Load Leveling and Dispatchability of a Medium Voltage Active Feeder through Battery Energy Storage Systems: Formulation of the Control Problem and Experimental Validation

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Abstract— **This paper proposes and experimentally validates a control algorithm for a grid-connected battery energy storage system (BESS) to level the consumption of a group of prosumers and dispatch their aggregated operation. The control strategy is layered in a two-stage procedure: day-ahead and intra-day operation. During day-ahead operation, the *load leveled* power consumption profile is determined by applying a scenario-based robust optimization using historical measurements of the aggregated feeder power consumption. In the intra-day phase, the operation of the group of prosumers is dispatched according to the profile defined during the day-ahead stage, which becomes the so-called dispatch plan. The dispatch plan is tracked in real-time by properly adjusting the injections of the BESS using model predictive control (MPC). The proposed control process is experimentally validated using a 750 kW/500 kWh BESS.**

I. INTRODUCTION

Thanks to the decreasing cost of the electrochemical energy storage technologies, utility-scale battery energy storage systems (BESSs) are gaining interest as an alternative to grid reinforcement to tackle the challenges arising from increased levels of renewable generation, like primary and secondary frequency support and consumption peak shaving [1]–[3].

In [4], the authors demonstrated a control process to achieve the dispatchability on a 5-minute basis of a group of prosumers according to a *dispatch plan* determined the day before operation. In this paper, we augment the work proposed in [4] by implementing the ability of performing load leveling on a daily basis. In general, the load leveling of a portion of the grid consists in altering the aggregated power consumption so that it is as smooth as possible on a given period of time (daily operation, weekly, etc.). This application is similar to peak shaving unless for the fact that, while the latter aims at reducing the peak consumption, the former has the primary objective of flattening the consumption profile [5]. Load leveling is important for several reasons, both from a consumer and system perspective:

- reduced electricity cost, since customers are normally penalized for the peak consumption;
- at system level, it allows to reduce the peak demand, which is mostly served by expensive peaking power plants;
- reduced transmission losses [6];
- postpone the grid infrustructure upgrades.

The second objective of the proposed control strategy is to achieve the dispatchability of a portion of distribution network, namely controlling the aggregated power consumption profile according to a given plan thanks to properly controlling a BESS. If applied on a large scale, this concept leads to reduce the amount of regulating power required to operate the grid, a key factor to enable a larger proportion of production from renewables. Whereas methods for decentralized control of distributed energy and demand side resources normally require invasive monitoring and control infrastructures, in the proposed dispatchable feeder configuration we only rely on a BESS as a controllable element and the measurements of the aggregated power consumption of prosumers at the grid connection point (GCP).

We achieve dispatchability and load leveling of a generic group of prosumers with a two-stage procedure:

- day-ahead: the aggregated consumption profile of the group of prosumers is forecasted using historical data and used to compute a leveled *dispatch plan* with a scenario-based robust optimization;
- intra-day: the mismatch between dispatch plan and actual power consumption is compensated by controlling the BESS active power injection with model predictive control (MPC).

The rest of this paper is structured as follows: Section II describes the methods applied for the formulation of the day-ahead load leveling problem and intra-day dispatch operation. Section III describes the experimental facility used to validate the proposed control strategy. Section IV presents and discusses the results from the experimental validation. Finally, Section V summarizes the outcomes of this work and proposes the perspectives.

II. METHODS

A. Problem statement

We consider a group of prosumers, for which we would like to smooth the consumption profile (load leveling) and dispatch their operation. As anticipated, the problem is formulated according to a two-stage procedure: day-ahead and intra-day phase. In the day-ahead stage, the objective is to determine the *dispatch plan*, namely the power consumption profile that the group prosumers is willing to follow during operation. The *dispatch plan* is built as the sum of the forecasted power consumption profile, obtained through data-driven forecasting, and an *offset profile*. This latter quantity, which is obtained by solving a convex optimization problem, has the objective of generating a *dispatch plan* with minimum variance, namely with minimum variation with respect to its average value such that, during operation, the BESS will charge (discharge) when the load profile exceeds (is below) the levelled profile and viceversa.

The intra-day operation consist in controlling the BESS active power injection in order to track the *dispatch plan*, namely compensating for deviations between the dispatch plan and actual consumption, which are likely to differ due to the offset profile and to forecasting errors. This is accomplished using MPC, as illustrated in section II-C.

