REAL-TIME CONTROL FOR SERVICES PROVIDED BY BATTERY ENERGY STORAGE SYSTEMS IN A RESIDENTIAL LOW VOLTAGE GRID WITH A LARGE AMOUNT OF PV

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ABSTRACT

This paper presents real-time control strategies for peak shaving and voltage control provided by a Battery Energy Storage System in a low voltage grid. Two performance indices, one for peak shaving and one for voltage control, are proposed to quantify the results. The strategies are compared with a benchmark which is calculated as an ex post optimization that solves the control problem together with the sizing problem. First, a rule-based strategy for peak shaving is presented which only injects active power. Afterwards, the strategy is extended with voltage control through reactive power injection. In the latter case, an optimization problem is solved at each time step to decide at which rate active and reactive power should be injected.

I INTRODUCTION

In the last decade, a significant growth in the amount of distributed generation has taken place. A substantial fraction of this electricity is produced in the distribution grid, by locally installed PV [1,2]. The residential low voltage grid, which was originally designed for 'top-down' electricity supply, poses limits to the increasing penetration of PV. Overloading of grid components, especially transformers, and voltage deviations outside acceptable margins, are considered unfavourable consequences [1]. Besides grid reinforcements, a number of mitigation techniques are suggested in literature [3]. In this paper a Battery Energy Storage System (BESS) is used. The BESS considered in this paper consists of a Li-ion battery, a DC-link and a three-phase inverter. The BESS is capable of controlling active and reactive power in each of the three phases independently.

A theoretically optimal BESS control strategy [4] for the overloading and voltage deviation problem provides the starting point for this work. The method presented by Tant et al. [4] solves the control problem and the sizing problem simultaneously with a multiobjective optimization method. The results are presented as a trade-off between voltage control, peak shaving, and annual cost.

In this paper, real-time strategies are developed to pursue the voltage control and peak shaving goals. Real-time control implies an instant control decision at every time step in absence of complete knowledge of future events. The real-time strategy performance is therefore lower than the performance of the optimal strategy, which is based on accurate knowledge of events over the whole evaluation period. The real-time strategies are benchmarked with the optimal strategy to assess their performance.

In section II, a model for the low voltage grid with BESS support is set up. A possible future scenario in a residential area with 60 % penetration of PV is considered. In section III, performance indices are proposed for the peak shaving goal and the voltage control goal. In the last two sections, real-time strategies to control the BESS power output are proposed. Section IV focuses primarily on minimizing the peak shaving index. The BESS is controlled with a rule-based strategy using active power only. In section V, voltage control is additionally considered. The BESS deploys active and reactive power to influence the voltage. This complicates the problem and therefore the rule-based solution is replaced by an optimization problem in every time step.

II. MODEL FOR A LOW VOLTAGE GRID WITH A BESS

The low voltage grid in Figure 1 is based upon previous work [4]. The parameters of the substation transformer, feeder cables, and connection cables are listed in TABLE 1. The future scenario implies a large amount of PV. 60 % of the 62 households have PV with a capacity of 5 kWp installed. These are indicated as coloured houses in Figure 1. They are located at the end of the feeder lines, because this represents a worst-case scenario. The households have a single-phase connection and are equally distributed among the three phases. The PV production profiles used, are measured at a rooftop PV installation of KU Leuven in 2008. Load profiles are residential profiles based on measurements of active power consumption by two Flemish distribution grid operators in 2008. These measured profiles have been transformed to construct an untraceable set of data, which is statistically equivalent to the original set [5]. Use of these profiles assumes a unity power factor and a voltage-independent power consumption in every time step. The BESS is connected to node 'A' in Figure 1, because injection at this node has the largest impact on voltage control [4]. Characterizing parameters and the equations for the BESS-model are presented by Tant et al. [4]. A Backward-Forward-Sweep algorithm [6] is used to calculate voltage profiles.

