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DAY-AHEAD DISPATCH OF AN ACTIVE DISTRIBUTION NETWORK HOSTING STOCHASTIC DISTRIBUTED GENERATION VIA GRID-AWARE CONTROL OF A BESS

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The control time scales for ADNs

mins-seconds — time — hours-minutes

Problem	Required methods	Required technologies
▪ Renewables short-term volatility	▪ Real-time knowledge of the system state	▪ Distributed sensing (e.g. PMU) ▪ Real-time state estimators
▪ Grid congestions ▪ Voltage control	▪ Exact optimal power flow ▪ Explicit control methods ▪ Stability assessment of complex systems (low inertia)	▪ Distributed storage ▪ (Demand response)
▪ Heterogeneous resources aggregation ▪ Ancillary services (system stability)	▪ Real-time estimation of system flexibility ▪ Robust optimization ▪ Short-term forecast	▪ Agent-based software frameworks ▪ Demand response

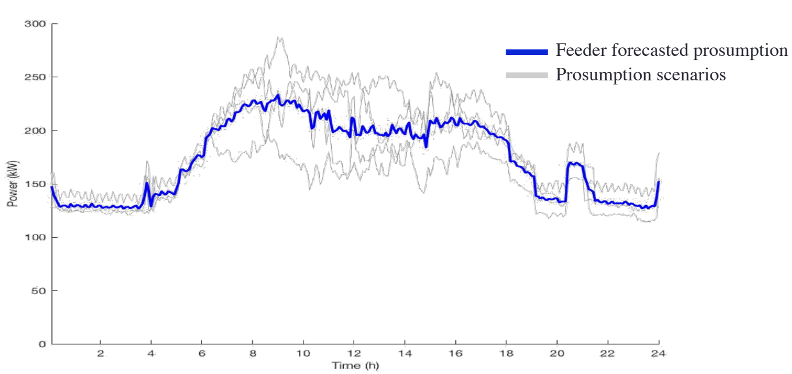
Objective

Experimental validation of day-ahead dispatchability of a distribution network hosting stochastic RES-based generation via grid-aware real-time control of a BESS

Control in two stages: a **day-ahead optimization** and a **real-time control**

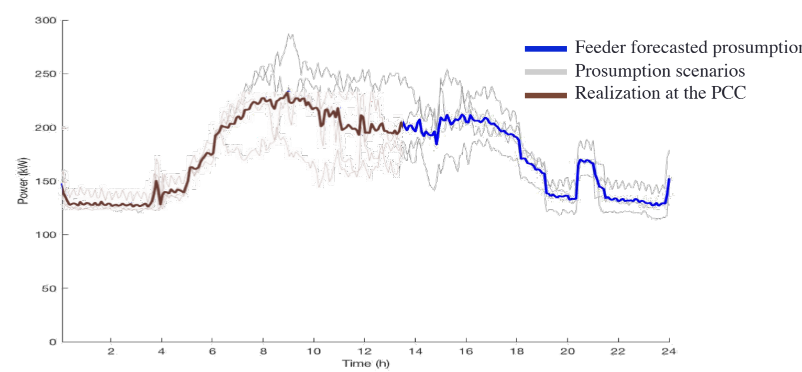
Optimal profile of the feeder power for the **next day** and determination of BESS offset profile:

