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REEL Demo – Romande Energie ELectric network in local balance Demonstrator

Deliverable: 2overall Compilation of real-time control strategies for heterogeneous resources at MV and LV

Demo site: Aigle

Developed by

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1. Description of deliverable and goal

1.1. Executive summary

The core of this activity is to provide distribution system operators with tools for the operation of utility-scale distributed battery energy storage systems (BESSs) in order to optimize the integration of stochastic distributed generation. The main goal of this deliverable is to assess two possible strategies for the real-time control of a utility-scale BESS to follow a day-ahead computed dispatch plan. In particular, one solution is based on a grid-aware optimal power flow (OPF)-based control accounting for both grid and BESS operational constraints (thoroughly described in D1.4.4c) [1], whereas the second one is based on the COMMELEC (thoroughly described in D1.2.3c) [2], [3].

The goal of the first method is to achieve the real-time dispatch plan tracking using a grid-aware model predictive control (MPC) to determine the active and reactive power set-points of the BESS so that the aggregated power of all the resources connected to a medium voltage power grid contribution track the dispatch plan while obeying to BESS's operational constraints as well as the grid's ones. The grid constraints are modelled using the Augmented Relaxed OPF [4].

COMMELEC is a framework proposed in the literature ([2], [3]) for the real-time control of power grids. It uses a hierarchy of agents to compute explicit active and reactive power setpoints for the resources connected to the grid. Each resource is equipped with a resource agent (RA) whose job is to translate the internal state of the resource into a device-independent format (advertisement). The advertisements are collected by the grid agent (GA), which computes the optimal power setpoints that optimize a global objective. The global objective is the weighted sum of various objectives, including tracking a predetermined dispatch plan at the slack bus, minimizing grid's nodal voltage deviations from the nominal value, limiting the line currents below the respective ampacities and achieving target internal states for the resources.

The proposed control frameworks are validated by dispatching the operation of a 12kV/20MVA MV distribution network in Aigle, Switzerland (i.e. the REeL demonstrator) using a 1.5 MW/2.5 MWh BESS, which is controlled in real-time given the online grid state estimation enabled by the deployed distributed PMU-based sensing infrastructure.

1.2. Research question

The research question that this activity aims to respond is the following: how can distribution system operators operate utility-scale distributed BESSs with the aim of optimizing the integration of stochastic distributed generation while enforcing the physical grid constraints, namely the constraints on nodal voltages, lines and transformer capacities?

1.3. Novelty of the proposed solutions compared to the state-of-art

The exploitation of controllable distributed generation (DG), flexible demand and storage systems is seen by the modern power system community as the most promising approach for increasing the hosting capacity of stochastic power generation in active power distribution networks, while maintaining minimal the impact on the local grid infrastructure as well as the fluctuations of the power exchanged with the upper grid level.

In this regard, previous works have investigated and developed strategies for the day-ahead prediction of DGs' and loads' behavior, acting on the controllable BESS to compensate for predictions vs realizations mismatches taking place at the moment of the realization during real-time applications (e.g., [1], [5], [6]).

Within the framework of the REeL demonstrator, as thoroughly presented in Deliverables D1.2.3c and D1.4.4c, we developed and experimentally validated multiple real-time grid-aware control strategies in a utility MW-scale MV distribution grid. In particular, a grid-aware OPF-based control framework was validated as an alternative to the COMMELEC control framework.

Within this context, the core novelties of the proposed work are three-fold, and are identified as:

- Development of a computationally-efficient intra-day OPF-based real-time control of the controllable resources to track the dispatch plan.
- Use of the COMMELEC control framework embedding a new method for the computation of resources and grid weights with the objective of following the dispatch plan, while minimizing voltage deviations and limiting the line currents. This new method translates the weights into auxiliary quantities with physical meaning, such as maximum deviation from the dispatch plan or maximum grid's nodal voltage variations. Unlike the weights, these quantities can intuitively be

chosen by the user, minimizing the time and effort needed to configure the parameters of the control algorithm and providing a priori a general idea of how the control will perform.

- Validation and performance assessment of the proposed methodologies in a full-scale real environment via the REeL demonstrator site in Aigle, Switzerland.

