)|}{|X(k_m-\varepsilon)| + 2|X(k_m)| + |X(k_m+\varepsilon)|},$$

a = 1.5 cos, a = 2 hann

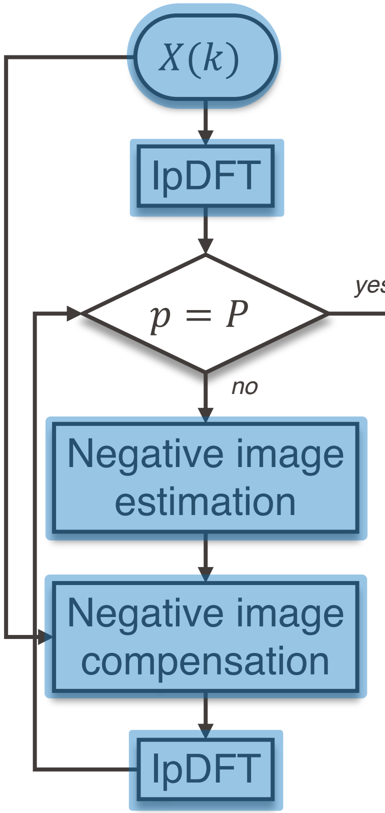
$$f_0 = (k_m + \delta)\Delta f$$
$$\varphi_0 = \angle X(k_m) - \pi\delta$$
$$A_{0C} = 4 \cdot |X(k_m)| \left|\frac{\delta^2 - 0.25}{\cos(\pi\delta)}\right|$$
$$A_{0H} = |X(k_m)| \left|\frac{\pi\delta}{\sin(\pi\delta)}\right| |\delta^2 - 1|$$



Functions – Situational awarenes

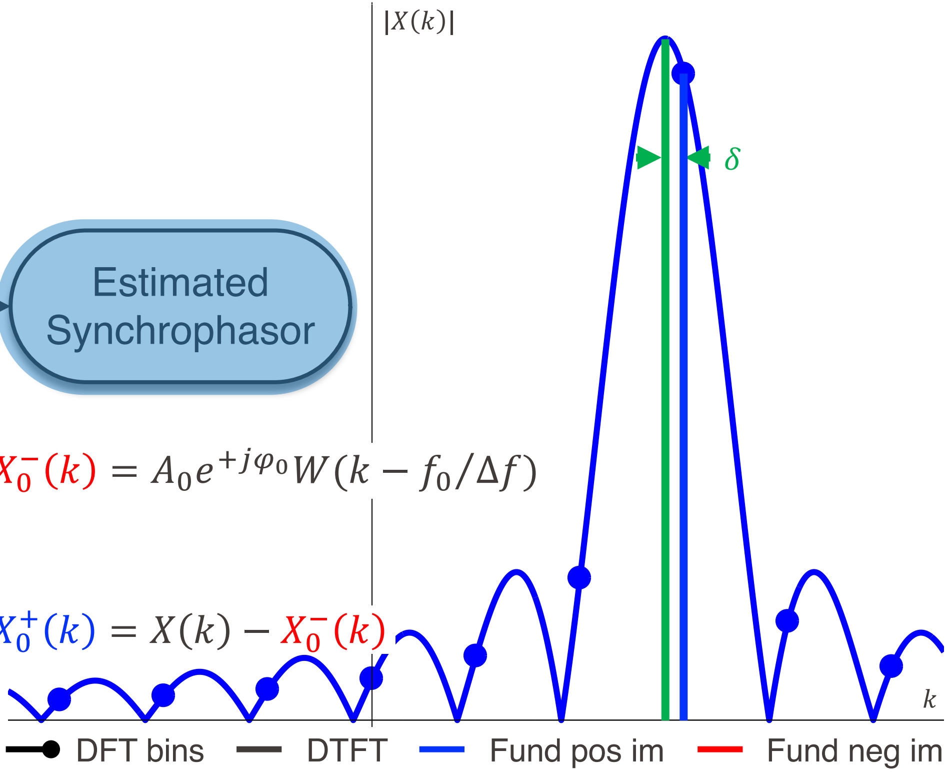
Synchrophasors estimation in power distribution systems

Joint P+M class synchrophasor estimation – Enhanced-IpDFT algorithm



$$X_0^-(k) = A_0 e^{+j\varphi_0} W(k - f_0/\Delta f)$$

$$X_0^+(k) = X(k) - X_0^-(k)$$



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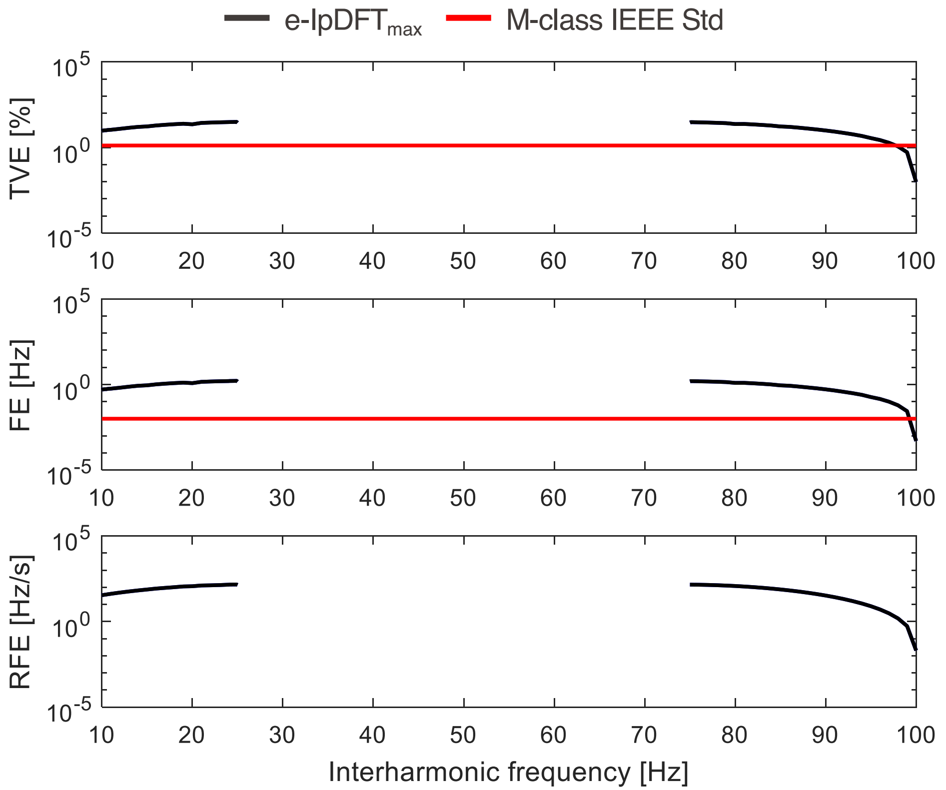
Functions – Situational awarenes

Synchrophasors estimation in power distribution systems

Joint P+M class synchrophasor estimation – Enhanced-IpDFT poor performance vs OOBI



Max Errors:

TVE

IEEE Std = 1.3%

e-IpDFT = 31%

FE

IEEE Std = 10 mHz

e-IpDFT = 1.6 Hz

RFE

e-IpDFT = 145 Hz/s

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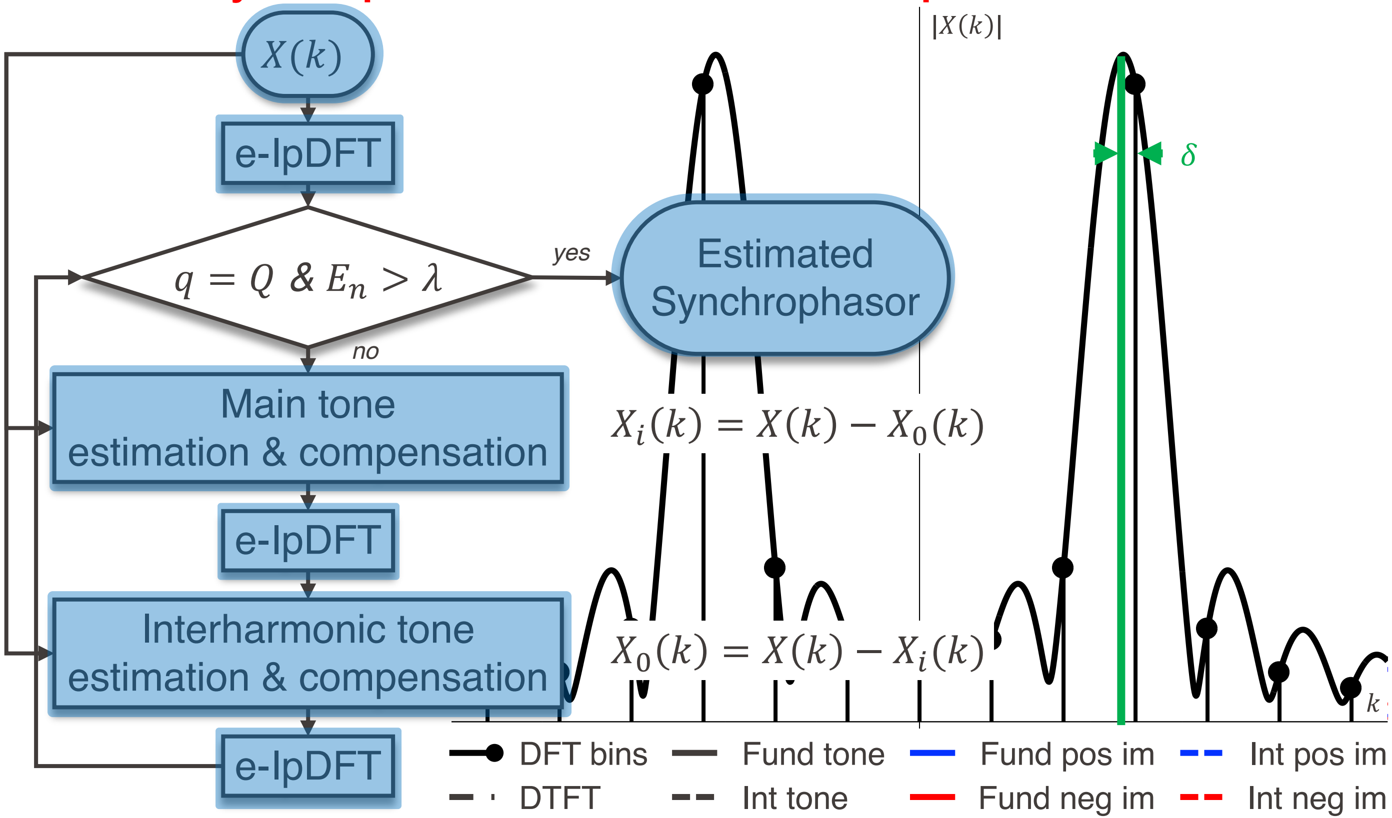
Functions – Situational awarenes

