Integration and Operation of Utility-Scale Battery Energy Storage Systems: the EPFL's Experience[⋆]

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Abstract: The experimental integration and control of an utility-scale 720 kVA/500 kWh battery energy storage system (BESS) in the medium voltage network of the Swiss Federal Institute of Technology of Lausanne (EPFL) to achieve dispatched-by-design operation of a heterogeneous group of prosumers is discussed. The motivation for such an objective is twofold: *(i)* dispatching the operation of prosumers reduces the uncertainty associated with their operation, thus the amount of regulating power required to operate power systems, a key issue when considering large-scale integration of renewable energy; *(ii)*, the *dispatch plan* is built in order to satisfy a given design objective for the local network, such as congestion management, load levelling or economic optimization of the prosumers operation according to the electricity price. The proposed framework relies on a minimally invasive monitoring infrastructure, trying to maximize the effort on the use of data analytics to identify prediction models of the consumer behavior and BESS voltage dynamics for an efficient control policy.

Keywords: Electric Power Systems, Load dispatching, Prosumers forecasting, Modelling, Model Predictive Control, Utility-Scale Battery Energy Storage Systems.

1. INTRODUCTION

Increasing electricity storage capacity is a key factor to achieve a larger proportion of production from stochastic renewable resources, allowing to restore an adequate level of controllability after the displacement of conventional controllable generation, as an alternative to large-scale deployment of fast ramping generating units, see e.g. Troy and O'Malley (2010). Electricity can be stored in two ways: either indirectly, by shifting the consumption of so-called flexible demand, or directly, by implementing storage technologies, like batteries, power to gas and hydro-pumping. The former solution refers to achieving the non-disruptive controllability of a large number of loads (normally thermostatically controlled loads, such as heat pumps, electric radiator, water heaters and refrigerator units), exploiting the fact that their thermal mass allows to temporarily defer or anticipate the consumption without a notable degradation of the primary service they are providing to the consumers. As a matter of fact, solutions based on demand side management struggle to emerge because *(i)* harvesting flexibility from a large number of demand side resources (DSRs) requires an extended monitoring and control infrastructure, until the very low end of LV distribution networks, and *(ii)* the energy storage capacity of single DSRs is low: operators might prefer alternative storage technologies with larger capacity, which can be used to provide a wider range of services, from primary frequency reserve to secondary and tertiary regulating power, more efficiently. On the other hand, the declining cost and high level of maturity make of battery-based energy storage a prompt technology to implement *smarter* grid technologies with industrial-grade reliability. Already at the current stage, going for the installation of battery energy storage systems (BESSs) might be an economically viable alternative for DSOs to traditional grid upgrades, in the case of, e.g., network congestions management and peak shaving, while enabling innovative kinds of ancillary services, such as self-consumption or dispatchability.

Sossan et al. (2016) described a process to dispatch on a 5 minutes basis the operation of a group of prosumers by

Fig. 1. The 720kVA/500 kWh grid-connected BESS installed at the Swiss Federal Institute of Technology of Lausanne (EPFL) used to validate the "dispatchable feeder" concept.

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using an utility-scale 720 kVA/500 kWh BESS as a controllable element, while relying on a minimally pervasive monitoring infrastructure. The control process has been experimentally demonstrated on a MV feeder of the EPFL campus (called *dispatchable feeder*) and operates on a daily basis to dispatch the operation of a group of buildings with a considerable proportion of distributed generation from rooftop PV installations. From this standpoint, in this paper, we summarize the *dispatchable feeder* concept with the objectives of showing how it can be achieved in practice, developing the author's vision for large-scale integration of utility-scale BESSs to achieve dispatched-by-design operation, and discussing challenges related to their operation and control.

The paper is organized as follows. Section II explains the dispatchable feeder configuration, with particular emphasis on the rationale behind it and requirements. Section III describes the BESS, its integration in the EPFL medium voltage (MV) network and how it is operated. Section IV shows the experimental results of the dispatchable feeder.