- data-driven forecasting
- scenario-based optimization

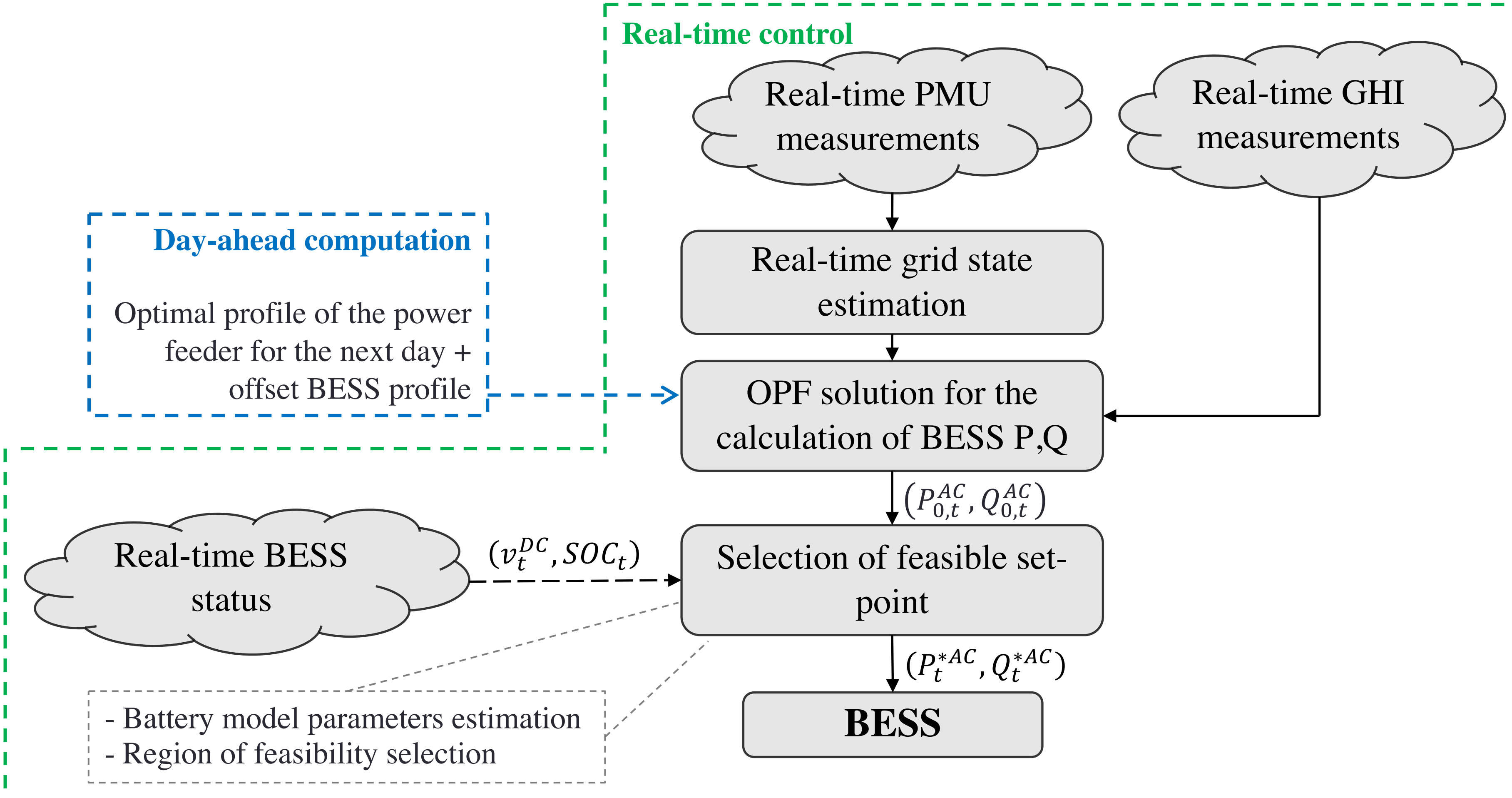


In **real-time**, the BESS is controlled to track the optimal profile:

- grid-aware OPF-based control
- battery equivalent circuit model



Overall framework



Dispatch plan definition

Day-ahead

Every 24 hours, we solve a **robust optimization** problem:

find:
- a dispatch plan for the next 24 hours using a scenario-based iterative AC OPF (**Codistflow**), which accounts for forecasts of RESs and load profiles with 95% confidence interval with 1h time resolution

  such that:
  - the **dispatch error** (|sum(dispatch plan – PCC power)|) is **minimized** within 1h
  - the BESS offset profile for **SoC compensation** is included

  and such that:
  - the BESS **energy limits are respected**
  - the BESS **power limits are respected**
  - the grid **ampacity and voltage constraints are respected**
  - **end-of-day SoC is within 10% around initial SoC**

RT OPF-based BESS control

Real-time control

For each 1 hour slot, we solve **robust OPF** problems every 1 min, that considers the dispatch plan and BESS offset profile:

$i=1,2,\ldots,i^{max}(=61)$

while $i<i^{max}$ do:

- solve $(i^{max}-i)$ OPF for each time step of the 1h interval in **receding time horizon**

  such that:
  - the **dispatch error** (|sum(dispatch plan – PCC power)|) is **minimized** within 1h
  - the BESS offset profile for **SoC compensation** is included
  - the **accumulated error** during the previous (i-1) timesteps is considered and **compensated**

  and such that:
  - the BESS **energy limits are respected**
  - the BESS **power limits are respected**
  - the grid **ampacity and voltage constraints are respected**

end

Different OPF methods

Accuracy VS Computation Complexity

- **Linearized OPF [1]**
  - The system states are modeled by the sensitivity coefficients which can be uniquely determined as a function of grid states and topology, and are assumed to be constant within the control time interval.

- **Second-order cone ACOPF (SOC-ACOPF) [2]**
  - Relying on the branch flow formulation based on the transmission line Π-model.
  - The original AC-OPF is convexified by employing SOC programming relaxation on the ampacity constraint associated to power losses
  - The loop constraint of V phase angle is derived so that the branch flow model is valid also for meshed power networks.
  - The feasible solution of the original AC-OPF can be recovered from the optimal solution of the SOC-ACOPF and the relaxation of the SOC-ACOPF model is tight under high power load conditions.