B. Day-ahead problem

The objective is to build the *dispatch plan*, namely the power consumption profile that the feeder should follow during operation, the day after. The *dispatch plan* $\widehat{P}$ is defined as the sequence of $N = 288$ (i.e., the number of 5-minute intervals in 24 hours) average power consumption values for the incoming day. The feeder *dispatch plan* is composed by the sum of the prosumers forecasted consumption profile $\widehat{L}_t$ and the *offset profile* F_t:

$$\widehat{P}_t = \widehat{L}_t + F_t \qquad t = 1, \dots, N \tag{1}$$

which are determined as detailed in the next two paragraphs.

1) Prosumers data-driven forecasting: The prosumers forecasted consumption profile, denoted by $\widehat{L}$, is produced through a nonparametric black-box method based on vector auto-regression. We assume that D daily sequences of 5 minutes average power consumption measurements are known from historical data: these are denoted by $\mathscr{L}^d \in \mathbb{R}^N, \quad d = 0, \dots, D-1$. The day for which the forecast profile is to compute is said target day and is identified by d^*. At first, a set Ω' of indexes d that are representative scenarios of the target day is determined. This is accomplished according to the following fuzzy rules:

IF:
d^* is a public holiday,
THEN:
Ω' contains the indexes which refer to public holidays;
ELSE:
Ω' contains indexes which refer to working days and with same weekday as d^* (Sunday, Monday,...);

Finally, we create the set Ω which contains the first p elements in Ω' with day of year closest to the target day. The sequence of point predictions for the day d^*, denoted by $\widehat{L}_0, \dots, \widehat{L}_{N-1}$, is obtained by equally averaging the daily sequences identified by the indexes contained in Ω:

$$\widehat{L}_t = \frac{1}{|\Omega|} \sum_{d \in \Omega} \mathscr{L}_t^d \qquad t = 1, \dots, N, \tag{2}$$

where $\mathscr{L}_t^d$ denotes the value at the discrete time interval t of the scenario $\mathscr{L}^d$.

2) Dispatch plan offset profile: The objectives of the *offset profile* are

- altering the dispatch plan so that it is with mininum variance;
- making sure that an adequate level of charge is available in the BESS to achieve dispatchability during intra-day operation.

We define the average daily power consumption value as:

$$\widehat{L}_{avg} = \frac{1}{N} \sum_{t=1}^{N} \widehat{L}_t. \tag{3}$$

The offset profile $\boldsymbol{F}^o = \left(F_1^o, \dots, F_N^o\right)$ is determined by a constrained optimization problem that minimizes the movement of the forecasted consumption sequence $\widehat{L}_1, \dots, \widehat{L}_N$ around its average daily value $\widehat{L}_{avg}$. The optimization problem constraints are:

- the dispatch plan should respect the nominal rating values of the MV substation transformer at the grid connection point (GCP);
- the BESS apparent power injections should respect the BESS converter nominal power;
- the BESS state of energy (SOE) should be within its nominal limits.

The BESS constraints are built by adopting a robust optimization approach: each forecast consumption scenario (as defined in Section II-B.1) is implemented in the constraints to model the fact that it may be actually realized during real-time operation. This is with the objective of ensuring that enough energy and power capacity are available in the BESS to accomplish the dispatchability, therefore enforcing the feasibility of the intra-day control objective. The optimization problem is formulated as:

$$\boldsymbol{F}^o = \underset{\boldsymbol{F} \in \mathbb{R}^N}{\arg\min} \sum_{t=1}^{N} \left(\left(\widehat{L}_t - \widehat{L}_{avg}\right) - F_t\right)^2 \tag{4}$$

subject to:

$$\widehat{P}_t = \widehat{L}_t + F_t \tag{5}$$

$$\widehat{B}_t^d = \widehat{P}_t - \mathscr{L}_t^d \tag{6}$$

$$\left|\widehat{B}_t^d\right| < B_{\text{max}} \tag{7}$$

$$\text{SOE}_t^d = \text{SOE}_0 + \eta \frac{\Delta T}{C_{nom}} \sum_{j=1}^{t} \widehat{B}_j^d \tag{8}$$

$$0 < \text{SOE}_t^d < 1, \tag{9}$$

for $t = 1, \dots, N$ and $d = 1, \dots, p$. The equality constraint (5) sets the relationship between *dispatch plan*, prosumers consumption forecast and *offset profile*, (6) is the predicted BESS active power injection for each consumption forecast scenario $\mathscr{L}^d$ with $d = 1, \dots, p$, and (7) imposes that the BESS injection is within the nominal power capacity of the BESS converter (BESS operates at unitary power factor). Finally, (8) and (9) respectively models the SOE evolution as a function of the BESS injection for each consumption forecast scenario and imposes that the SOE is within the limits. The SOE model is from [7].