Synchrophasors estimation in power distribution systems

Joint P+M class synchrophasor estimation – Iterative-IpDFT



Functions – Situational awarenes

Synchrophasors estimation in power distribution systems

	TVE [%]						FE [mHz]						RFE [Hz/s]					
	IEEE Std		i-IpDFT				IEEE Std		i-IpDFT				IEEE Std		i-IpDFT			
	P	M	cos SNR [dB]		Hann SNR [dB]		P	M	cos SNR [dB]		Hann SNR [dB]		P	M	cos SNR [dB]		Hann SNR [dB]	
			60	80	60	80			60	80	60	80			60	80	60	80
Sign Freq	1	1	0.024	0.002	0.03	0.003	5	5	1.3	0.1	1.5	0.1	0.4	0.1	0.095	0.009	0.126	0.012
Harm Dist 1%	1	1	0.108	0.094	0.028	0.003	5	25	5.4	4.7	1.3	0.1	0.4	-	0.086	0.009	0.112	0.011
Harm Dist 10%	1	1	0.055	0.047	0.026	0.003	5	25	2	1.1	1.2	0.1	0.4	-	0.085	0.009	0.124	0.011
OOBI f_0=47.5 Hz	-	1.3	0.056	0.022	0.108	0.082	-	10	2.7	1.1	5.6	4.1	-	-	0.217	0.101	0.513	0.369
OOBI f_0=50 Hz	-	1.3	0.026	0.003	0.033	0.004	-	10	1.3	0.1	1.7	0.2	-	-	0.104	0.009	0.153	0.013
OOBI f_0=52.5 Hz	-	1.3	0.043	0.004	0.044	0.011	-	10	2.1	0.2	2.2	0.6	-	-	0.143	0.022	0.150	0.032

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Functions – Situational awarenes

Synchrophasors estimation in power distribution systems

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Functions
Real time situational awareness

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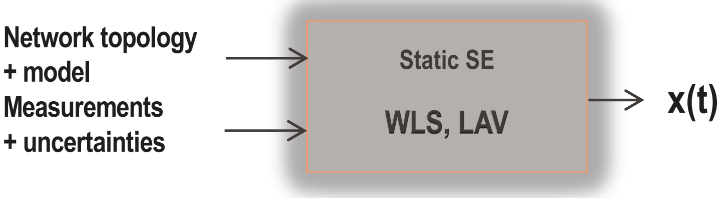
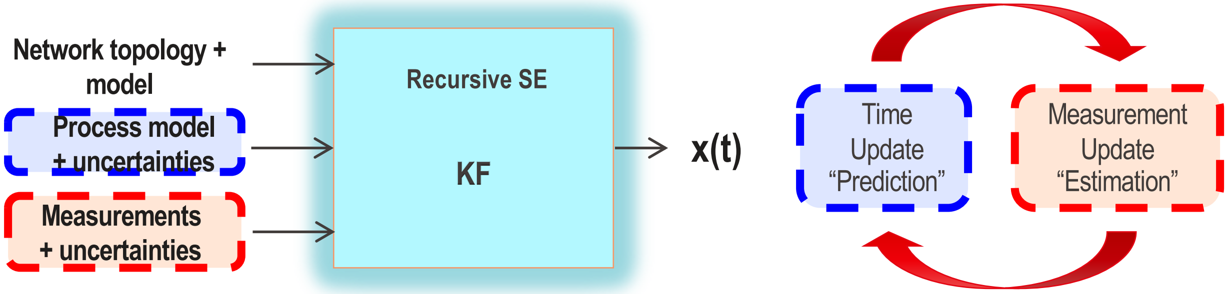
Functions – Situational awarenes

Real-time state estimation - Methods

- **Static SE:** infers the system state by using only current time information (e.g., **Weighted Least Squares – WLS – or Least Absolute Value methods**).



- **Recursive SE:** takes into account information available from previous time steps and predict the state vector in time (e.g., **Kalman Filter – KF – method**).



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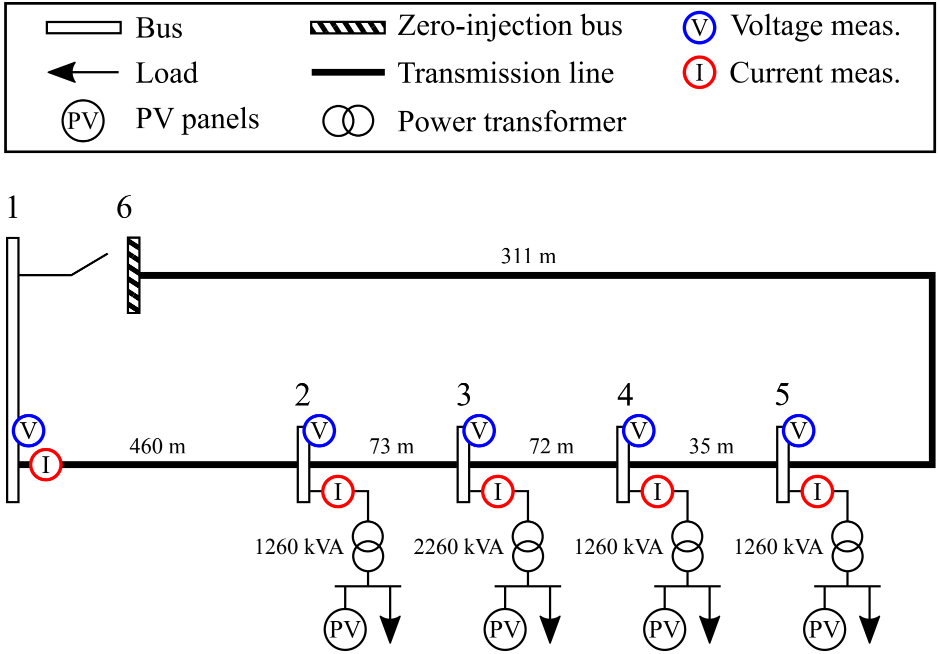
Functions – Situational awarenes

Example of installed sensors and PMUs

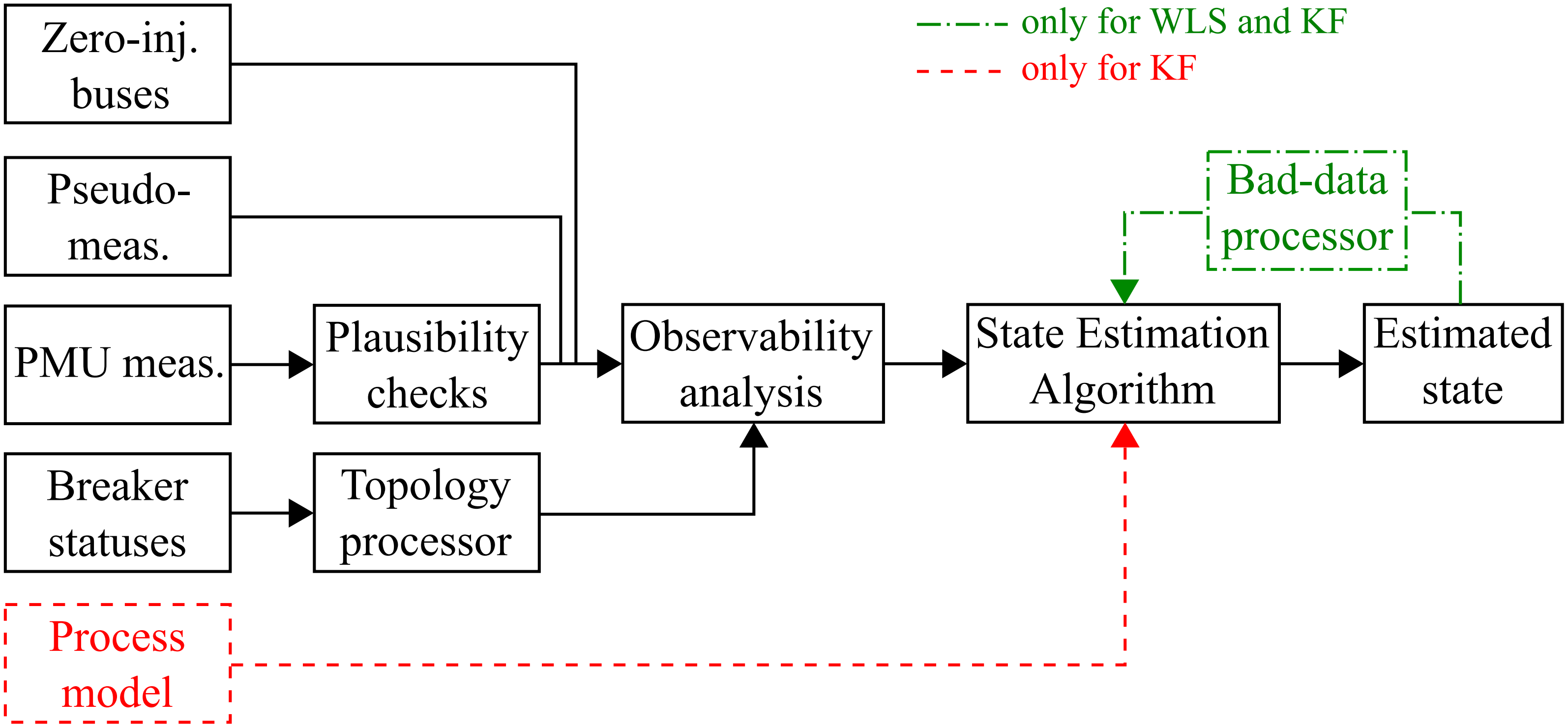


Rated voltage	20 kV
Voltage sensors	Capacitive 0.1-class
Current sensors	Rogowsky 0.5-class