2. THE DISPATCHABLE FEEDER CONCEPT

2.1 General Overview

Sossan et al. (2016) described a framework to dispatch the operation of a generic group of prosumers according to a profile, said *dispatch plan* and determined the day before operation, thanks to the integration of a prosumption forecasting tool and controlling the power injections of an utility-scale BESS. The control framework, which currently operates on a daily basis to dispatch the operation of a MV feeder in the EPFL campus (see Figure 2 and Section 3), is organized according to a two layers structure:

- **Day-ahead**: this phase takes place 1 hour before the beginning of the day of operation, at time 23 UTC each day. Historical measurements of the aggregated power consumption of the prosumers are used to compute the consumption forecast profile for the next day of operation using vector autoregression, as described in 2.3. The forecasted consumption profile is therefore used to determine the *dispatch plan*, that is the sequence of discretized average power consumption values at 5 minutes resolution that the *dispatchable feeder* is committed to follow during the next day. At the beginning of the day of operation, time 00 UTC, the dispatch plan comes into effect and the intra-day/real-time operation begins.
- **Intra-day/real-time**: the objective of this phase is to control the real power injection of the BESS in order that the aggregated average power consumption in each 5-minute interval matches the respective value in the *dispatch plan*. It is formulated as a *trajectory tracking problem* and accomplished with receding horizon MPC which, with respect to conventional feedback control loop, allows accounting for BESS operational constraints and efficiently implementing ultra-short-term forecasting of the consumption.

2.2 Motivations

The rationale behind the dispatchable feeder concept is twofold: *i)* at local level, the *dispatch plan* is built in order to achieve a given design control objective, such as implementing congestion management, peak shaving, self-consumption of locally generated electricity, or minimizing the cost of operation according to the electricity price; *ii)*, at system level, dispatching the operation of a group of prosumers reduces the uncertainty associated to variable consumption and stochastic generation during grid operation. Extending this concept to a larger scale (e.g., dispatchable district, city or region) would allow to drastically reduce the need of intra-day regulating power, the excess of which can be allocated to compensate for the variability of a larger proportion of production from renewable generation, finally allowing to increase its penetration. It is noteworthy that regulating power during nowadays power system operation is normally procured in intra-day or real-time electricity markets to restore an adequate amount of system reserve for primary frequency control. In this sense, we say that the dispatchable feeder concept is a reverse bottom-up solution for the problem of regulating power procurement because the consumption is *dispatched by design*.

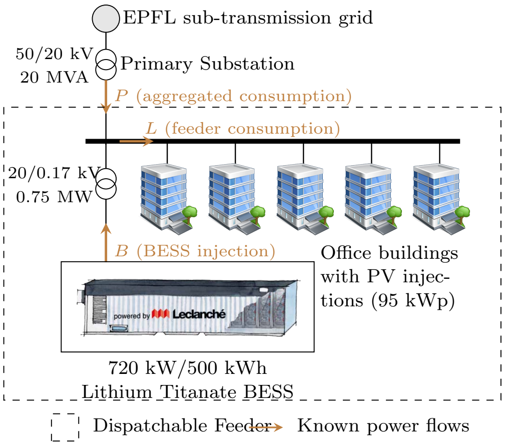

Fig. 2. The dispatchable feeder configuration (Sossan et al. (2016)).

We note that alternative decentralized control strategies for provision of regulating power and ancillary services to the grid, such as virtual power plants or demand response (e.g. Zugno et al. (2012); Mhanna et al. (2016)), normally relies on the need of aggregating in real-time a large number of resources, a challenging operation if considering that it requires hard real-time computation and relies on communication. In the dispatchable feeder concept, the complexity is entirely hidden behind the commitment of the operator to control the BESS injection in order to track the *dispatch plan*. Indeed, communication requirements are limited to advertise the *dispatch plan* to the TSO (transmission system operator)/load balance responsible, without the need of further real-time coordination mechanisms[1]. Additional noteworthy aspects of the dispatchable feeder concept are:

- it relies on a minimally pervasive monitoring and control infrastructure, as exemplified by the EPFL experimental setup (see Section 3);

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[1] Contingency situations (e.g., failure of the dispatch control strategies) might require coordination mechanisms: this will be the focus of future investigations

- the control action is performed by a dedicated BESS[2], nowadays a mature technology with industrial-grade reliability and reduced level of aging thanks to existing electrochemical designs, that can be easily integrated in already existing DSOs' facilities, like in primary substations;
- it can seamless operate in the current vertically operated power systems and markets. Nevertheless, a rewarding mechanism to remunerate the ability of promoting and achieving dispatched-by-design operation should be identified.