1.4. Description

The deployed framework consists of two algorithmic layers. In the first one (day-ahead scheduling) an aggregated dispatch plan is determined, then in the second one real-time operations are performed, where two possible control strategies are proposed and compared, namely a grid-aware OPF-based model predictive control strategy vs the COMMELEC one.

The dispatch plan is defined in the day-ahead phase for the next 24-h, identifying the active power trajectory that the distribution network should follow at its upper grid connection point during operations. As thoroughly presented in Deliverables D1.3.4c and D1.4.4c, the dispatch plan is computed with a stochastic optimization framework, where the stochastic injections of distributed generation and demand are modelled through forecast scenarios, grid constraints are modelled using CoDistFlow [4], while the operational constraints of the battery are modelled accounting for the PQ capability of its power converters and for the state-of-energy constraints [1].

For the real-time control, the two deployed methods are implemented for the control on the 1.5 MW/2.5 MWh BESS installed at the 21 kV MV grid of Romande Energie in Aigle, Vaud, Switzerland, as discussed in D1.4.4c and D1.2.3c.

Formulation of OPF-based real-time operation

For the real-time operation, we utilize Augmented Relaxed Optimal Power Flow (AR-OPF) which presents a much better approximation compared to the other convex models [7]. This model allows us to have exact convex modeling of the non-linear power flow equations as proved in [7]. We refer to two-port equivalent Π model of the transmission circuit of Figure 1Figure 1 to model the grid constraints.

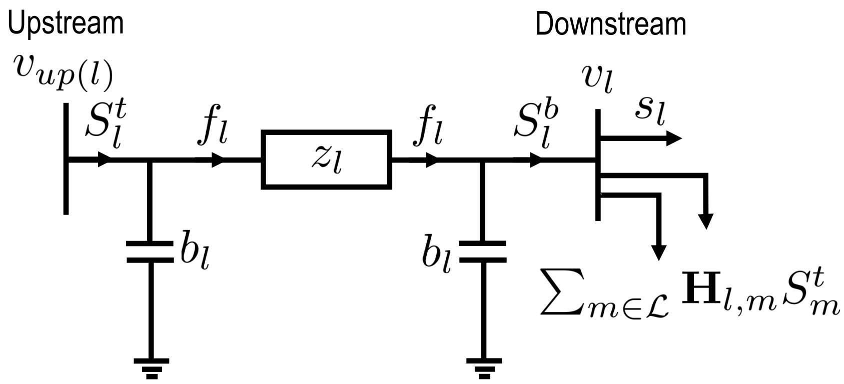

Figure 1. Illustration of the adopted nomenclature with respect to the classic two-port Π model of a transmission line.

In the following, we describe the real-time control problem for tracking the day-ahead dispatch plan. Its objective is to determine the set-point for the controllable resources (battery in this specific case) to track the dispatch plan while respecting the grid and resources constraints.

The problem is formulated as model predictive control (MPC) and its objective is to minimize the energy error incurred over a 5-min horizon length with control set points actuated at each 30 sec. The objective function is a multi-objective minimization of the weighted sum of grid losses and the dispatch energy error incurred at the GCP for the receding horizon interval. The problem is given as in Equation (1), and

$$\min_{\forall S,v,s^B} w_t \sum_{t\in T} \sum_{l\in L} r_l f_{lt} + w_e \sum_{t\in T} \epsilon_t^* \,, \forall l \in L, \forall t \in T \tag{1}$$

Where ϵ_t^* is the uncovered dispatch error at time t, r_l is the line resistance of line l, $f_{lt}$is an auxiliary upper bound variable related to the square of current magnitude causing losses at line l at time t, $w_{t,e}$ are weight coefficient associated to the power flow at the GCP and the dispatch error, respectively, $t \in T$ are the indices and set of time intervals, whereas and $l \in L$ are the indices and set of buses of lines connected upstream to the buses.

The problem is indeed subject to a set of constraints, which can be categorized in the following groups:

- power balance constraints;
- voltage constraints;
- current and power constraints;

- dispatch error constraints; and
- battery constraints.

The complete formulation of the problem is included in Deliverable D1.4.4c.