The parameter $C_{nom} = 560\ kWh$ is the capacity of the BESS and η is the efficiency of the BESS charging/discharging process

$$\eta = \begin{cases} 0.95 & B \geq 0 \\ 1/0.95 & B < 0. \end{cases} \tag{10}$$

The latter was determined experimentally by performing a series of cycling tests in the SOE range from 10% to 90%, with power rates from -100 to 100 kW and depth of discharge (DOD) of $\pm 5\%$.

C. *Real-time operation*

At the beginning of the day of operation, the feeder is dispatched according to the leveled dispatch plan defined in the day-ahead stage. During real-time operation, the BESS is controlled in order to compensate for the mismatch between the dispatch plan and the power consumption realization. Therefore, the averaged aggregated power on a five minutes basis as seen at the GCP is a levelled and controlled profile. It is noteworthy that intra-day operation works independently from the dispatch plan built in the day-ahead phase, as long as it respects proper constraints. It is possible therefore to build the dispatch plan in any relevant way (to perform load leveling, to minimize the cost of purchased energy, etc.) and still retain the feeder dispatchability.

The intra-day operation is implemented with MPC, that is applied in a receding horizon fashion once very 15 seconds with updated measurements. It determines the BESS real power injections necessary to compensate for the mismatch between the dispatch plan and consumption realization (said tracking error). In the following, we denote with the double subscript notation (t, k), the 5-minute interval t and the 15-second subinterval k. For each (t, k), the predicted tracking error $\widehat{e}_{tk+1}$ for the next subinterval is defined as the deviation of the load consumption from the respective dispatch plan value (cumulated in the 5-minute interval) plus the prediction for the next subinterval. As extensively described in [4], it is as:

$$\begin{aligned}\widehat{e}_{tk+1} &= \widehat{P}_t - \frac{1}{k+1}\left(\sum_{j=0}^{k-1}(L_{tj}+B_{tj}) + \widehat{L}_{tk} + B_{tk}\right)\\ &= \widehat{e}^{-}_{tk+1} + \frac{1}{k+1}B_{tk},\end{aligned} \tag{11}$$

The BESS active power injection B^0_{tk} for the interval (t, k) is found by minimizing the predicted tracking error, therefore:

$$B^0_{tk} = \underset{B_{tk}\in\mathbb{R}}{\arg\min}\left(\widehat{e}^{-}_{tk+1} - \frac{1}{k+1}B_{tk}\right)^2 \tag{12}$$

subject to:

$$B_{min} \leq B_{tk} \leq B_{max} \tag{13}$$

$$v_{min} \leq v_{tk+1} \leq v_{max} \tag{14}$$

$$0 \leq SOC_{tk+1} \leq 1 \tag{15}$$

$$v_{tk+1} = f(B_{tk}, SOC_{tk}) \tag{16}$$

$$SOC_{tk+1} = g(B_{tk}, SOC_{tk}). \tag{17}$$

The constraints above are in order to respect the BESS converter nominal power (13), the battery nominal voltage and state of charge limits (14)-(15). The equality constraints (16)-(17) impose that the voltage and state of charge predictions, v_{tk+1} and SOC_{tk+1}, are defined through the prediction models f and g. To find these functions, linear models of v_{tk+1} and SOC_{tk+1} as a function of the BESS DC current have been determined and validated. These are a three times constant equivalent circuit model for the voltage and a current integrator for the SOC. The equivalent circuit model has been identified though a grey-box modeling approach, consisting in: 1) model formulation, 2) parameter identification from experimental measurements and through means of maximum likelihood estimation and 3) model validation through residual analysis. The models f and g have then been found assuming that:

$$B_{tk} = i_{tk} \cdot \frac{v_{tk+1} + v_{tk}}{2} \tag{18}$$

and thus reformulating the expressions for v_{tk+1} and SOC_{tk+1} as functions of the decision variable B_{tk}. The resulting non linear functions have finally been linearized as shown in the following for the voltage model:

$$v_{tk+1} \approx f(B_{tk}) = h(B_x) + \left.\frac{dh}{dB_{tk}}\right|_{B_{tk}=B_x}(B_{tk} - B_x) \tag{19}$$

where h is the non linear model of v_{tk+1} as function of B_{tk} and B_x is the linearization point. This procedure holds as long as Δt does not exceed several seconds.

III. EXPERIMENTAL SETUP

The proposed control strategy is experimentally validated on a 20 kV distribution feeder that serves five office buildings of the EPFL campus, which have a nominal power consumption of 300 kW and are equipped with 95 kWp of PV roof installations, as skecthed also in Fig. 1. The controllable element of the so-called dispatchable feeder is a grid-connected 750 kW/500 kWh BESS based on the lithium titanate technology, which can perform up to 20.000 complete charge-discharge cycles at their maxium C-rate of 4C. Although the feeder under consideration is completely instrumented with a pervasive real-time PMU-based monitoring infrastructure [8], the intra-day control algorithm only relies on the aggregated power consumption measurements at the GCP. The control strategy currently operates on a daily basis.