2.3 Day-ahead operation: Prosumption Forecasting

Although being a well established practice at high aggregation levels with a blooming of applied techniques, forecast of the electricity demand for low levels of aggregation and with the presence of distribution generation has been a relatively unexplored topic and has become to prominence only in the recent literature in connection with local power systems control strategies, like for demand response, energy balancing strategies, self-consumption and microgrid operation. Consumption at such low level of aggregation is characterized by large volatility due to the predominant stochastic behavior of individual loads (loads insertions, inrush of induction generators, like pumps or elevators) and distributed generation (typically, PV plants) that, due to proximity of the installations, lacks of spatial smoothing effect.

As exhaustively described in Sossan et al. (2016), prosumption forecasts for the next day of operation are computed using a non-parametric method based on vector auto-regression. In a nutshell, it consists in considering historical daily sequences of the buildings prosumption at 5 minutes resolution and selecting those which are *similar* to the day for which the forecast is to compute. The similarity criterion is given by evaluating the day-of-the-year characteristics (holiday/working day/weekend) and the cumulative global horizontal irradiance content by incorporating numerical weather prediction. Once the selected profiles are available, the distribution of the components are used as empirical distribution of the realizations. For each time interval $i = 1, \dots, 288$ at 5 minutes resolution of the next day of operation, the point prediction, denoted by $\widehat{L}_i$, is given by the expected value of the distribution, while the estimated maximum and minimum realization are denoted by $l_i^{\uparrow}$ and $l_i^{\downarrow}$.

It is noteworthy that local consumption forecasting comes to play only in the definition of the *dispatch plan* and if a better performing forecasting tool is available, it can be plugged in the day-ahead strategy without requiring modifications to the control process.

2.4 Day-ahead operation: Dispatch Plan Computation

At a first glance, the *dispatch plan* should be given by the sequence of prosumption point predictions. However, we add a second component, called offset profile which serves the important task of restoring a suitable BESS state of energy (SOE) such that enough charge is available during the day of operation to compensate for the mismatch between actual prosumption realization and dispatch plan. In other words, during intra-day operation, the BESS power flow is controlled to compensate for the mismatch between the *dispatch plan* and the actual feeder consumption: in presence of a biased forecast error (i.e., the accumulated error is different than zero), the BESS SOC at the end of the current day of operation might be close to the limits, therefore with reduced level of flexibility, and indeed needs to be adjusted before the beginning of the next day of operation. As also argued in Abu Abdullah et al. (2015), including this contribution directly into the dispatch plan allows achieving continuous time operation without the need of putting in place any separate charge/discharge mechanisms or assuming that the BESS starts the day at 50% (see e.g. Teng et al. (2013); Marinelli et al. (2014)).

The *dispatch plan* value $\widehat{P}_i$ is then given by the algebraic sum between the prosumption point prediction and offset value F_i^o:

$$\widehat{P}_i = \widehat{L}_i - F_i^o \qquad i = 1, \dots, 288. \tag{1}$$

The offset profile is determined by a robust optimization problem which enforces the BESS SOE being in the allowed range $(\mathrm{SOC}_{\min}, \mathrm{SOC}_{\max})$ in the case of both lowest and highest power prosumption realizations according to the procedure summarized hereafter. The BESS compensation action is given by the difference between the dispatch plan and stochastic prosumption realization l_i:

$$\widehat{B}_i = F_i^o + \widehat{L}_i - l_i, i = 1, \dots, 288 \tag{2}$$

The smallest and largest BESS power flows are:

$$\inf\left\{\widehat{B}_i\right\} = F_i^o + \widehat{L}_i - \sup_{l_i \in \mathscr{L}_i}\{l_i\} = F_i^o + L_i^{\downarrow} \tag{3}$$

$$\sup\left\{\widehat{B}_i\right\} = F_i^o + \widehat{L}_i - \inf_{l_i \in \mathscr{L}_i}\{l_i\} = F_i^o + L_i^{\uparrow}. \tag{4}$$