Formulation of COMMELEC real-time control

The COMMELEC control framework deployed in this specific experiment consists of three entities, namely 1) the grid agent (GA), 2) the battery agent (BA) and 3) the shadow agents (SA) [2], [3].

The advertisement computed by the BA consists of the following 3 entities:

1. PQ profile: the BA computes a set of all the possible (P, Q) points that can be implemented by the battery. This set is computed using both measurements of the internal state of the battery, including SoC and DC voltage, and of the grid state, such as AC voltage and frequency.
2. Cost function: an appropriate cost value is chosen for any (P, Q) point within the PQ profile, in order to achieve a target SoC of 50%.
3. Belief function: The battery is considered as a fully controllable resource, meaning that it can implement any point that is requested by the GA within its PQ profile. Therefore, the belief function is a singleton.

A SA is placed on every node that cannot be controlled by the GA. This includes all nodes with loads and PVs. The purpose of the SAs is to forecast short-term bounds of the power prosumption of their respective node. To do this, the SAs employ both real-time state estimation and historical measurements. The power bounds are advertised to the GA in the form of a belief function. The purpose of this forecast is to ensure that the power setpoints computed by the GA in a given cycle will not steer the grid in an infeasible state until the next computation cycle.

The goal of the GA is to optimize an aggregated sum of various objectives in real-time (up to 100ms). The objectives used are the following:

1. Track the day-ahead dispatch plan

$$J_{P_s}(\boldsymbol{x}) = \frac{(P_s(\boldsymbol{x}) - P_t)^2}{2|P_s - P_t|_{\max}} \tag{2}$$

where $\boldsymbol{x}$ is the set of nodal power injections, P_s is the active power at the slack bus, P_t is the tracking value and $|P_s - P_t|_{max}$ is a user defined value, that defines the maximum desired deviation from the dispatch plan.

2. Minimize the voltage deviations from the nominal value

$$J_{V_k}(\boldsymbol{x}) = \frac{(V_k(\boldsymbol{x}) - V_{nom})^2}{\beta^2 - (V_k(\boldsymbol{x}) - V_{nom})^2} \tag{3}$$

Where V_k is the voltage at node k, V_{nom} is the nominal voltage and β is a hard voltage constraint which is 5% of the nominal value. This cost function tends to infinity as voltage V_k tends to the value $V_{nom} \pm \beta$.

3. Keep the line currents below the respective ampacities

$$J_{I_l}(\boldsymbol{x}) = \frac{I_l^2(\boldsymbol{x})}{\left(I_l^{\max}\right)^2 - I_l^2(\boldsymbol{x})} \tag{4}$$

where I_l is the current and I_l^{max} the ampacity of line l respectively. Similarly to the voltage cost function, this cost tends to infinity as I_l approaches I_l^{max}.

4. Achieve a target state of charge (SoC) for the battery

$$C_b(P, Q) = |\Delta SoC| \frac{P^2}{4S} - \frac{\Delta SoC}{2} P + a_Q \frac{Q^2}{2S} \tag{5}$$

where (P, Q) are the active and reactive power of the battery, S is its rated power and $|\Delta SOC|$ is the difference between its SoC and the target value (50% in our experiments). This function is designed in such a way that the charging of the battery is penalized if its SoC is above the target value, while the discharging is penalized otherwise. The purpose of third term of the objective, with a_Q a small positive constant, is to limit the internal losses of the power electronic converter that interfaces the battery with the grid.

Finally, the total aggregated objective that needs to be minimized by the GA is the following:

$$C_t(\boldsymbol{x}) = w_b C_b(P,Q) + w_{P_s} J_{P_s}(\boldsymbol{x}) + w_{Q_s} J_{Q_s}(\boldsymbol{x}) + \frac{1}{K}\sum_{k=1}^{K} w_{V_k} J_{V_k}(\boldsymbol{x}) + \frac{1}{L}\sum_{l=1}^{L} w_{I_l} J_{I_l}(\boldsymbol{x}) \tag{6}$$

where K is the number of buses, L is the number of lines and the weights $w_b, w_{P_s}, w_{Q_s}, w_{V_k}, w_{I_l}$ are computed according to our new method.