IV. EXPERIMENTAL RESULTS

In this section, the performance of the load leveling/dispatching strategy proposed in this paper is shown and analyzed. First, results are presented graphically in order to exemplify the operation of load levelled dispatchable feeder. Second, a quantitative analysis is proposed.

A. *Experimental operation of the proposed strategy*

Fig. 2 and 3 show the BESS experimental results during a typical day of operation. The experiment refers to March, 14th 2016. Fig. 2, shows the forecasted power consumption profile, the leveled dispatch plan, the *offset profile* and the predicted BESS SOE, which are determined in the day-ahead operation.

Fig. 3 shows the loads power consumption, feeder power demand, BESS power injection and BESS SOE realization in

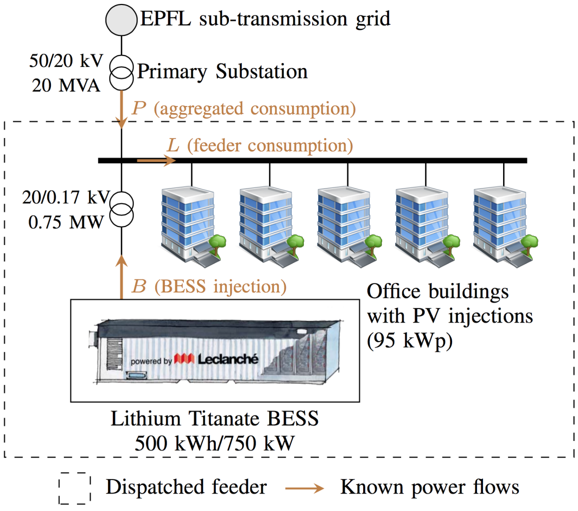

Fig. 1. Structure of the experimental setup (from [4]).

the day of operation. For the sake of comparison, the plots are obtained through 5-minutes averaging of the measurement data. It is therefore averaged the effect of the 15 seconds correction, so that the actual 5 minutes profile can be compared with the one defined the the day-ahead operation. It can be observed that while deviating from the *dispatch plan*, the SOE remains within feasible boundaries and thus the dispatchability is maintained along the whole day.

B. Performance assessment of the proposed strategy for a day of operation

The overall performance of the control strategy is evaluated with respect to three objectives:

- the ability of performing load leveling. This is measured by the load peak reduction $max(L_1, \ldots, L_N) - max(P_1, \ldots, P_N)$, the amount of energy shifted from the peak-demand to low-demand period $E_{shifted}$, and the ratio r_{var} between the consumption profile and load-leveled profile variance;
- the ability to dispatch the operation of the feeder, through evaluating the maximum, mean and root mean square of the tracking error (e_{max}, e_{mean} and e_{rms} respectively) in the realization of the dispatch plan are numerically presented, both in absolute and relative terms
- the dispatch plan robustness. This is quantified by namely the distance between the BESS SOE and its respective upper and lower bounds evaluated through computing the maximum and minimum SOE reached during the day of operation, SOE_{max} and SOE_{min}, and the portion of the BESS capacity used to perform the load leveling and the dispatch respectively, i.e. ΔSOE_{LL} and ΔSOE_D. The first is calculated as the difference between SOE_{max} and SOE_{min}, whereas the second corresponds to the maximum deviation of the SOE along the day from its forecasted evolution.

All the metrics calculated for the performed experiment are summarized in tables I-III.

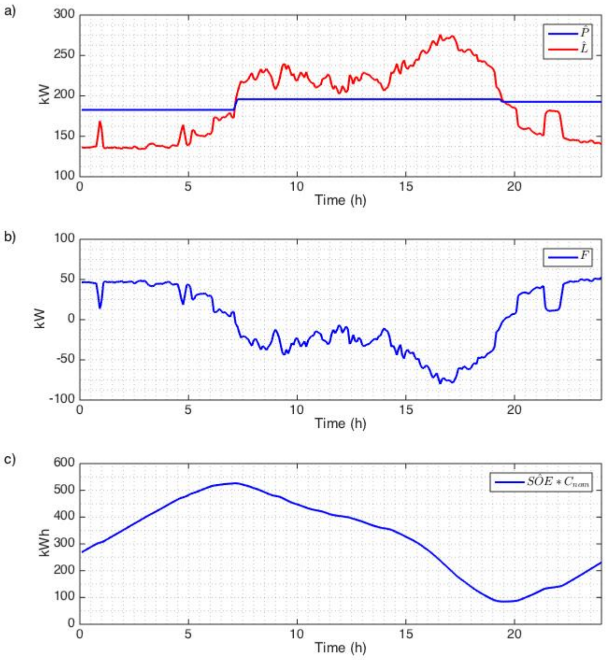

Fig. 2. Day-ahead scheduling: a) consumption forecast $\widehat{L}$ and leveled dispatch plan $\widehat{P}$; b) offset profile F; c) forecasted BESS stored energy evolution ($\hat{SOE}$).