Voltages	3 x 5
Current injections	3 x 5
Zero-inj. buses	1
Measurements	66
State variables	36
Redundancy	1.8

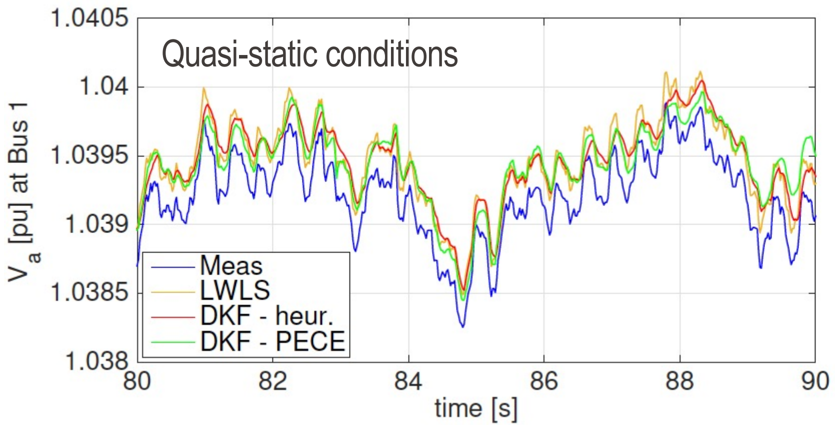
Functions – Situational awarenes

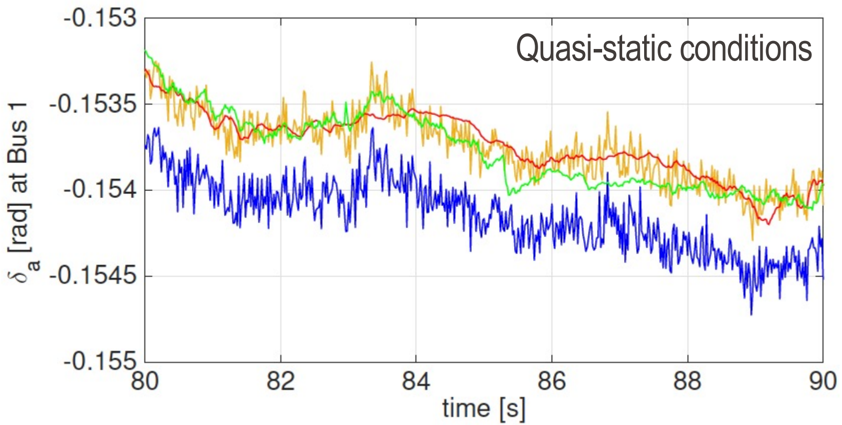
RTSE workflow

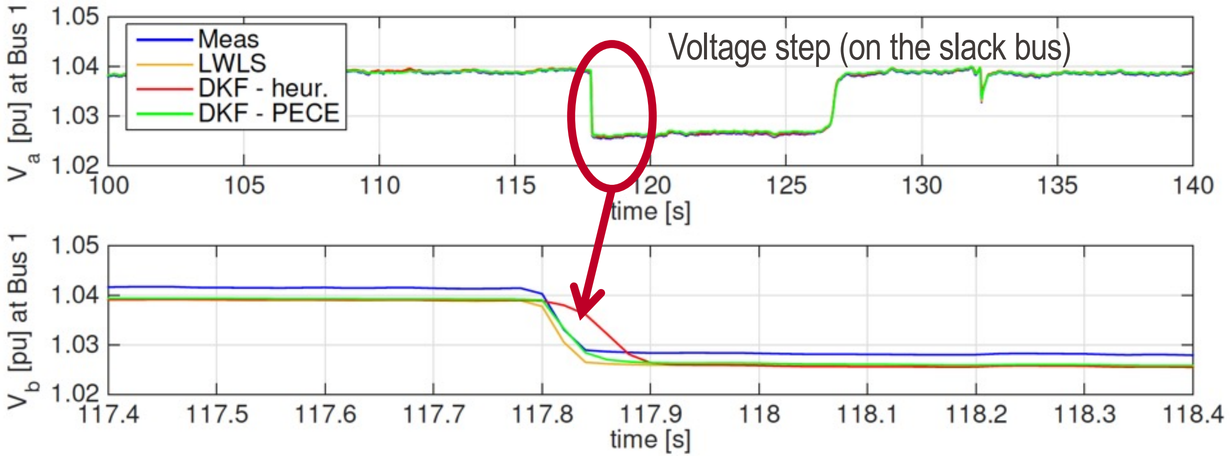


Functions – Situational awarenes

Example of RTSE performance







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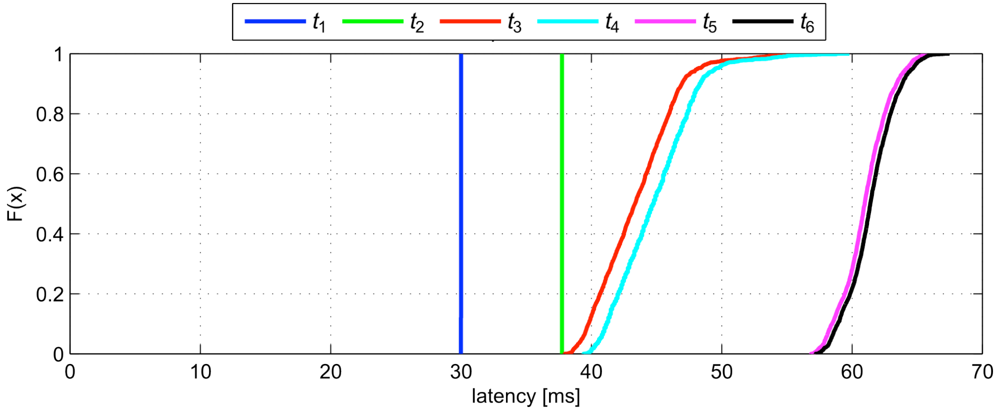
Functions – Situational awarenes

Example of RTSE performance (latency assesment)

PMU			Telecom	PDC+RTSE	
Signal acquisition	Synchrophasor estimation	Data encapsulation	Network delay	Data-frame alignment	State estimation
t1 (30ms)	t2 (8ms)	t3 (≈1-15ms)	t4 (≈1-3ms)	t5 (≈20ms)	t6 (<1ms)



Total latency:

- 61 ms (mean)
- 1.8 ms (std)

Refresh rate:

- 20 ms

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Applications
Forecasting and dispatch

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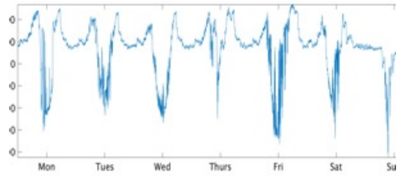
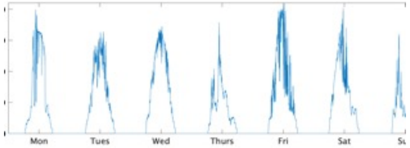
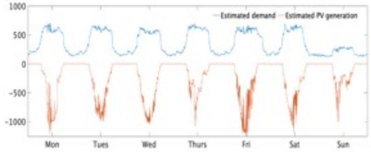
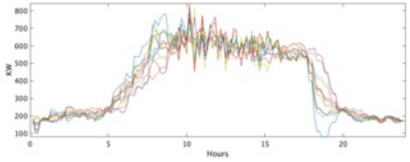
Applications – Forecasting for day-ahead









Historical power measurements from **PMUs**

Disaggregation algorithm to estimate the "true" demand by removing PV generation

Clustering the demand into different day-types

Train forecasting model for each cluster

Sample demand scenarios for the day-ahead

Day-ahead GHI forecast from MeteoTest

Historical GHI measurements from our **weather-boxes** and day-ahead forecast from MeteoTest

Find most similar days based on euclidean distance between the Day-ahead GHI and historical Day-ahead GHI forecast of MeteoSwiss

Compute the error incurred on MeteoSwiss forecast for similar days

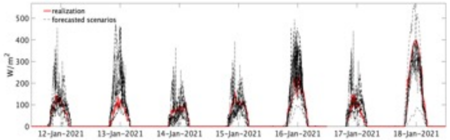
Add the error on Day-ahead GHI forecast from MeteoSwiss

Day-ahead GHI scenarios for GHI

PV configurations obtained by disaggregation model

PV model to compute PV generation

Compute day-ahead scenarios for nodal injections by aggregating scenarios on demand and PV generation



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Applications – Day-ahead dispatch

$p_{1,t}^{+,\omega}$ Incoming active power at the slack
$p_{1,t}^{-,\omega}$ Outgoing active power at the slack

$$\underset{\boldsymbol{p_b}, s^{\text{disp}}}{\text{minimize}} \sum_{\omega \in \Omega} \sum_{t=1}^{T} \left\{ (s_{1,t}^{\omega} - s_t^{\text{disp}})^2 + \mu\left((p_{1,t}^{+,\omega})^2 + (p_{1,t}^{-,\omega})^2\right) + \lambda (p_{b,t}^{\omega})^2 \right\}$$

subject to:

ESSs state-of-energy	$\text{SoE}_t^{\omega} = \text{SoE}_{t-1}^{\omega} + T_s p_{b,t}^{\omega}$	$\forall t \in \mathcal{T}, \omega \in \Omega$
BESS capability	$0 \leq ((p_{b,t}^{\omega})^2 + (q_{b,t}^{\omega})^2) \leq (P_{\max}^{b})^2$	$\forall t \in \mathcal{T}, \omega \in \Omega$
Energy capacity	$aE_{\max}^{b} \leq \text{SoE}_t^{\omega} \leq (1-a)E_{\max}^{b}$	$\forall t \in \mathcal{T}, \omega \in \Omega$
Grid constraints	$\Phi_{\Xi}(\boldsymbol{p}_t^{\omega}, \boldsymbol{q}_t^{\omega}) \leq 0$	$\forall t \in \mathcal{T}, \omega \in \Omega$
Constraint on slack reactive power	$p_{1,t}^{+,\omega} + p_{1,t}^{-,\omega} \geq q_{1,t}^{\omega} \tan(\pi/2 - \theta_m)$	$\forall t \in \mathcal{T}, \omega \in \Omega$
	$p_{1,t}^{+,\omega} + p_{1,t}^{-,\omega} \geq -q_{1,t}^{\omega} \tan(\pi/2 - \theta_m)$	$\forall t \in \mathcal{T}, \omega \in \Omega$
	$p_{1,t}^{\omega} = p_{1,t}^{+,\omega} - p_{1,t}^{-,\omega}$	$\forall t \in \mathcal{T}, \omega \in \Omega$
	$p_{1,t}^{+,\omega} \geq 0, p_{1,t}^{-,\omega} \geq$	$\forall t \in \mathcal{T}, \omega \in \Omega.$

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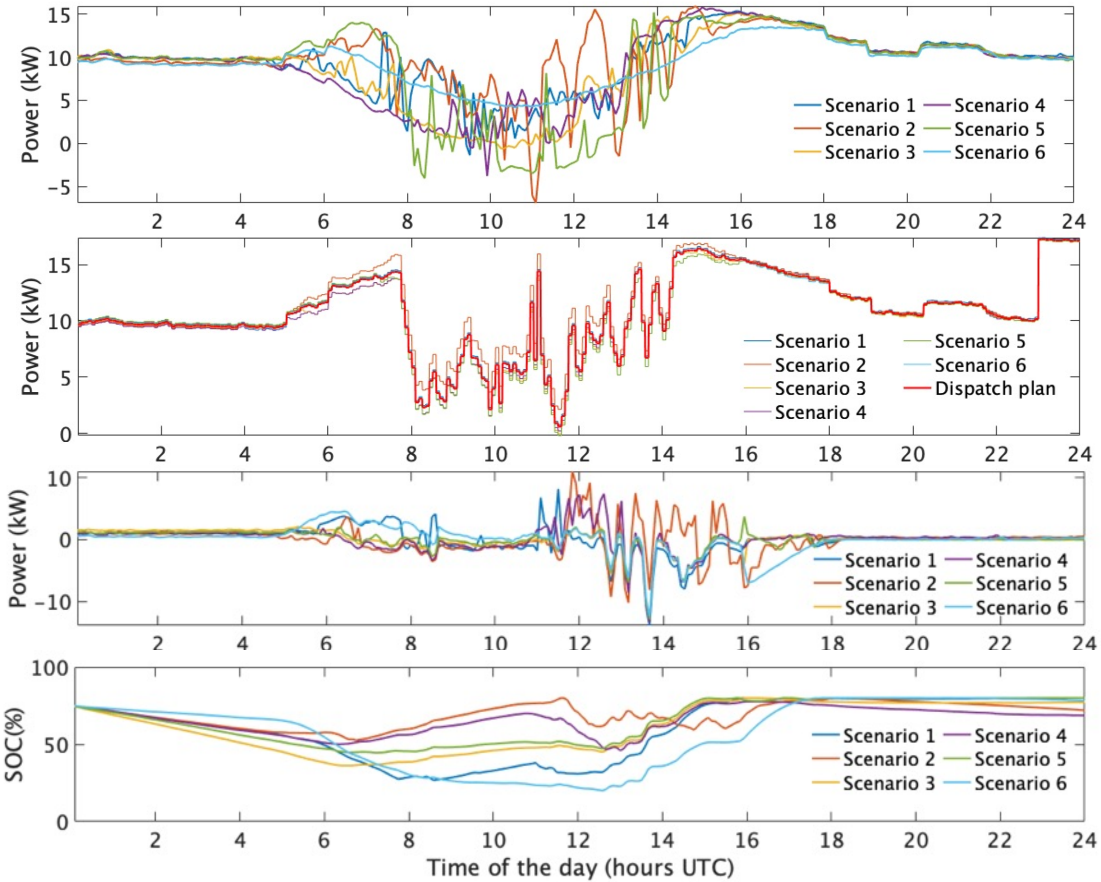
Applications – Day-ahead dispatch

Experimental validation on the LV microgrid



Day-ahead scenarios using PV and load forecasting

Optimally-determined day-ahead dispatch plan

Battery power injections and SoC for the scenarios

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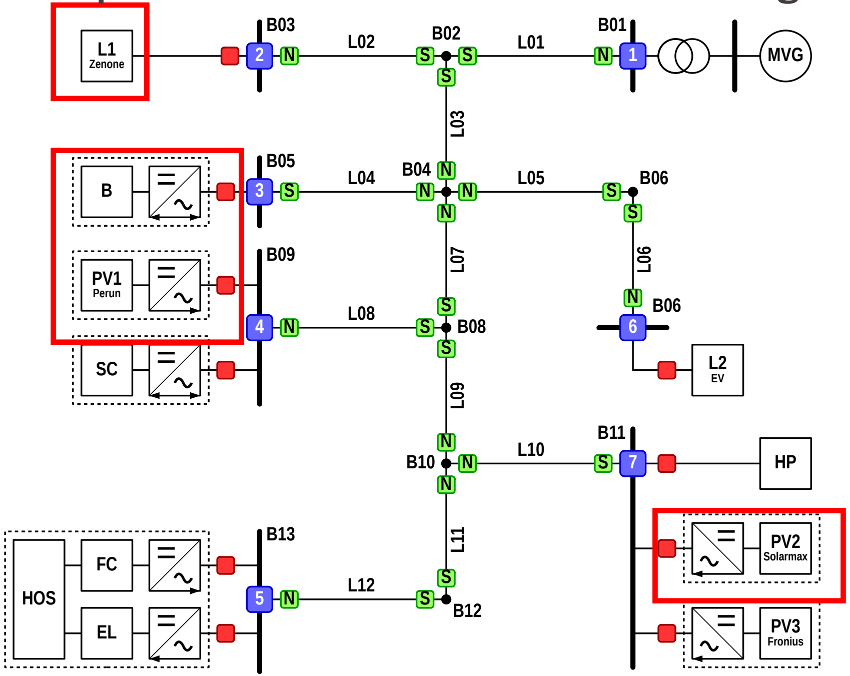
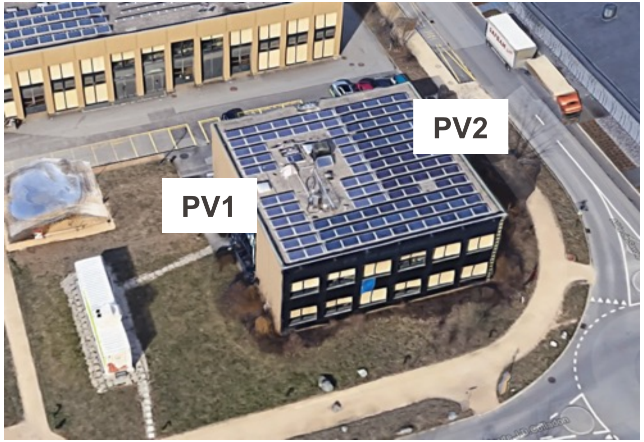
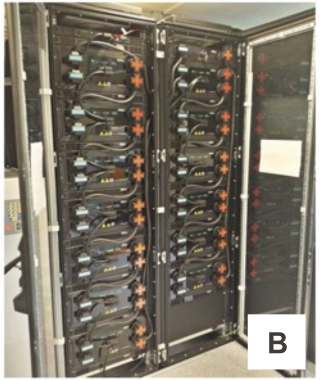
Applications – Day-ahead dispatch

Experimental validation on the LV microgrid



PMUs	L Controllable Load	FC Fuell Cell	EV Electric Vehicle
Breakers	B Battery Storage	EL Electrolyzer	HP Heat Pump
Agents	PV Photovoltaic Plant	HOS Hydro-/Oxygen Storage	MVG Medium-Voltage Grid