To optimize these objectives, the GA uses a gradient descent based algorithm. At each computation cycle it receives 1) an advertisement of the internal state of the battery by the BA, 2) short-term power forecasts by the SAs and 3) real-time estimation of the grid state. Then, it performs one step of gradient descent using a linearization of the power flow equations around the current state to estimate the gradient of the objectives. Since the battery is the only controllable resource of the system, we only need to compute the new power setpoint $\widehat{\boldsymbol{x}_b} = (\hat{P}, \hat{Q})$ for it:

$$\widehat{\boldsymbol{x}_b} = \Pr_A\left\{\boldsymbol{x}_{0,b} - s\nabla_{\boldsymbol{x}} C_t(\boldsymbol{x})|_{\boldsymbol{x}=\boldsymbol{x}_0}\right\} \tag{7}$$

where $\boldsymbol{x}_0$ is the current set of setpoints, s is the gradient descent step size and $\Pr_A\{\}$is the Euclidean projection to the PQ profile A of the battery.

An iterative algorithm is also used to compute the gradient descent step s that yields the minimum total cost within the battery capabilities in a given cycle, in order to improve the performance of the real-time optimization. As a final step of the algorithm, the belief functions of the SAs are also employed, to ensure that the step size chosen will not steer the grid to an infeasible state until the next computation cycle.

Validation and performance assessment

The medium voltage (MV) distribution grid hosting the full-scale field validation is located in the municipality of Aigle, Vaud, Switzerland and is operated by the local distribution grid operator Romande-Energie. It has a nominal voltage and power level are 21 kV and 20 MVA respectively. A detailed description of the technical characteristics of the controllable utility-scale 1.5 MW/2.5 MWh BESS and of the MV grid is included in Deliverable D1.4.4c.

An example of validation of the proposed grid-aware OPF-based control framework was carried out on Friday the 13th of March 2021, and the results reported herein below are adapted from Deliverable D1.4.4c. The real-time dispatch tracking using the OPF based grid-aware MPC is shown in Figure 2, where positive power values mean power production of power from the slack/battery and negative power mean power consumption. It shows the dispatch plan in black, the tracked power at the GCP in shaded grey and the power at the slack without MPC in red. As it can be observed that the MPC helps to track the dispatch plan during the day with its power compensation respecting the constraints of the grid and its own capacity. From Figure 3, it can be seen that at one point when the battery saturated (the upper SoC limit was reached), it stops charging, then after few time steps, it starts tracking again as the dispatch error results in discharging of the battery. The saturation of the battery might be due to imperfect prediction of the day-ahead scenarios and can be improved by more historical data into the forecasting tool.

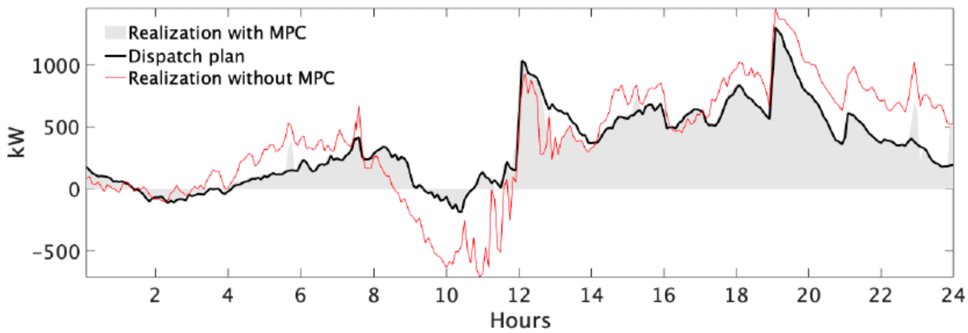

Figure 2. Dispatch plan and slack power with and without the OPF-based MPC BESS control.