The smallest and largest possible value of BESS SOE are modeled by propagating the previous two worst case scenarios in a discretized integral model:

$$\mathrm{SOE}_{i+1}^{\downarrow} = \mathrm{SOE}_i^{\downarrow} + \beta^+ \left[F_i^o + L_i^{\downarrow}\right]^+ + \beta^- \left[F_i^o + L_i^{\downarrow}\right]^- \tag{5}$$

$$\mathrm{SOE}_{i+1}^{\uparrow} = \mathrm{SOE}_i^{\uparrow} + \beta^+ \left[F_i^o + L_i^{\uparrow}\right]^+ + \beta^- \left[F_i^o + L_i^{\uparrow}\right]^- \tag{6}$$

where the operator $[\cdot]^+$ denotes the positive part of the argument and vice-versa, and β^+ and β^- are the asymmetric charging and discharging efficiency. Finally, the offset profile $\boldsymbol{F}^o = [F_0^o, \dots, F_{N-1}^o]$ is:

$$\boldsymbol{F}^o = \underset{\boldsymbol{F} \in \mathbb{R}^N}{\arg\min} \left\{\sum_{i=1}^{N} F_i^2\right\} \tag{7}$$

subject to:

$$\text{Eq.(5) and Eq.(6)} \tag{8}$$

$$\mathrm{SOE}_{i+1}^{\downarrow} \geq \mathrm{SOE}_{\min}, \tag{9}$$

$$\mathrm{SOE}_{i+1}^{\uparrow} \leq \mathrm{SOE}_{\max} \tag{10}$$

$$F_i + L_i^{\downarrow} \geq B_{\min} \tag{11}$$

$$F_i + L_i^{\uparrow} \leq B_{\max} \tag{12}$$

$$\widehat{P}_i \leq P_{\max}, \tag{13}$$

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[2] Extension to multiple controllable elements (multiple storage units or smart buildings) is possible by applying, e.g., distributed model predictive control policies as in Costanzo et al. (2013)

for $i = 0, \dots, N-1$ and a given SOE_1 [3]. The inequality constraints in (11) and (12) are in order not to violate the BESS converter nominal power constraints, while (13) is for the dispatch plan to be equal or smaller than a threshold tunable by the operator to implement peak shaving at the GCP.

The optimization problem in (7)-(13) is nonconvex because the $[\cdot]$ operator. An equivalent convex formulation capable of managing the non-ideal BESS efficiency is proposed in Sossan et al. (2016). We note that the BESS sizing, which is indeed an important aspect because it impacts the amount of forecasting errors the dispatchable feeder can absorb, will be investigated in future works. An alternative formulation that achieves load levelling is proposed in Namor et al. (2016), and, hypothetically, formulation based on the minimization of the cost of the electricity, such as in Tascikaraoglu et al. (2014); Zamani et al. (2016), could be also considered.

2.5 Real-time operation: Dispatch Plan Tracking

The control objective during real-time operation is adjusting the real power injection of the converter by applying MPC such that the power flow at the GCP tracks the dispatch plan. MPC is applied in a shrinking horizon fashion once every 10 seconds interval, which is denoted by the index $k = 0, \dots, K-1$, where $K = 5760$ is the number of 10-second intervals in 24 hours.

At the beginning of each interval k, the prosumers aggregated power consumption and generation for the previous interval $k-1$, denoted as L_{k-1}, become known from real-time measurements. This, together with short-term point predictions of the prosumption is used to determine an estimate of the average prosumption in the 5 minutes interval. This quantity is subtracted from the respective value extracted the dispatch plan in order to determine the tracking error.

Finally, a convex optimization problem (fully detailed in Sossan et al. (2016)) is used to determine the BESS real power injection to minimize the tracking error while obeying to BESS voltage, current and SOC constraints. BESS operational constraints are embedded with to open-loop predictions elaborated with an equivalent circuit model of the cell stack identified from measurements. The optimization problem is repeated every 10 s in a shrinking horizon fashion with updated information. At each time interval, the control trajectory for the residual horizon is available, but only the first portion is used for actuation.