- **Augmented Relaxed OPF (AR-OPF) [3]**
  - Relying on the branch flow formulation based on the transmission line Π-model.
  - While employing the SOCP relaxation on the ampacity constr. associated to P losses, aux. variables related to the state variables (line P-flow, V and I) are introduced to build a set of augmented operating constraints to guarantee the exactness of the SOCP relaxation.
  - The exactness is valid under mild conditions which holds for realistic radial distribution networks.

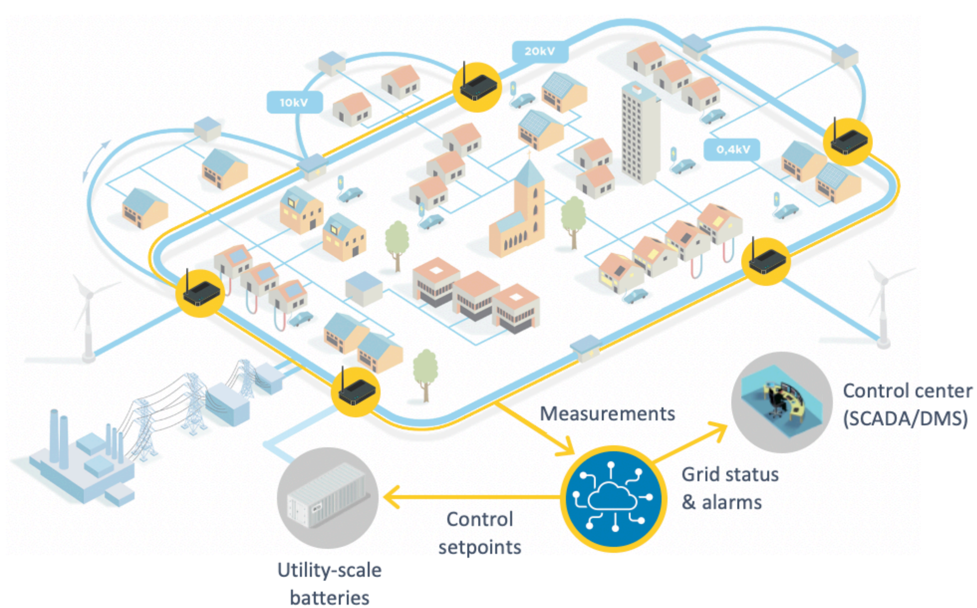
[1]. Gupta, Rahul, Fabrizio Sossan, and Mario Paolone. "**Performance Assessment of Linearized OPF-based Distributed Real-time Predictive Control**." *2019 IEEE Milan PowerTech*. IEEE, 2019.
[2]. Yuan, Zhao, and Mario Paolone. "**Properties of convex optimal power flow model based on power loss relaxation**." *Electric Power Systems Research* 186 (2020): 106414.
[3]. Nick, Mostafa, et al. "**An exact convex formulation of the optimal power flow in radial distribution networks including transverse compone**nts." *IEEE Trans. on Autom Control* 63.3 2017: 682-697.

Employed state estimation method

Zaphiro develops the **first grid automation system** based on **high-speed & time-synchronized PMUs**

17 Zaphiro's PMU (Phasor Measurement Unit) devices:

- Time-synchronized
- High-speed measurements (50 meas/sec)



Modular and scalable big-data processing software platform

Real-time monitoring
→ Estimation of entire grid state up to 50/60 times per second

Outage management
→ Automated fault location to reduce the duration or even prevent blackouts

Battery control
→ Control of a 1.5 MW battery to:
- Maximize PV generation
- Guarantee grid stability
- Provide ancillary services