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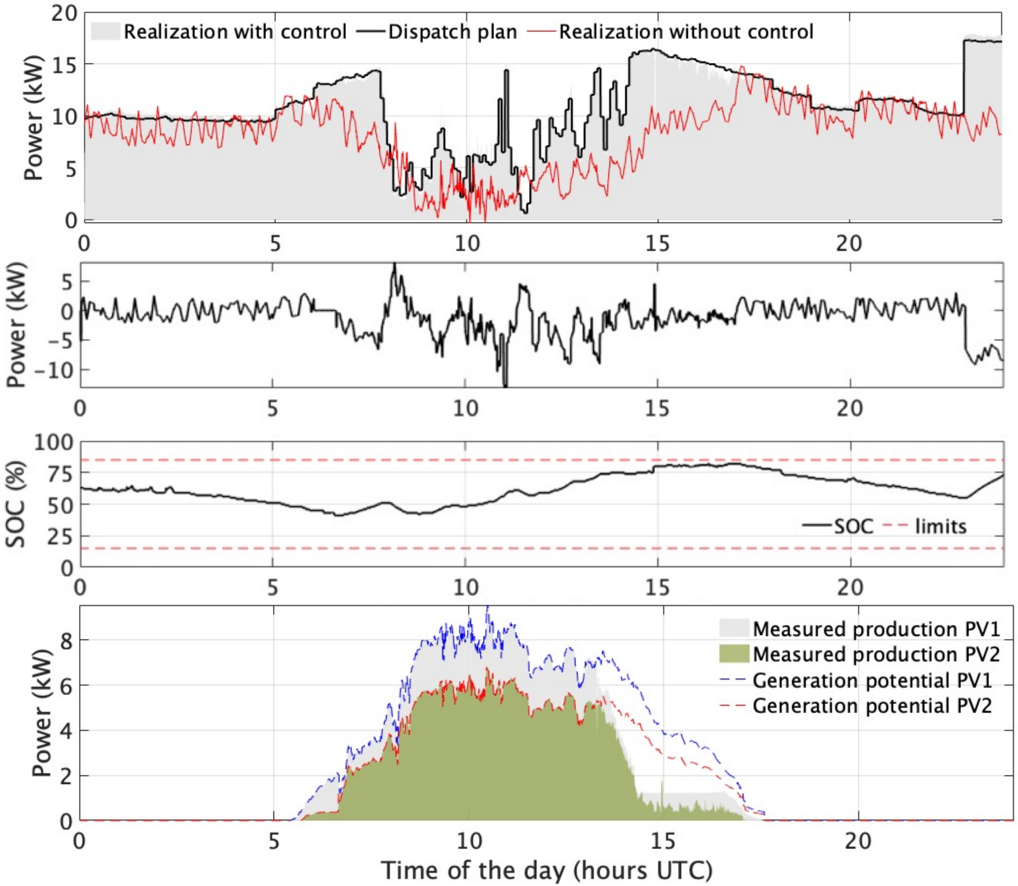
Applications – Day-ahead dispatch

Experimental validation on the LV microgrid using MPC



Real-time tracking of the dispatch plan

Battery power injection and SoC

PV curtailment action to help tracking the dispatch plan to avoid the saturation of the battery SoC.

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Applications
Agent-based real-time control

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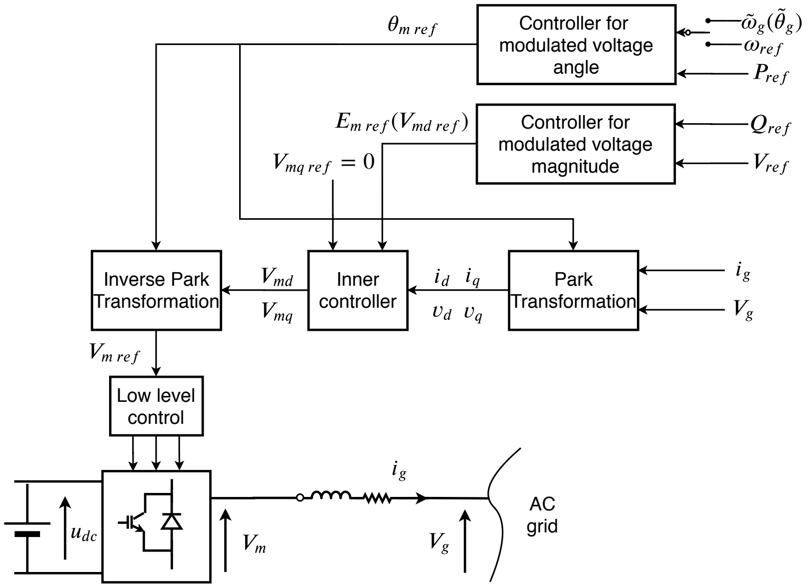
Applications
Clustering of ancillary services

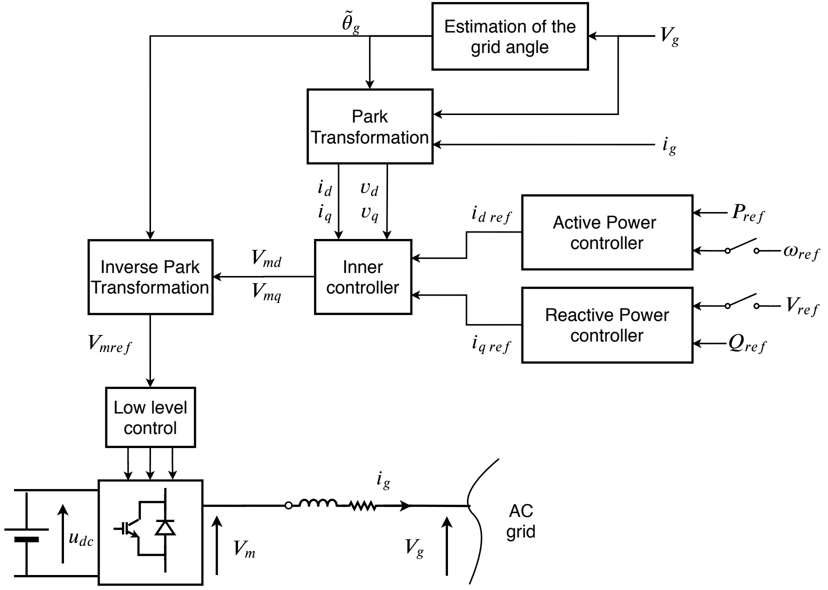
Applications – Assessment of power electronics ctrl

Grid-forming (GFM)



Inertia & FCR | **Dispatch** | **Reactive power control**

Grid-following (GFR)



FCR | **Dispatch** | **Reactive power control**

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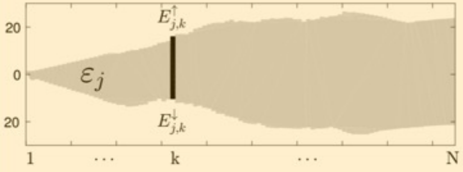
Applications – Assessment of power electronics ctrls

Multi-service framework

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

Day-Ahead[1]

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

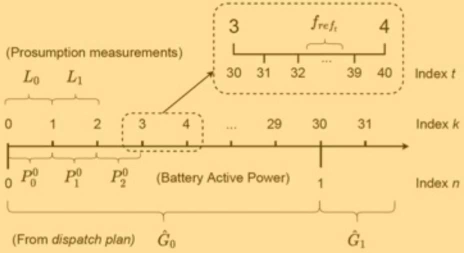


$\sigma_f, \sigma_v, \hat{P}_d$

[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)

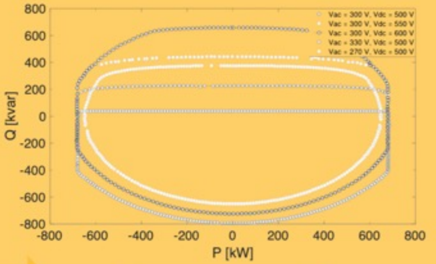


P_{ref}, Q_{ref}

[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

BESS model (TTC)

Capability curve

BESS model

Measured values (AC voltage, etc.)

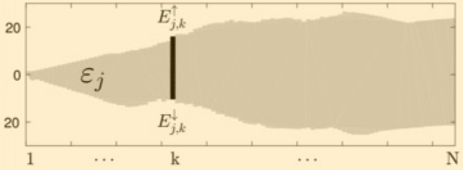
Applications – Assessment of power electronics ctrls

Multi-service framework

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

Day-Ahead[1]

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



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

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

Long term prediction of prosumption

Frequency time series

Voltage time series

$$[\sigma_f^0, \boldsymbol{F}^o] = \arg\max_{\sigma_f \in \mathbb{R}^+, \boldsymbol{F} \in \mathbb{R}^N} (\sigma_f) \quad (4a)$$

subject to:

$$SOE_0 + \frac{1}{E_{\text{nom}}}\left[\frac{T}{N}\sum_{i=0}^{n}(F_i + L_i^{\uparrow}) + \sigma_f W_{f,n}^{\uparrow}\right] \leq SOE_{\max}, \quad (4b)$$

$$SOE_0 + \frac{1}{E_{\text{nom}}}\left[\frac{T}{N}\sum_{i=0}^{n}(F_i + L_i^{\downarrow}) + \sigma_f W_{f,n}^{\downarrow}\right] \geq SOE_{\min}, \quad (4c)$$

$$F_n + L_n^{\uparrow} + 0.2\sigma_f \geq P_{\max}, \quad (4d)$$

$$F_n + L_n^{\downarrow} + 0.2\sigma_f \leq P_{\max}, \quad (4e)$$

Applications – Assessment of power electronics ctrls

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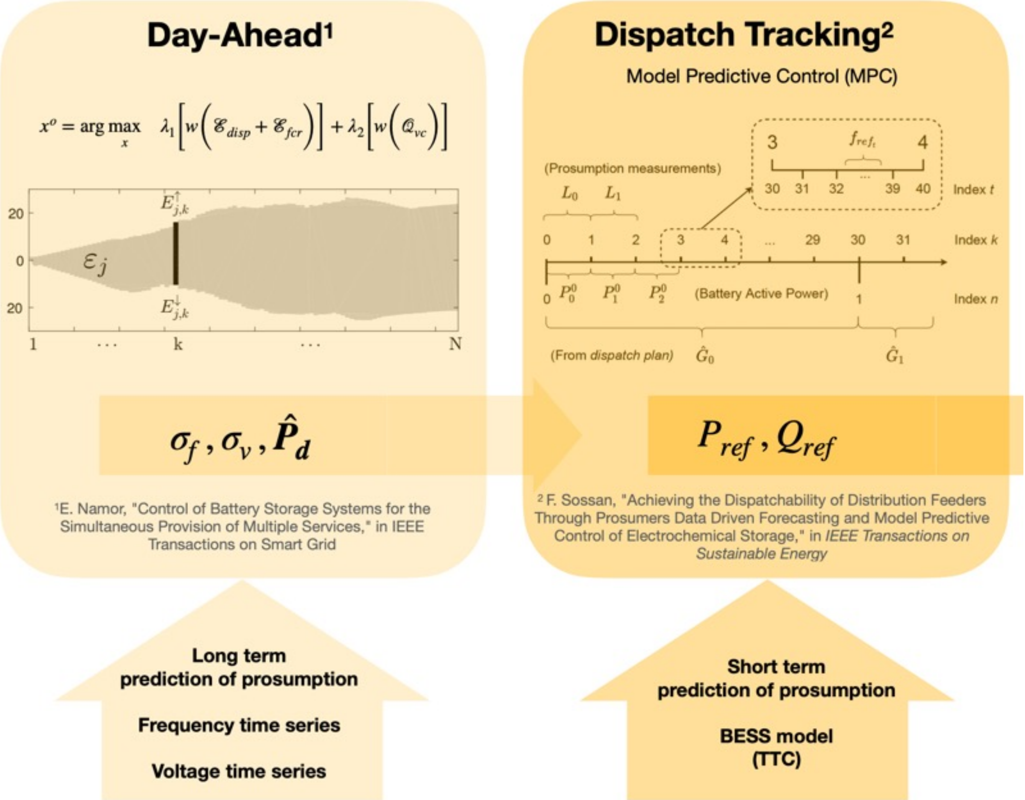
Multi-service framework