An example is sketched in Fig. 3, which depicts the situation at 20 seconds past midnight, where the first two prosumption measurements are available and the BESS real power set-point for the next 10 seconds time interval is to determine.

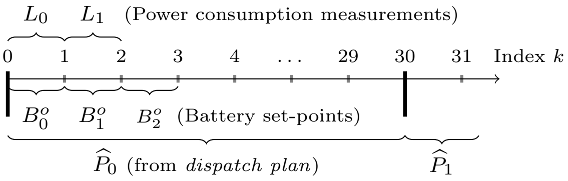

Fig. 3. The first thirty-one 10 seconds intervals of the day of operation. The situation sketches the situation at the beginning of the time interval 2.

3. EPFL EXPERIMENTAL SETUP

3.1 Battery Energy Storage System

The BESS installed at EPFL is a grid-connected 720 kVA-500 kWh unit. It consists in the battery (2.3 V 9000 cells, 9 parallel racks, voltage range on the DC bus 600-800 V), a three-phase DC/AC power converter and a 300 V/20 kV voltage transformer. The system is installed in a container, shown in Fig. 1, which is equipped with an air conditioning unit and fire extinguisher system. In normal operating conditions, auxiliaries are powered directly from the converter, using the energy stored in the battery. The installation is completely self-standing (two-wire system: power + communication line), therefore suitable as a plug-and-play system to be installed, e.g., by DSOs at primary/secondary substation level. For the *dispatchable feeder* application, the converter is used in the current source operating mode.

Battery electrochemical technology Battery cells are based on the lithium titanate technology which, in spite of having lower energy capacity than conventional lithium, it is rated for a significantly larger number of cycles, namely 20 thousand at 4C before reaching a capacity fading of 20%. This important characteristic makes of lithium titanate an ideal technology in terms of robustness for stationary BESS application, where the weight and size are not normally a practical concern: notably, the large number of cycles increases the longevity of the whole system (accounting one cycle for day, the expected time life is approximately 50 years, normally the life cycle of conventional power system components) without the need of implementing aging-aware control strategies for batteries, e.g. Haessig et al. (2015), which normally results in stiff and conservative control laws.

Interfaces for operation and control The system comes with two communication interfaces for control and operation: Modbus and Ethercat. The former enables communication with the proprietary battery management systems (BMS) to read electric parameters and BESS state (DC/AC voltage and current, errors, warning and dynamic power limitations) and send active/reactive power set-point with a refresh rate of approximately 500 ms, mostly suitable for energy management. The latter allows direct communication with the BESS power converter. It has deterministic reaction time, indeed suitable for grid real-time control, such as for support to primary frequency and voltage regulation. For the application described in this paper, we use Modbus.

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[3] Since the dispatch plan is computed one hour before operation, this quantity is known. It is estimated by using a persistent predictor, namely the SOE at midnight equals the one at 11PM.

3.2 Supervisory Control and Data Acquisition System

The SCADA system consists of three main components.

Data acquisition Measurements of the feeder aggregated power consumption (real and reactive, available from a PMU placed at the grid connection point and streamed over an Ethernet network using UDP according to the IEEE C37.118 standard) and from the BESS battery management system (real and reactive power, DC voltage and current, and BESS state) are acquired at 1 second resolution.

Data acquisition Data are stored in a time series database and used to compute prosumers consumption forecast.

Control computation The computation of the day-ahead and the intra-day procedures are implemented in Matlab on a Linux machine and scheduled as `cron` jobs. They are respectively scheduled at 23 and 24 UTC every day. Since all the involved optimization problems are convex, the computation is efficient and with guaranteed convergence (if the problem is feasible). Computed BESS set-points are communicated over Modbus.

3.3 Actuation of the real-time control strategy

A diagram showing the flow of operation necessary to operate the dispatchable feeder setup is shown in Fig. 4.