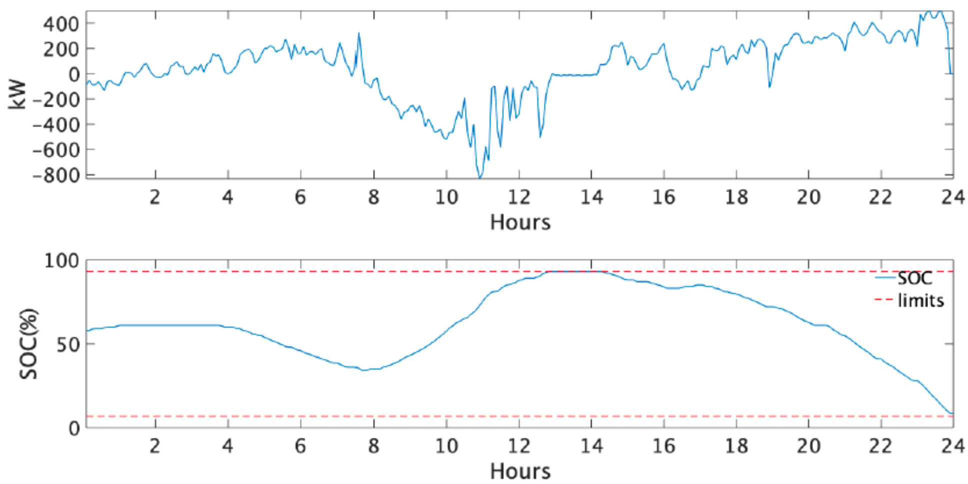

Figure 3. Measured BESS active power for tracking the dispatch plan with the OPF-based MPC BESS control and SoC.

An example of validation of the COMMELEC framework was carried out on Friday the 19th of March 2021, and the results reported herein below are adapted from Deliverable D1.2.3c. Figure 4 shows the dispatch plan and the measured slack power with the BESS control contribution, as well as in the case the COMMELEC-based BESS control would have not been activated. Figure 5 reports the BESS active power and the evolution of the SoC. As for the previous experimental validation, in both Figure 4 and Figure 5, positive power is production of power from the slack/battery and negative power is consumption of power.

It can be noticed that between 14:20 and 17:40 the tracking of the dispatch plan was missed because the SoC of the battery reached its upper limit of 90%, as shown by Figure 5. The dispatch plan required the slack to produce more power during this period, but the battery could not charge any further. The maximum tracking difference defined in the slack cost function (as presented above) is chosen to be 100kW. COMMELEC is expected to track the dispatch plan within the desired bound, assuming that the battery has enough controllability to do so. However, when SoC>90%, the battery is restricted from consuming power, so COMMELEC loses tracking.

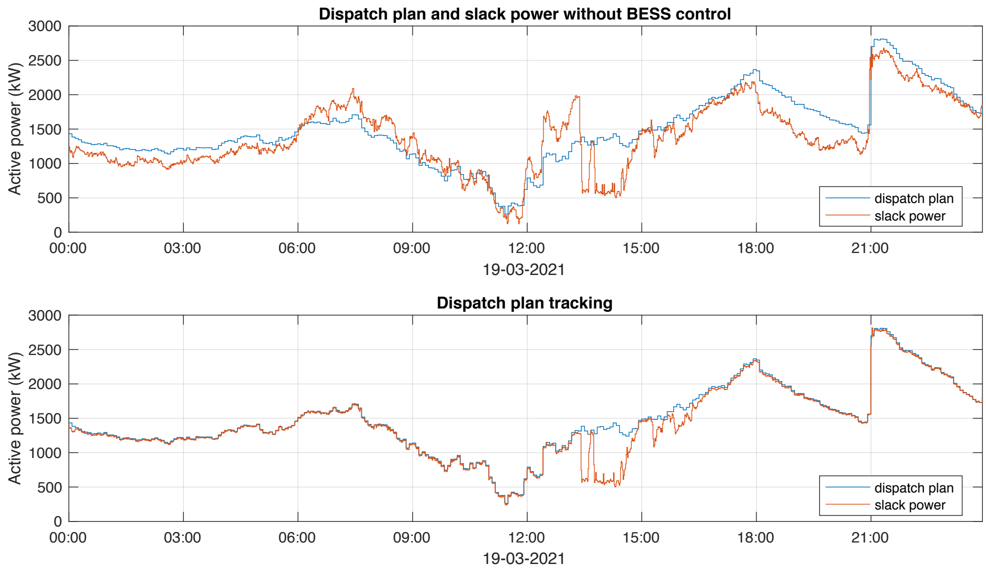

Figure 4. Dispatch plan and slack power without Commelec BESS control (upper plot) and with COMMELEC BESS control (lower plot).