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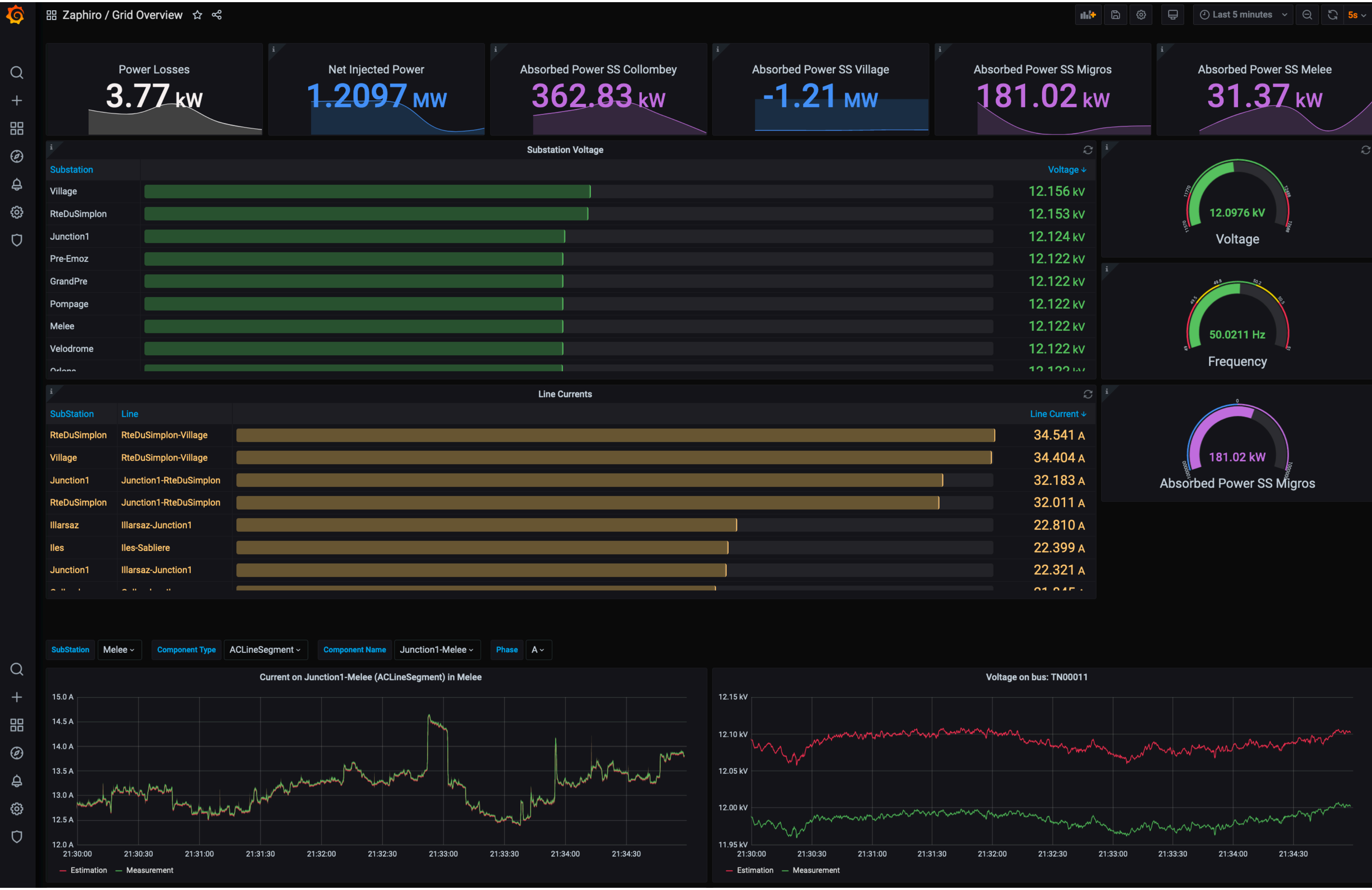
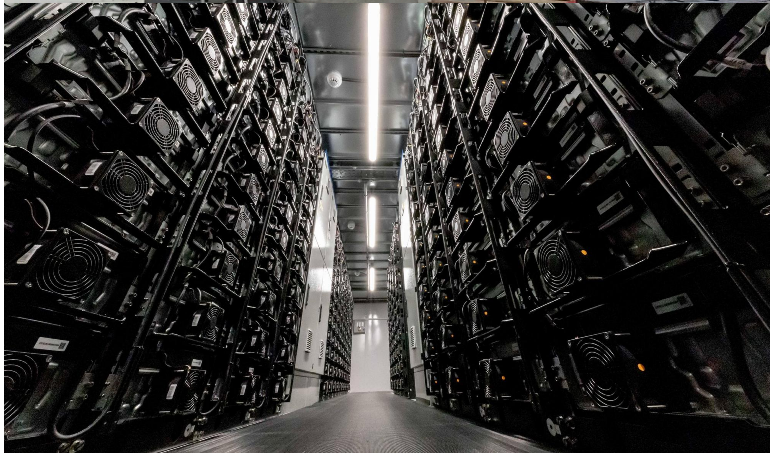
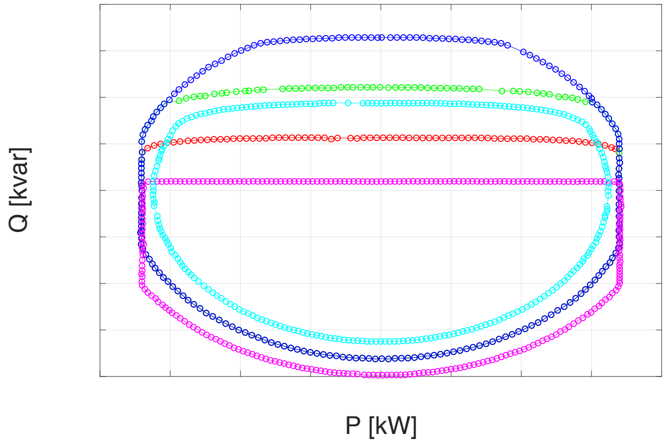