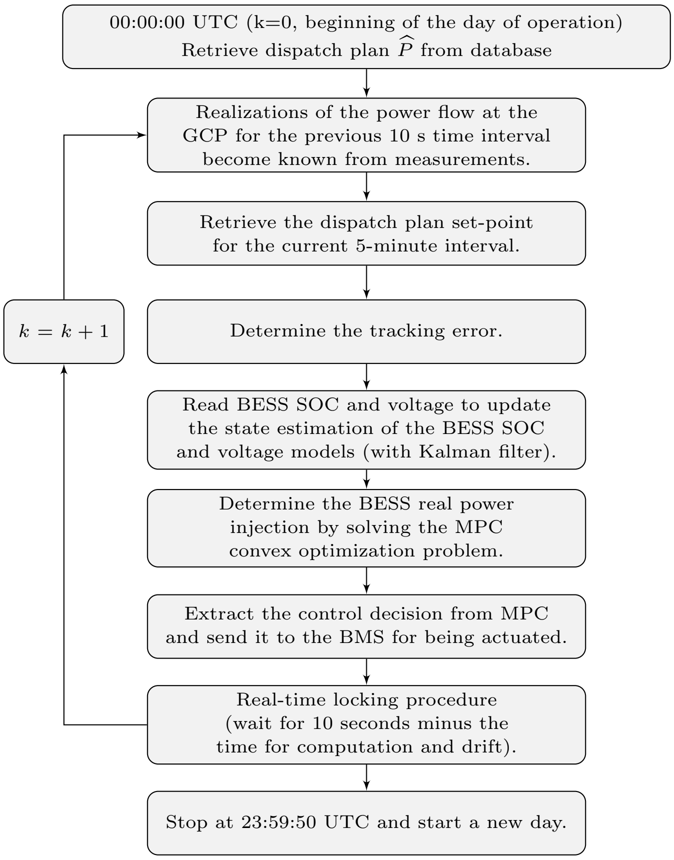

Fig. 4. Flow chart showing real-time operation during 24 hours.

4. EXPERIMENTAL RESULTS

4.1 Performance of Data-Driven Consumption Forecasting

Fig. 5 compares the prosumption scenarios and forecast produced by the discussed forecasting tool against the prosumption realization for a sample day of operation. The statistics for the reported situation are summarized in Table 1. The forecast error accumulated over the day is 235 kWh, approximately 20% of the total daily electricity consumption, while the average error is approximately 5% of the average prosumers consumption.

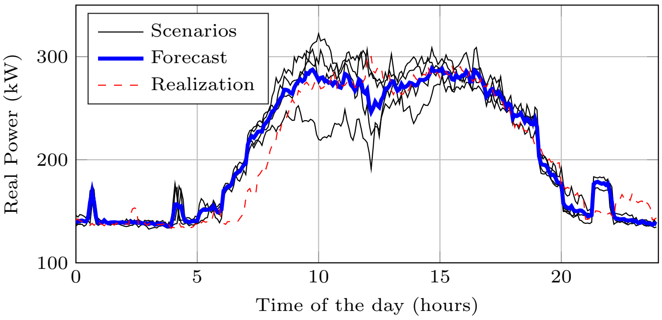

Fig. 5. Prosumption scenarios and forecast as computed by the forecasting tool compared with the realization.

Table 1. Statistics on the prosumers consumption and respective forecasting error

Parameter	Unit	Value
Average Consumption	kW	181.64
Total Consumption	kWh/day	4360
Average Error	kW	-9.05
RMS Error	kW	21.98
Total Error	kWh/day	235

4.2 Dispatchable feeder operation

The experimental operation of the dispatchable feeder for two sample days of operation are shown in Fig. 6 and 7 for January, 13 2016 and Fig. 8 and 9 for January, 14 2016. For each day, the first plot shows the *dispatch plan* $\widehat{P}$, which, recalling from the previous section, is 5 the minutes resolution prosumption profile that prosumers should follow during operation. In real-time, prosumers consumption L is different than the *dispatch plan* due to forecast errors. Finally, the BESS real power injection is controlled in order to correct the mismatch between the *dispatch plan* and aggregated power consumption profile. As a result, the composite power transit P (BESS contribution + consumption realization) matches the dispatch plan: the control objective is therefore accomplished. For each day, the second plot shows the BESS SOC and DC current.