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



The **expected average composite power flow at PCC at the end of 5-minutes window** is

$$G_k^+ = \frac{1}{30}\left((k - \underline{k}) \cdot G_k + \sum_{j=k}^{\overline{k}} \hat{L}_{j|k} \right)$$

The **energy error** between the realization and the target in the 5-minute slot

$$e_k = \frac{300}{3600} \cdot (G_k^* - G_k^+ + \Delta G_k^F)$$

where the additional term ΔG_k^F considers the **deviation caused by FCR** of the converter:

$$\Delta G_k^F = \frac{1}{30} \sum_{j=\underline{k}}^{k-1} (50 - f_j) \cdot \sigma_f$$

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Applications – Assessment of power electronics ctrls

Multi-service framework

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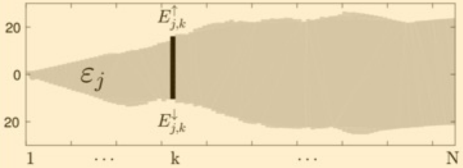
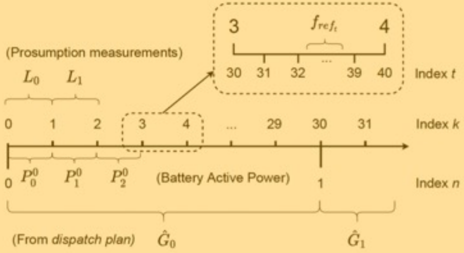


$\sigma_f, \sigma_v, \hat{P}_d$

[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)

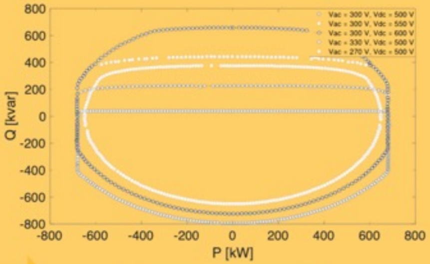


P_{ref}, Q_{ref}

[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

BESS model (TTC)

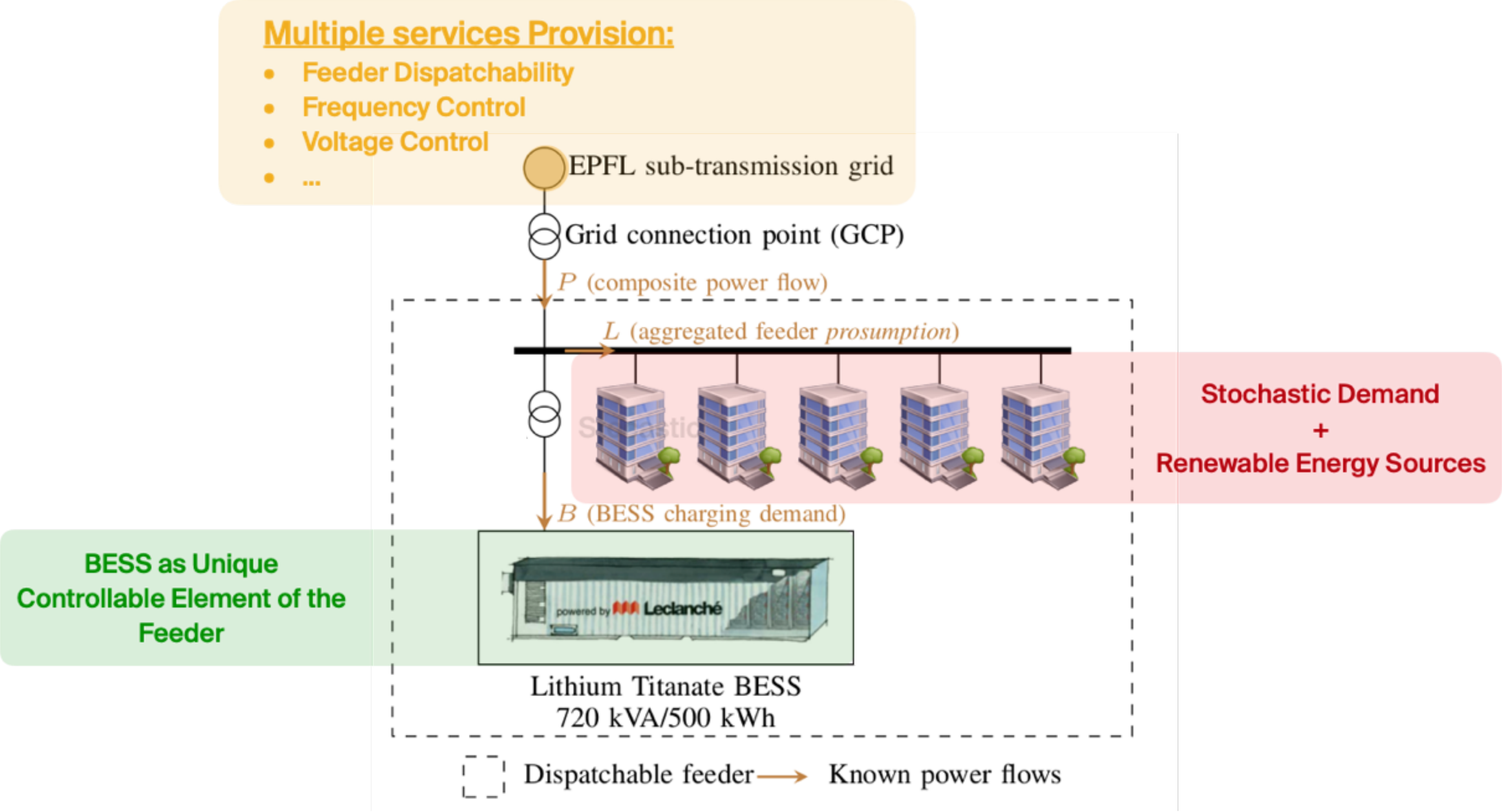
Capability curve

BESS model

Measured values (AC voltage, etc.)

Applications – Assessment of power electronics ctrls

The MV platform



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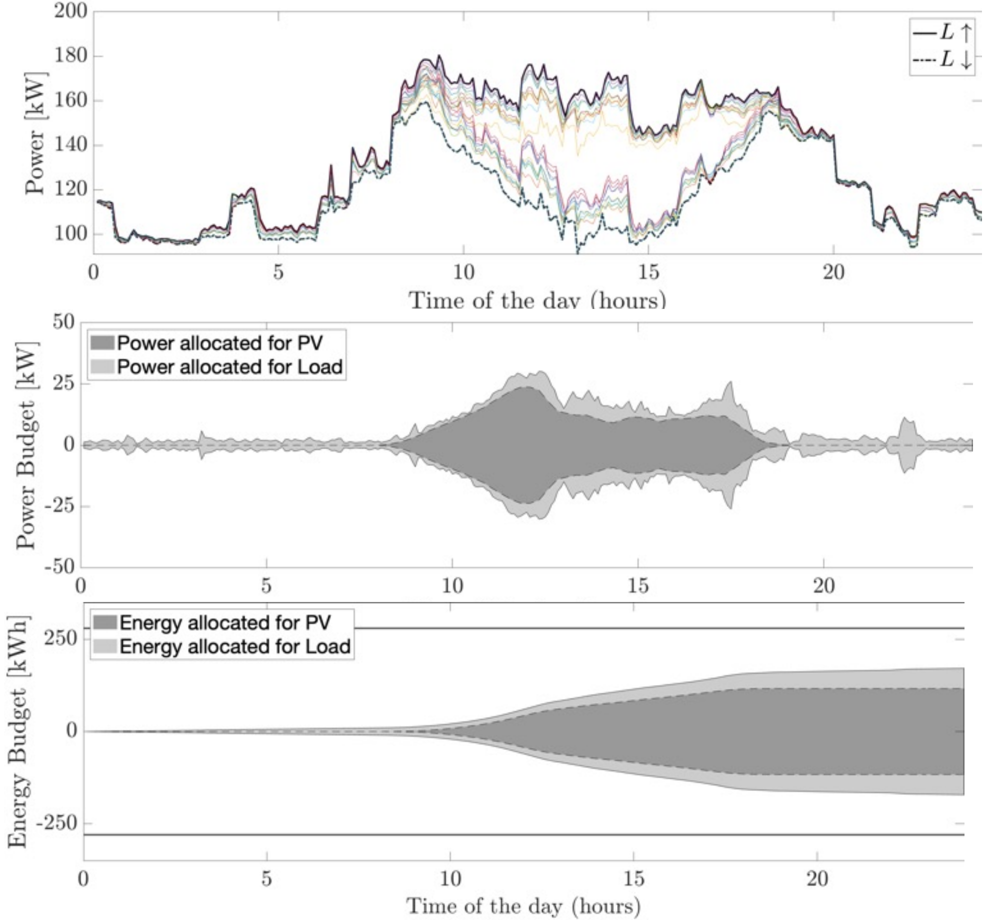
Prosumption (net demand) scenarios

- **Power and energy budgets** are allocated to compensate the forecasting uncertainty of stochastic PV production and demand.
- The remaining energy budget is allocated for the **FCR service** (resulting in a droop of $\sigma_f = 116$ kW/Hz).