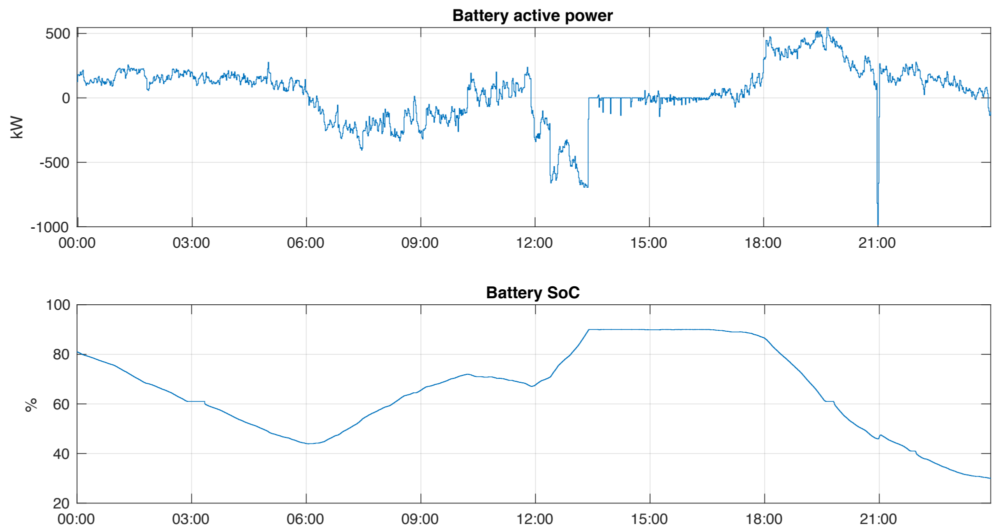

Figure 5. Measured active power and SoC of the battery in case of COMMELEC control.

To provide a comparison of the two controllers, we include in Figure 6 the cumulative distribution function (CDF) of the dispatching errors in the uncontrolled case and in the case of the BESS control. In particular, the blue lines show the case of the MPC BESS control, while the red lines refer to the COMMELEC case. For the sake of a fair comparison, for both the tested days the time windows characterized by the saturation of the BESS have been excluded by the computation. In general, one has to note that COMMELEC has the joint objective to achieve a target SoC, which is independent of the dispatch plan, meaning that when the SoC is close to the limit, the tracking performance may be reduced. However, it can be noticed that in both the cases with the active BESS control, the errors are dramatically more contained than in the uncontrolled cases, confirming the high performance in tracking the dispatch plan with both the proposed control frameworks.