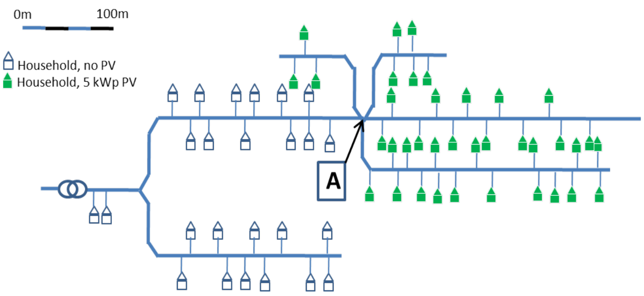

Figure 1: Schematic representation of the low voltage grid.

III. OPTIMAL STRATEGY

A strategy defines the active, P_k^{inv}, and reactive BESS power, Q_k^{inv}, in every timestep. The performance of the delivered BESS services is quantified using performance indices [4]. The total aggregated apparent power in the grid at time step k and in phase p is given by:

$$S_{k,p}^{\text{tot}} = -P_{k,p}^{\text{inv}} + j \cdot Q_{k,p}^{\text{inv}} + \sum_{h=1}^{\#\text{houses}} P_{k,p}^{h}.$$

For every day, the maximum apparent power peak is determined over all phases and all time steps. The index for peak shaving is defined as the rms value of these daily maximal peaks:

$$S_{\text{rms}}^{\text{peak}} = \sqrt{\frac{\sum_{d=1}^{\#\text{days}} \max_{\substack{k \in \text{time steps\_in\_day}(d) \\ p \in \{1,2,3\}}} \left|S_{k,p}^{\text{tot}}\right|^2}{\#\text{days}}}.$$

The index for voltage control is defined as the rms value of the daily maximal voltage deviations from the setpoint $U_{\text{nom}} = 230$ V:

$$\Delta U_{\text{rms}}^{\text{peak}} = \sqrt{\frac{\sum_{d=1}^{\#\text{days}} \max_{\substack{k \in \text{time steps\_in\_day}(d) \\ p \in \{1,2,3\} \\ h \in \kappa_{\text{control}}}} \left(\left|U_{p,k,h}^{\text{peak}}\right| - U_{\text{nom}}\right)}{\#\text{days}}}.$$

Both indices are to be minimized. Moreover they are used to compare the performance of all strategies that control the BESS' active and reactive power exchange $P_{k,p}^{\text{inv}}$ and $Q_{k,p}^{\text{inv}}$. Additionally, the annual cost of a strategy is calculated with the cost calculations of Tant et al. [4] and [7]. The optimal strategy is determined with the weighted multiobjective optimization method of [4], by using the performance indices directly as objective functions that need to be minimized. The optimal strategy is represented by a Pareto-optimal trade-off curve between the two performance indices, for a given maximum annual cost. The algorithm also determines the optimal dimensions of battery and inverter, which are limited by the maximum allowed annual cost.

TABLE 1: GRID COMPONENTS [4]

	Type	Impedance at 45 °C
Feeder cable	EAXVB 1 kV 4x150 mm²	0.206 + j 0.248 Ω/km
User cable	EXVB 1 kV 4x10 mm²	1.830 + j 0.278 Ω/km
Transformer	10 kV/400 V 250 kVA	0.013 + j 0.038 p.u.

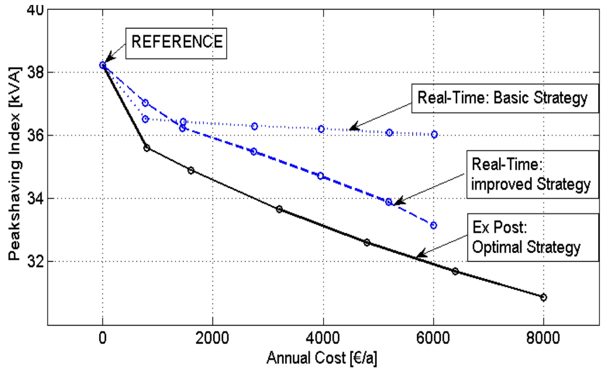

Figure 2: Trade-off curve for peak shaving: ex post optimal vs. real-time basic and improved.