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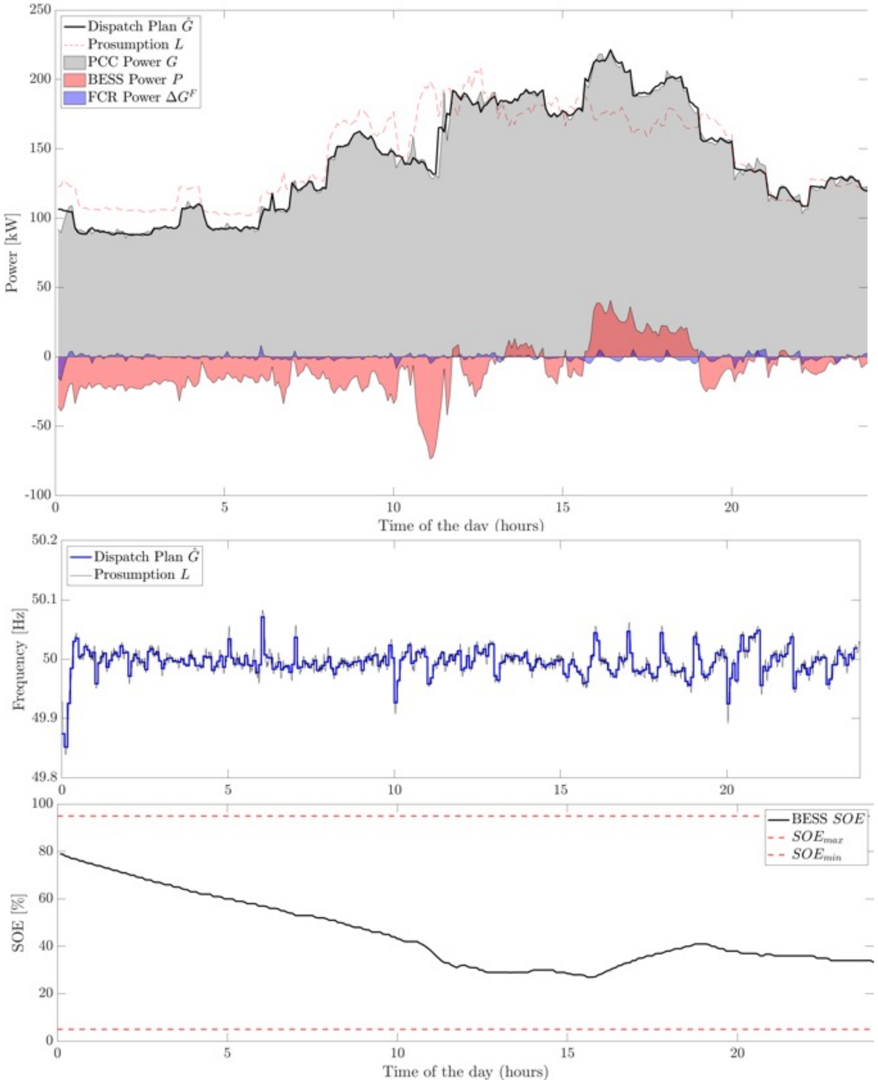
Apps – Assessment of power electronics ctrls

Experimental results

- The grid-forming converter-controlled BESS corrects the prosumption (**in dashed red**) such that the PCC power (**in shaded grey**) is tracking the dispatch plan (**in black**).
- The deviation of the PCC power from the dispatch plan is the result of BESS providing FCR service.
- BESS SOE is contained within its physical limits all over the day (as well as other constrained variables not shown here).



Applications – Assessment of power electronics ctrls

Experimental results

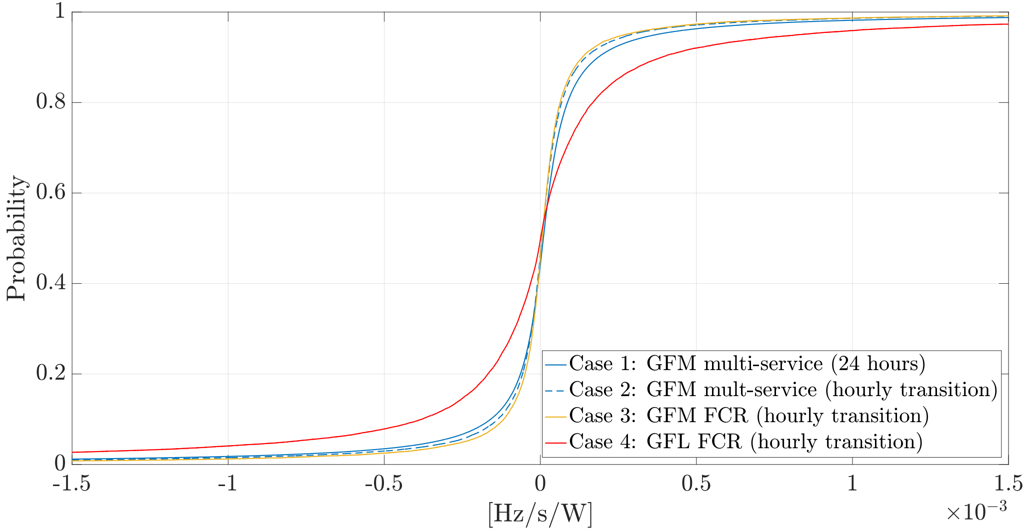
- Post-process analysis of the local grid frequency associated to **grid-forming** and **Grid-following** experimental sessions.
- **Relative Rate-of-Change-of-Frequency (rRoCoF) [Hz/s/W]**

$$rRoCoF = \left| \frac{\Delta f / \Delta t}{\Delta P} \right|$$

This **metric is independent from the actual frequency variation** since the RoCoF is divided by the delivered BESS power.

Applications – Assessment of power electronics ctrls

Experimental results



- ***Case 1***: the 24 hour-long experiment with GFM-controlled BESS providing multiple services.
- ***Case 2:*** a 15-minute window around the hourly transition (i.e., 00:00 CET) for the same day-long experiment.
- ***Case 3:*** a dedicated 15-minute experiment around the hourly transition with the GFR-controlled BESS providing only FCR (droop of 1440 kW/Hz).
- ***Case 4:*** a dedicated 15-minute experiment around the hourly transition with the GFL-controlled BESS is providing only FCR (droop of 1440 kW/Hz).

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The PATHFNDR activities

École polytechnique fédérale de Lausanne

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Motivations

A primer on Swiss electricity market

- **Day-ahead market** is organized as a uniform auction with hourly contracts
  - Opens 45 days before delivery time and cleared the day before operation at 11.00.
  - Minimum bid size and step is 0.1 MW with prices between -500 to 3000 Euro/MWh.

- Given the day-ahead results, the **balancing responsible parties** (BRPs) of buyer and seller have to submit their schedules to the TSO (Swissgrid) until 14.30 the day before delivery.

- **Balancing groups** (BGs) represented by BRPs, are used for three purposes
  - Quantification of energy delivered,
  - **coordination and accounting** between TSO and market participants,
  - trade in day-ahead and intra-day markets.

- Swissgrid verifies that the schedules match based on day-ahead and BRPs input.
- BGs are **not constrained geographically.**

Modèle de marché pour l'énergie électrique – Suisse (www.strom.ch)
Jan Abrell, The Swiss Wholesale Electricity Market

The PATHFNDR setup

1. ***Improving performance -*** *efficiency, resilience cost competitiveness*

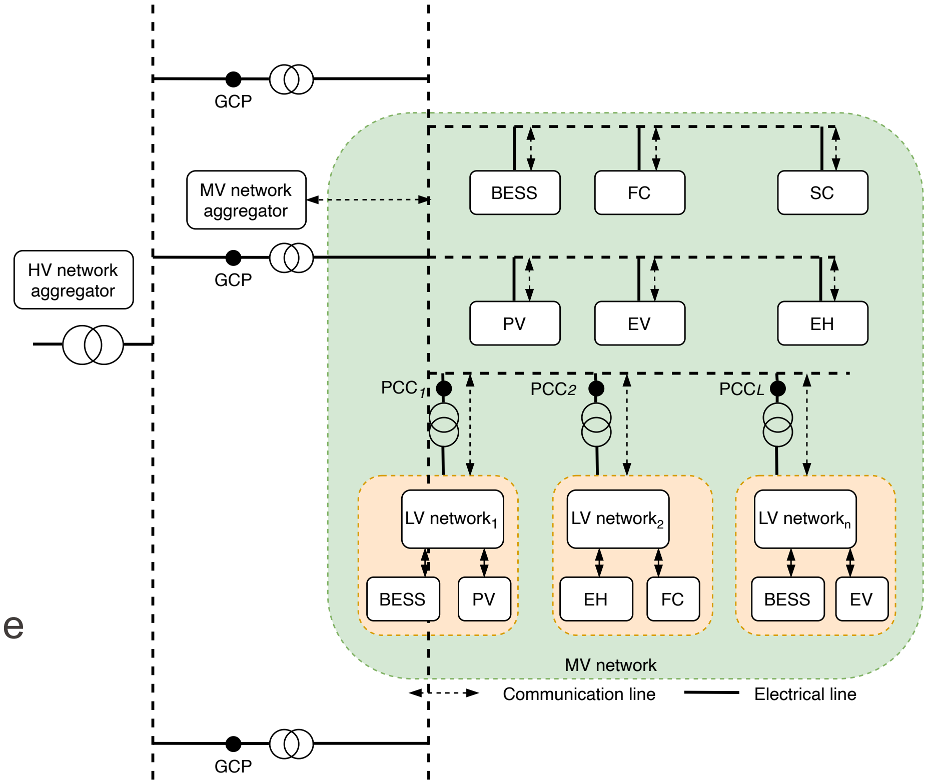
3. ***Feeding sector coupling*** *– evaluate technologies, business mdoels*

2. ***Enabling flexibility -*** *assessing flexibility across various sectors*

- Flexible resources across different sites can be controlled to provide an aggregated flexibility,
- Could use existing platforms like *ReMap* to connect resources at DESL-EPFL, PSI, EMPA, HSLU etc.