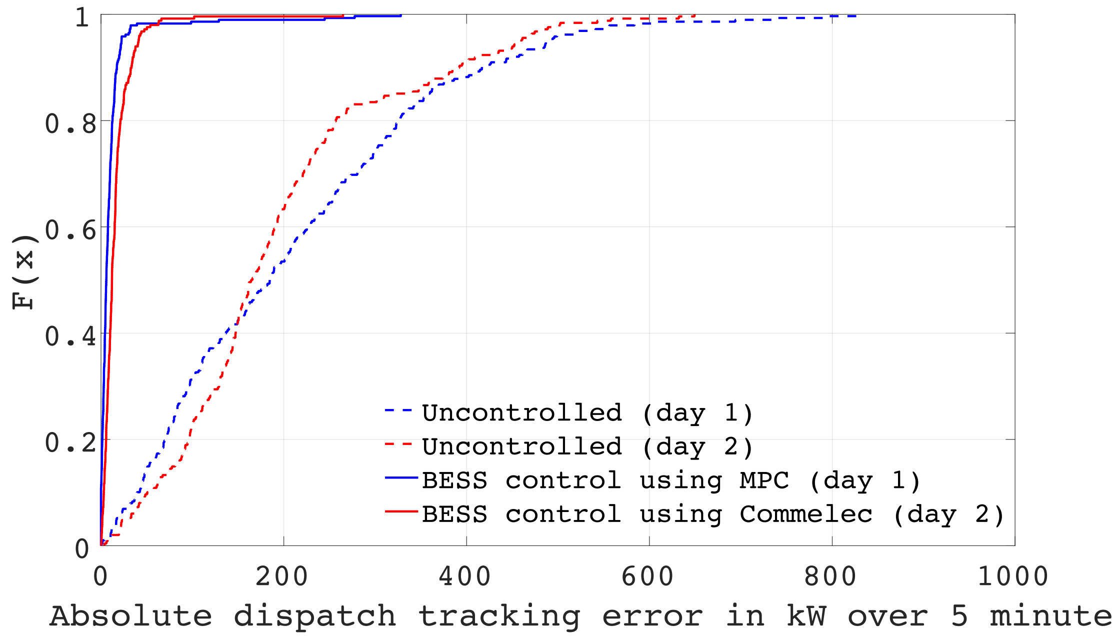

Figure 6. CDF of dispatch tracking absolute difference with and without MPC BESS control (day 1) and with and without COMMELEC BESS control (day 2).

1.5. Regulatory and legal barriers for implementation

There is not any regulatory or legal barrier associated to the implementation of the proposed method per se.

2. Achievement of deliverable:

2.1. Date

March 2021

2.2. Demonstration of the deliverable

This deliverable has been achieved through:

- the development and the validation of a computationally-efficient intra-day OPF-based real-time control of the controllable resources to track the dispatch plan;
- the development and the validation of a Commelec-based control system to track the dispatch in real-time, while ensuring a feasible state for the grid.

3. Impact

This deliverable focuses on the comparative analysis of two control frameworks, the Commelec and OPF-based control. While those frameworks are described more exhaustively in deliverables D1.2.2a, D1.2.3b and D1.2.3c for the former and D1.3.4c and D1.4.4c for the latter, such analysis enable the definition of the use cases that the one or the other solutions should be preferred. Even more, our KPI-based method, allows the DSOs to opt for a more tailored to their own priorities' selection of the solution to use.

4. Scientific publications

[1] R. K. Gupta, F. Sossan and M. Paolone, "Grid-aware Distributed Model Predictive Control of Heterogeneous Resources in a Distribution Network: Theory and Experimental Validation," in IEEE Transactions on Energy Conversion, doi: 10.1109/TEC.2020.3015271.

[2] A. Bernstein, L. Reyes-Chamorro, J. Le Boudec, M. Paolone, "A composable method for real-time control of active distribution networks with explicit power setpoints. Part I: Framework", Electric Power Systems Research, vol. 125, 2015, pp 254-264, ISSN 0378-7796, doi: 10.1016/j.epsr.2015.03.023.

[3] L. Reyes-Chamorro, A. Bernstein, J. Le Boudec, M. Paolone, "A composable method for real-time control of active distribution networks with explicit power setpoints. Part II: Implementation and validation", Electric Power Systems Research, vol. 125, 2015, pp 265-280, ISSN 0378-7796, doi: 10.1016/j.epsr.2015.03.022.

[4] E. Stai, L. Reyes-Chamorro, F. Sossan, J. Le Boudec and M. Paolone, "Dispatching Stochastic Heterogeneous Resources Accounting for Grid and Battery Losses," in IEEE Transactions on Smart Grid, vol. 9, no. 6, pp. 6522-6539, Nov. 2018, doi: 10.1109/TSG.2017.2715162.

[5] E. Namor, F. Sossan, R. Cherkaoui, and M. Paolone, "Control of battery storage systems for the simultaneous provision of multiple services," IEEE Transactions on Smart Grid, vol. 10, no. 3, pp. 2799–2808, 2019.

[6] F. Sossan, E. Namor, R. Cherkaoui, and M. Paolone, "Achieving the dispatchabil-ity of distribution feeders through prosumers data driven forecasting and modelpredictive control of electrochemical storage,"IEEE Transactions on SustainableEnergy, vol. 7, no. 4, pp. 1762–1777, Oct 2016.

[7] M. Nick, R. Cherkaoui, J. L. Boudec and M. Paolone, "An Exact Convex Formulation of the Optimal Power Flow in Radial Distribution Networks Including Transverse Components," in IEEE Transactions on Automatic Control, vol. 63, no. 3, pp. 682-697, March 2018, doi: 10.1109/TAC.2017.2722100.