IV. REAL-TIME STRATEGY: PEAK SHAVING

The first approach for a real-time strategy uses only active power injection through the BESS. The goal is to reduce the index for peak shaving as much as possible, for limited annual costs.

Because the performance indices cannot be used directly in real-time strategies, some degrees of freedom are introduced. These degrees of freedom, $P_{\text{cut-off}}$ and SoC_{start}, are fine-tuned to attempt to minimize the performance indices over the whole evaluation period. The first, $P_{\text{cut-off}}$, indicates the level of peak power that is tolerated. In every phase, the BESS uses active power to reduce aggregate power peaks larger than $P_{\text{cut-off}}$ and ignores peaks smaller than $P_{\text{cut-off}}$. The second, SoC_{start}, denotes the State-of-Charge (SoC) of the battery at 6 am every day.

A first basic controller uses a static SoC_{start} of 50 % and $P_{\text{cut-off}}$ of $-11/+11$ kW, based on the benchmark solution. Whenever the aggregate load falls outside of $-11/+11$ kW, the load profile peaks are cut-off and balanced as good as possible, through the exchange of active power with the BESS.

The 60 % penetration level of the future scenario leads to significant negative peaks in power demand, dependent on varying sun and cloud conditions. Using the static cut-off level like the basic controller, the BESS cannot cope with this volatile power profile. The irregular power demand complicates improving the peak shaving index: the battery will run empty or full before highest peaks of the day will be seen. In order to improve battery management, a dynamic cut-off level $P_{\text{cut-off},d}$ is proposed. This day-to-day varying value is determined using day-ahead sun-predictions from the Belgian Pedological Service [8]. The predicted amount of energy from the sun per day and the predicted hours of sun per day are two values that are used in a linear regression on the optimal solution. The linearization is used to daily compute a cut-off level $P_{\text{cut-off},d}$ for real-time control. In Figure 2 the optimal control strategy is displayed as the benchmark. Two real-time strategies are shown.

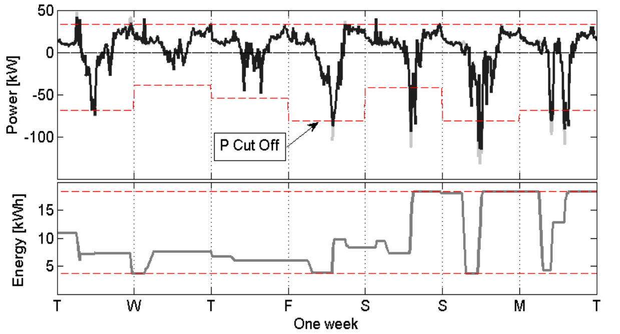

Figure 3: Power profile and battery profile improved strategy (with BESS)

The basic strategy with a static $P_{\text{cut-off}}$ has a stagnating index improvement on the vertical axis, for a rising maximum annual cost on the horizontal axis. The improved strategy with a dynamic $P_{\text{cut-off},d}$ leads to continuing improvements for rising costs, due to the varying cut-off level per day. Power flow and battery level results of the real-time improved control strategy are presented in Figure 3. The dynamic cut-off level is indicated with a dashed line in Figure 3. It allows the strategy to use the battery capacity in a more intelligent way. The dynamic $P_{\text{cut-off},d}$ is supported with a State-of-Charge modification. The energy level at the beginning of each day is then adjusted in line with $P_{\text{cut-off},d}$.

V REAL-TIME STRATEGY: VOLTAGE CONTROL AND PEAK SHAVING

In this section, voltage control is added to the real-time strategy. This strategy uses both the active and reactive power of the BESS. Active power can be used to improve the index for peak shaving directly and the index for voltage control indirectly. The active power is linked to the physically available energy in the battery of the BESS. This implies that succeeding time steps may impose limits on the amount of active power that can be delivered through the BESS (when e.g. the battery runs out of energy). The reactive power, on the other hand, can be chosen optimally in every time step, because it is not linked to the energy in the battery. Injected reactive power can improve the index for voltage deviations, but can also increase the total apparent power, which would worsen the index for peak shaving.