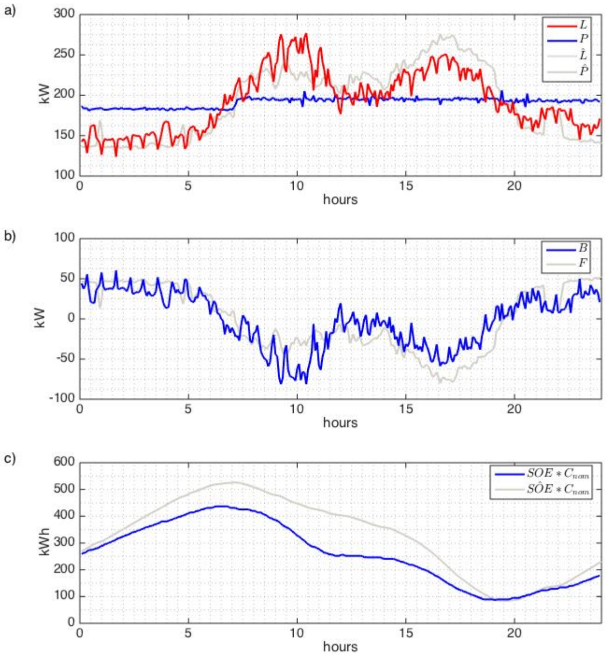

Fig. 3. Intra-day operation: a) actual feeder consumption L and leveled feeder power profile P; b) actual BESS power injection B; c) actual BESS SOE evolution. The profiles forecasted in the day-ahead scheduling are reported in grey color.

TABLE I

LOAD LEVELING PERFORMANCE EVALUATION

Metric	Value
P_{max}	206 kW
L_{max}	277 kW
$\|L-P\|_{max}$	81 kW
$E_{shifted}$	365 kWh
r_{var}	42.14

TABLE II

FEEDER DISPATCH PERFORMANCE EVALUATION

Metric	Value
e_{max}	13.35 kW
	7.16 %
e_{mean}	1.43 kW
	0.75 %
e_{rms}	2.19 kW
	1.13 %

It can be observed in table I that the peak power consumption is reduced from $277kW$ to $206kW$ and that $365kWh$ are shifted from the peak-demand to the low-demand period. The realized power profile is greatly smoothed, with regard to the actual consumption profile, the ratio between the variances of these two profiles being $r_{var} = 42.14$. Table II describes the performance of the feeder dispatch operation. It can be seen that the mean tracking error along the day is lower than 1%. Finally, it can be seen in table III how the BESS SOE remains within its limits along the day of operation.

V. CONCLUSIONS

We described and experimentally validated a control algorithm for a grid-connected battery energy storage system (BESS) that achieves to level the consumption and dispatch the operation of a group of prosumers. These control requirements are with the objective of smoothing their power demand profile and meant as a bottom-up solution to decrease the amount of regulating power required to operate the grid, a key factor to achieve a larger proportion of production from renewable energies. The control strategy is structured according to a two-stage structure: day-ahead and intra-day/real-time operation. In the former, a leveled load profile (minimum variance dispatch plan) for the day of operation is built by accounting for forecast of the demand. In the latter, the feeder *dispatch plan* is tracked thanks to controlling the BESS power injections, by receding horizon model predictive control (MPC).

TABLE III

CONTROL STRATEGY ROBUSTNESS EVALUATION

Metric	Value
SOE_{max}	78 %
SOE_{min}	15.5%
ΔSOE_{LL}	62.5%
ΔSOE_{D}	26.7%

The double objective proposed is attained in a robust way by defining in the load leveling day-ahead optimization problem a set of constraints based on all the relevant forecast scenarios available in the historical data set. The power profile $\widehat{P}$ is built so that, for any of these scenarios both the day-ahead load leveling operation and the intra-day feeder dispatch operation remains feasible, i.e. the battery power and SOE remain within their operating limits.

The experimental results obtained with a 750 kW/500 kWh BESS have shown the ability of achieving the double control objective.

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