Aggregation of DERs flexibilities in distribution grids

- **Modeling of local constraints**
  - Distribution grids (model-based or model-less)
  - Flexible assets
    - BESSs, Super-caps
    - PVs, EVs, Res. dem.
    - EL+FC .. etc.
- **Aggregation**
  - Forecast of stochastic flexibilities
  - Allocation of resources
- **Communication**
  - Common IT infrastructure for all the assets to communicate at scheduling/control stage.
  - Historian and RT Monitoring.



Architecture of multi-grids aggregation

Multi-grid aggregation case study (simulation)

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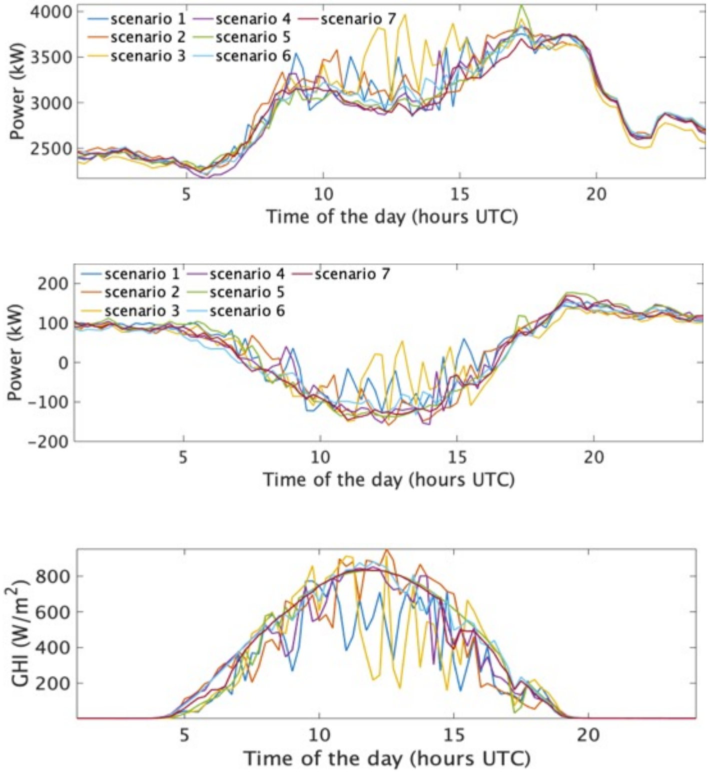
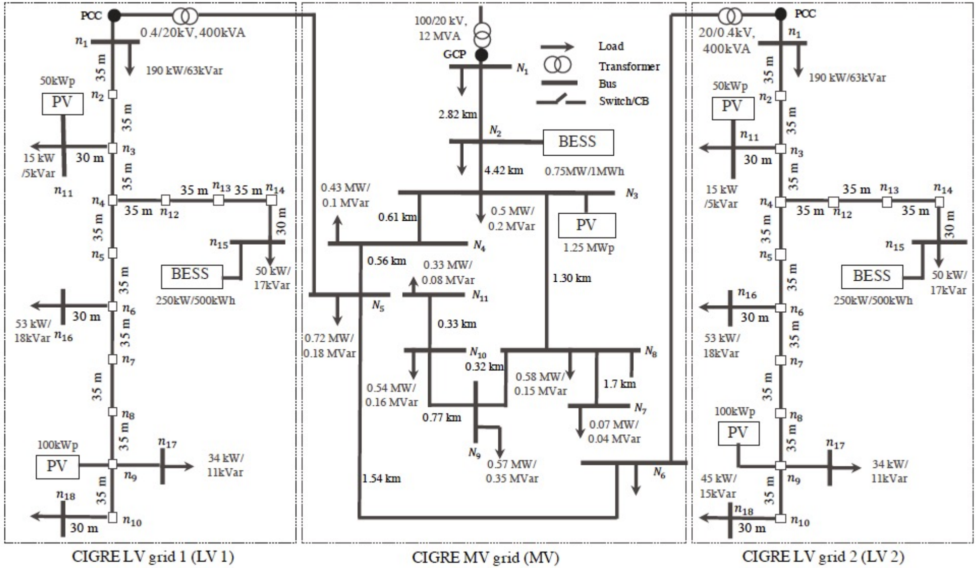
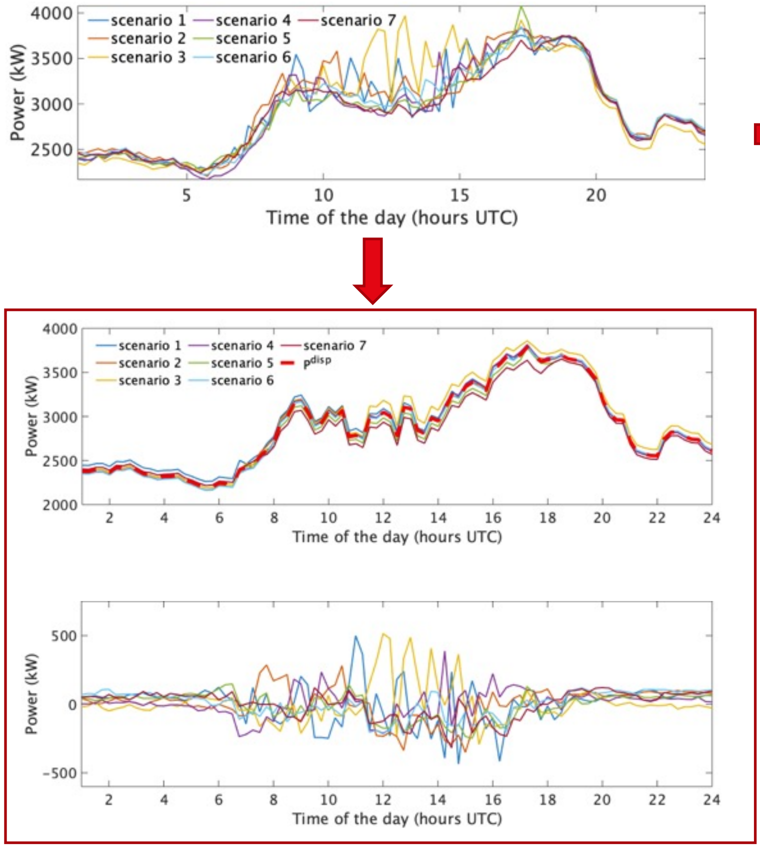


Scenarios of load and GHI for MV and LV systems

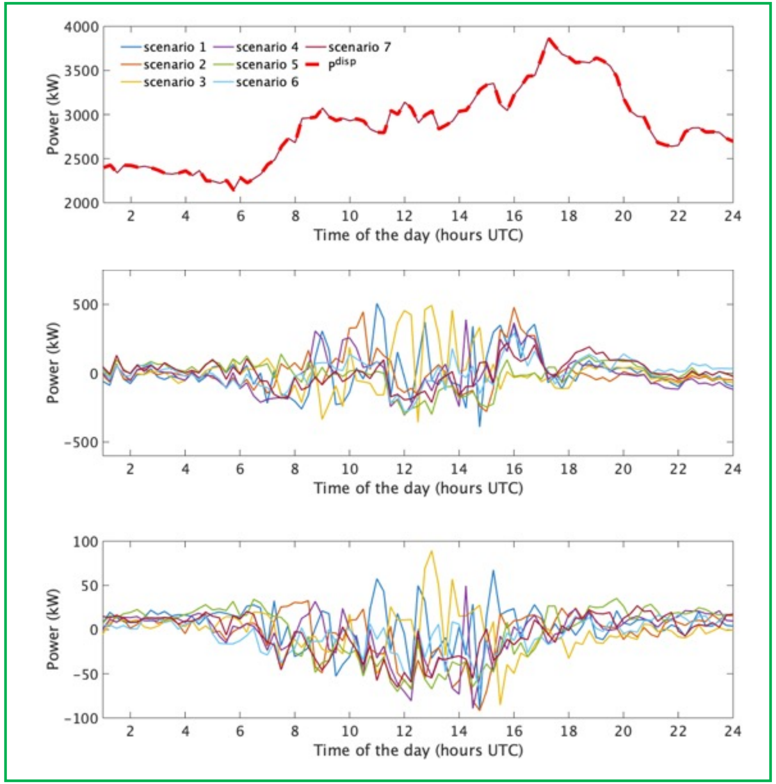


Flexibilities from downstream LV networks such as BESS could help dispatching the MV network at the GCP

Performance assessment



No coordination with downstream networks



With coordination with downstream networks

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Final remarks

Final remarks

- The EPFL smart grid platform is an ongoing project for the innovative and sustainable management of stochastic energy resources, power generation facilities and end-users.
- It represents an advanced model for students, research staff, industry, authorities and the general public to develop technologies for the operation of future power distribution systems and their coupling with other energy systems.
- The involvement of the platform within the PATHFNDR project will demonstrate how to coordinate multi-site and multi-time dispatching of geographically-distributed microgrids that mutualise power/energy flexibilities made available by fully-controllable and stochastic energy resources.