It is worth noting by comparing Fig. 7 and 9 that the BESS starts the day of operation with different SOC levels. However, thanks to the offset profile, the *dispatch plan* is such to restore an adequate SOC to perform day-ahead operation. Therefore, it is not necessary to put in place a separate mechanism to charge the BESS, as this happens naturally with the *dispatch plan.*

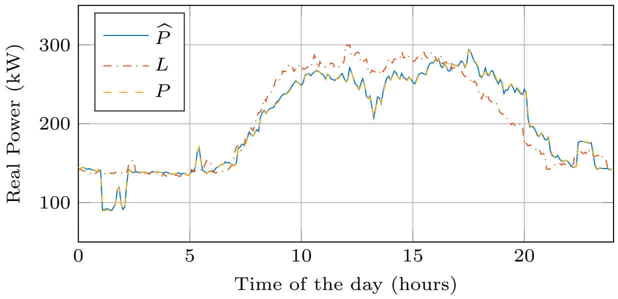

Fig. 6. Experimental dispatchable feeder operation on 13/01/2016.

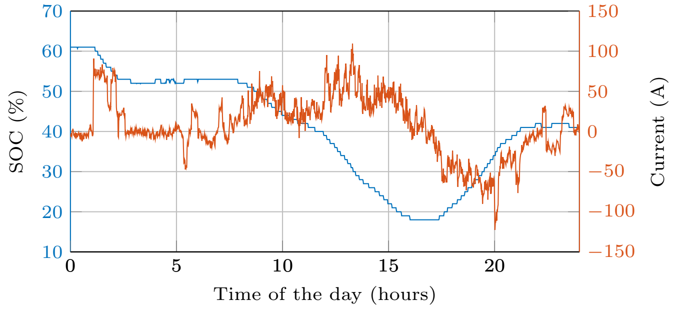

Fig. 7. Measured BESS SOC and DC current on 13/01/2016.

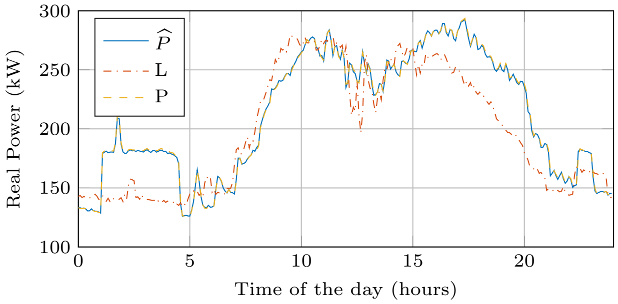

Fig. 8. Experimental dispatchable feeder operation on 14/01/2016.

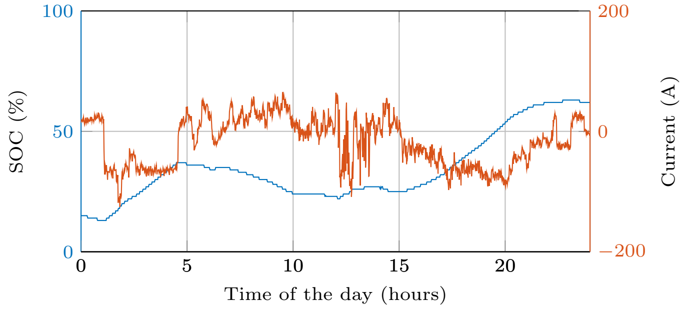

Fig. 9. Measured BESS SOC and DC current on 14/01/2016.

5. CONCLUSIONS AND PERSPECTIVES

An experimental framework to enable dispatched-by-design operation of unobserved prosumers by controlling an utility-scale battery energy storage systems was described. The system can dispatch the operation of a group of buildings with rooftop PV generation of the EPFL campus according to a profile at 5 minutes resolution established the day before the operation, and it is characterized by a minimal set of monitoring requirements.

In comparison with other control strategies for distributed storage, the proposed framework does not rely on real-time communication with an upper grid layer or an aggregator because all the complexity is masked behind the commitment of the operator to track the dispatch plan.

The future work is in the direction of developing a comparison of the cost of a dispatched-by-design architecture based on electrochemical storage and conventional regulating power procurement through electricity markets.

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