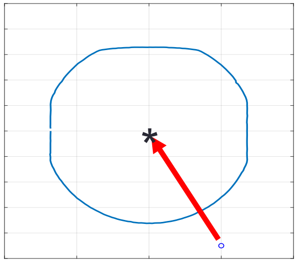
1.5 MVA/2.5 MWh BESS

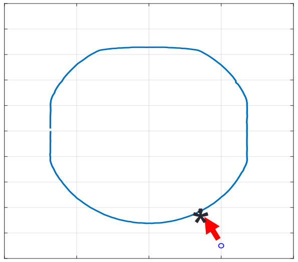


$$h(P_t^{AC}, Q_t^{AC}, v_t^{DC}, v_t^{AC}, SOC_t) \leq 0$$



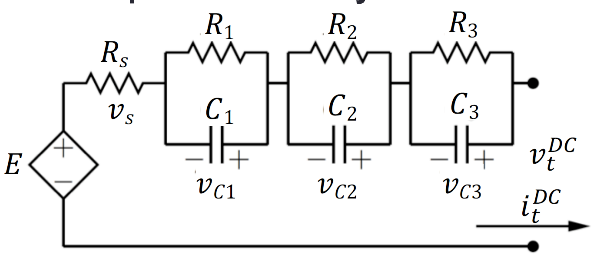
PQ capability curves as function of the real-time BESS status & grid status



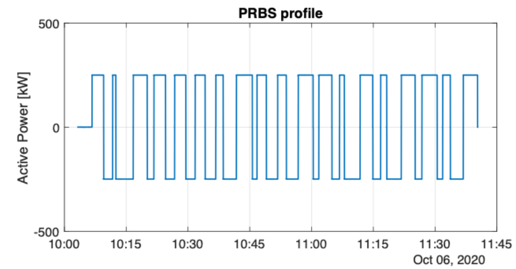


BESS modelling

Equivalent battery TTC model

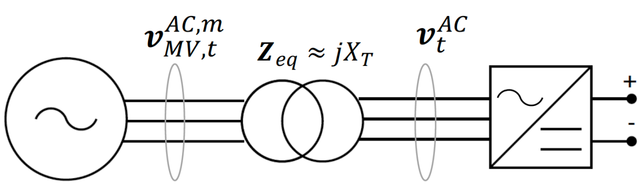


$$
\begin{cases}
C_1 \frac{\mathrm{d}v_{C1}}{\mathrm{d}t} + \frac{v_{C1}}{R_1} = \frac{v_s}{R_s} \\
C_2 \frac{\mathrm{d}v_{C2}}{\mathrm{d}t} + \frac{v_{C2}}{R_2} = \frac{v_s}{R_s} \\
C_3 \frac{\mathrm{d}v_{C3}}{\mathrm{d}t} + \frac{v_{C3}}{R_3} = \frac{v_s}{R_s} \\
v_s + v_{C1} + v_{C2} + v_{C3} = E - v_t^{DC} \\
E(SOC_t) = a + b \cdot SOC_t
\end{cases}
$$



SOC	0-20%	20-40%	40-60%	60-80%	80-100%
a	100.0098597	100.016163	100.014469	100.0134207	100.0146099
b	549.2836773	245.2360282	284.9052456	344.9751672	324.8422745
R_s	0.009312694	0.008569196	0.008364214	0.007948302	0.007679508
R_1	0.003305801	0.003323378	0.002586195	0.002919781	0.003248674
C_1	7576.472133	8813.047231	5631.309052	7282.444433	7792.395409
R_2	0.000217164	0.000334839	4.53043E-05	4.17458E-05	0.003885566
C_2	1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06
R_3	2.00E-06	3.51E-05	4.13E-06	4.17E-06	5.80E-04
C_3	1.00E+07	1.00E+07	1.00E+07	1.00E+07	1.00E+07

Reference BESS scheme for the AC voltage prediction



$$\mathbf{v}_t^{AC} = \mathbf{v}_t^{AC,m} + \mathbf{Z}_{eq} conj\left(\frac{\mathbf{S}_{0,t}^{AC}}{\sqrt{3}\mathbf{v}_t^{AC,m}}\right)$$

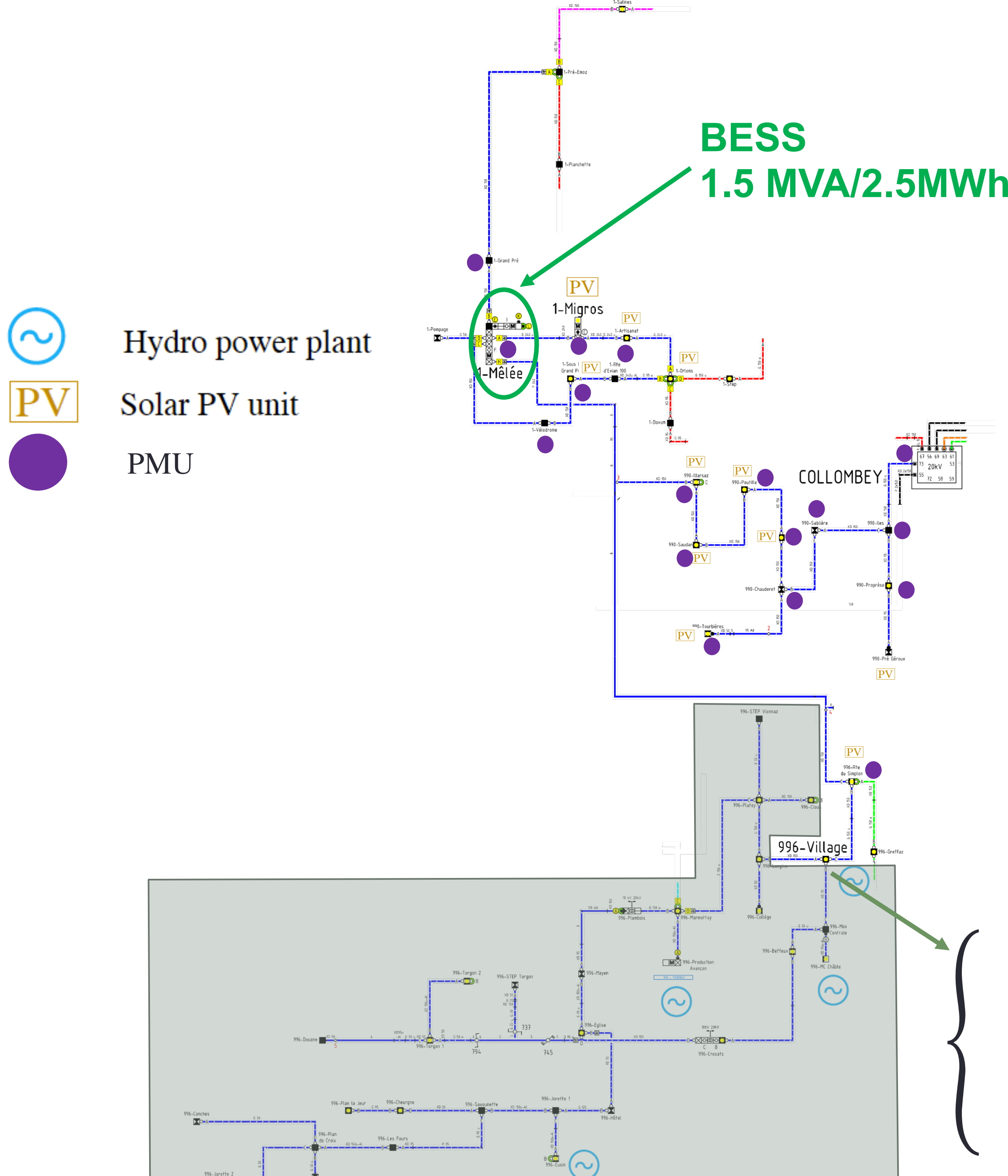
$$v_t^{AC} \approx \sqrt{(v_t^{AC,m})^2 + X_T^2 \frac{(P_{0,t}^{AC})^2 + (Q_{0,t}^{AC})^2}{3(v_t^{AC,m})^2}}$$

- **Prediction of DC voltage** (v_t^{DC}, SOC_t)
- **Prediction of AC grid voltage** (v_t^{AC})

$$h(P_t^{AC}, Q_t^{AC}, v_t^{DC}, v_t^{AC}, SOC_t) \leq 0$$

Converter feasibility region

Zecchino, A., Yuan, Z., Sossan, F., Cherkaoui, R. and Paolone, M., **"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, Vol. 190, Jan. 2021.



Base voltage: 21 kV

Base 3-phase power: 6 MVA

Total PV gen. capacity: 3.2 MWp (1xMW-scale)

Total hydro gen. capacity: 3.4 MVA (1xMW-scale)

17 PMUs distributed along the network

$$\left\{ \begin{array}{l} \sum_i P_{load_i} \; ; \quad \sum_i Q_{load_i} \\ \sum_j P_{PV_j} \; ; \quad \sum_j Q_{PV_j} \\ \sum_k P_{hydro_k} ; \quad \sum_k Q_{hydro_k} \end{array} \right.$$

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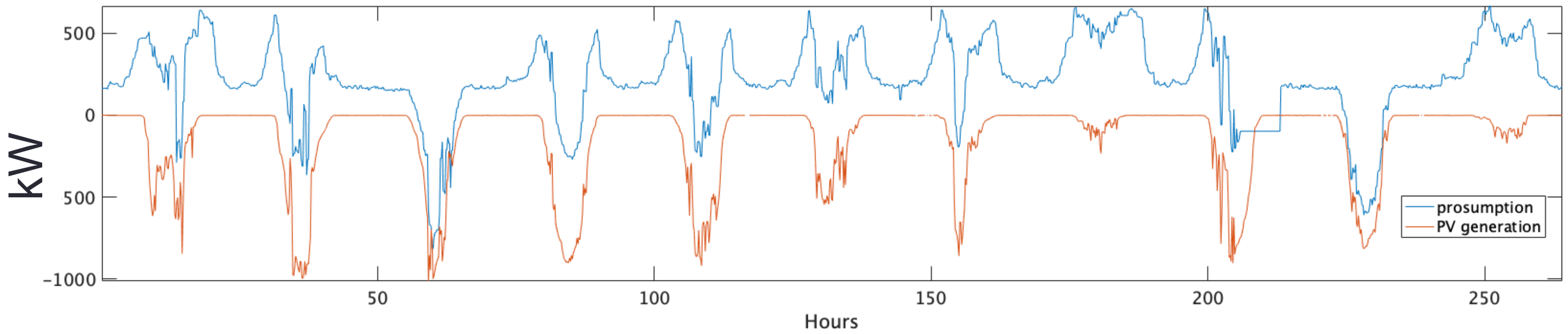
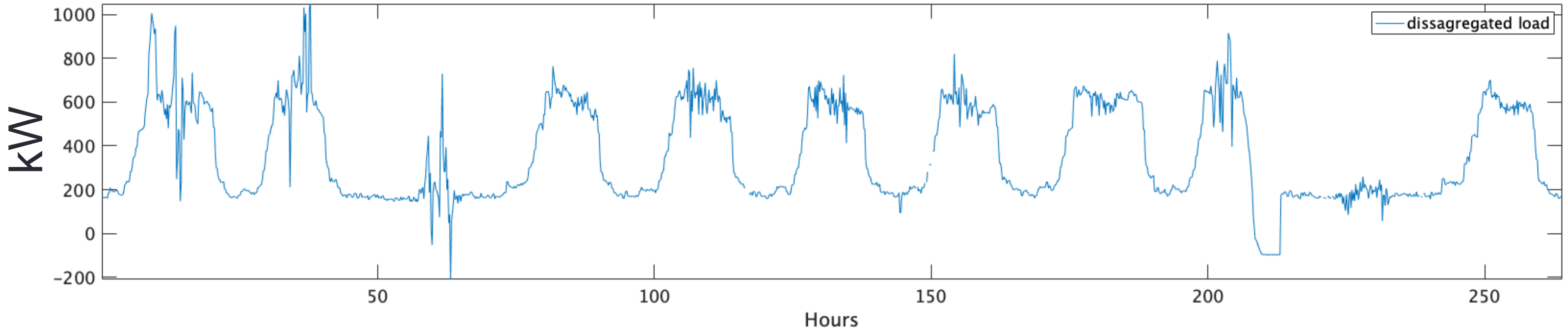
Prosumption data analysis and PV disaggregation





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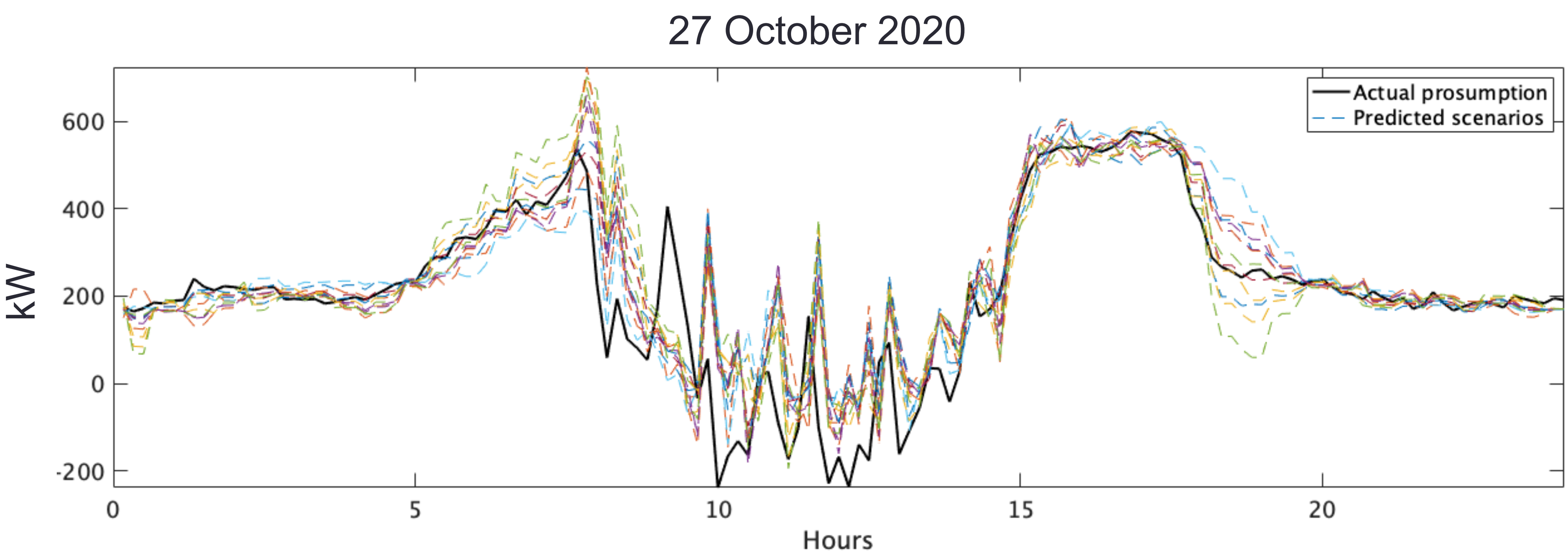
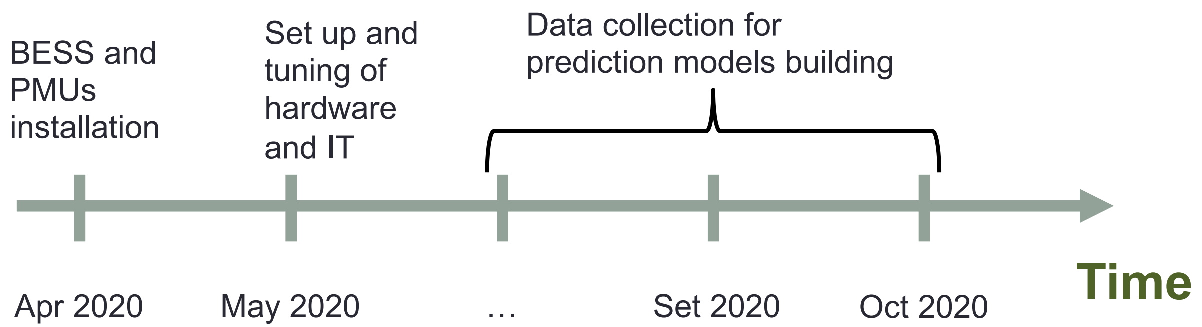
Day-ahead scenarios generation and Realization

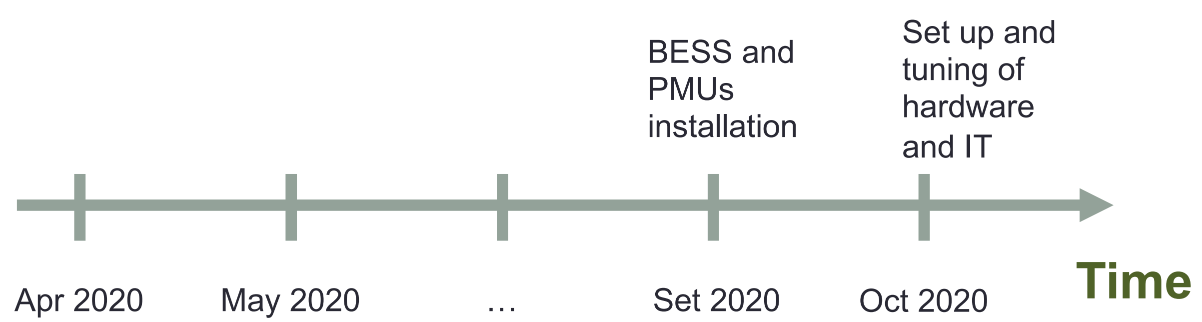


Where we are now

Original plan



Actual plan due to pandemic



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Conclusions

- We are deploying a framework for the day-ahead dispatchability of a distribution network hosting stochastic RES-based generation via grid-aware RT control of a BESS
- We have put in place a field experimental setup with advanced top-edge technology for the real-time monitoring and control of an ADN
- We have established field data collection and performed first analysis to assess the stochastic behavior of loads and distributed RESs after disaggregation
- We have performed BESS equivalent model identification tests for its optimal control
- An online disaggregation and forecasting tool for PV production and load consumption is operational.
- The RT dispatcher will be fully operational by mid-November

Thank you

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