A shift in the optimal strategy from pure peak shaving to more voltage control will result in an increased usage of reactive power. The optimal dimensions of the BESS will change accordingly. Less active power and more reactive power lead to a smaller battery and larger inverter size.

The real-time strategy minimizes the peak shaving index and the index for voltage control by using three degrees of freedom: $P_{\text{cut-off},d}$, SoC_{start}, and $\Delta V_{\text{cut-off}}$.

$P_{\text{cut-off},d}$ and SoC_{start} are defined in the previous section. $\Delta V_{\text{cut-off}}$ determines the threshold for voltage deviations that are not tolerated.

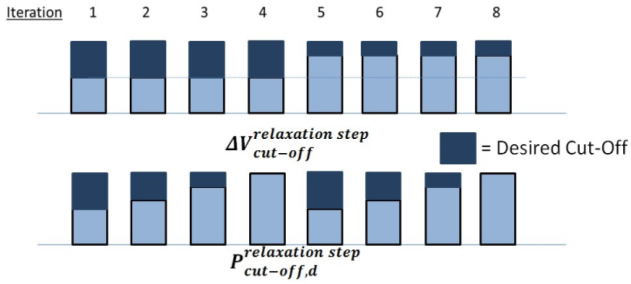

Figure 4: Relaxation scheme.

The control strategies with voltage control are more complicated because the rate of active and of reactive power injection must be determined simultaneously. Therefore, an optimization problem is solved at every time step. The degrees of freedom enter this optimization problem as constraints. The objective is to use the battery as little as possible to prioritize inverter solutions over battery solutions to avoid battery depreciation as well as the cost of energy losses in the battery. The optimization problem per time step k becomes:

$$\underset{P_{p,k}^{\text{inv}},Q_{p,k}^{\text{inv}}}{\text{minimize}}\ P_k^{\text{batt}}$$

$$s.t.\ \begin{cases} \text{Grid loadflow model} \\ \text{BESS model} \\ \forall p\colon \left|P_{k,p}^{\text{tot}}\right| \le \max\limits_{p}\left(\left|\sum\limits_{h}^{\#\text{houses}} P_{k,p}^{\text{h}}\right|\right) \\ \forall p\colon \left|P_{k,p}^{\text{tot}}\right| \le P_{\text{cut-off},d}^{\text{relaxation step}} \\ \forall p\colon \left|\Delta V_{p,k}^{230}\right| \le \Delta V_{\text{cut-off,d}}^{\text{relaxation step}} \end{cases}$$

The constraints might prevent the optimizer from finding a feasible solution in some time steps. This is solved by increasing $P_{\text{cut-off},d}^{\text{relaxation step}}$ iteratively until a feasible solution can be found that satisfies the relaxed constraints. If a feasible solution can still not be found, $\Delta V_{\text{cut-off,d}}^{\text{relaxation step}}$ is also increased and the process is repeated. A representation of this relaxation scheme is given in Figure 4. Solutions of these optimization problems in every time step determine the real-time control. Depending on the configuration (battery and inverter size) of the BESS, a peak shaving only strategy, a voltage control only strategy, or a strategy combining both at the same time, are compared. The results are shown in Figure 5. The full black line represents the benchmark solution of the multi-objective ex-post optimization for a cost of € 8000/a.

TABLE 2: BESS CONFIGURATIONS AND ANNUAL COSTS FOR DIFFERENT REAL-TIME STRATEGIES (EX POST OPTIMAL)

	A_1	B_1	C_1	A_2	B_2	C_2
Battery [kWh]	0 (0)	9.6 (13.6)	19.2 (17.3)	0 (0)	3,84 (1.0)	7,86 (6.9)
Inverter [kVA]	156.5 (147.2)	104.3 (64.4)	52.6 (35.4)	62,6 (60.2)	41,7 (56.0)	20,9 (19.9)
$\text{Cost}_{annual}^{total}$[€]	8210 (8000)	7940 (8000)	7620 (8000)	3330 (3200)	3270 (3200)	3080 (3200)

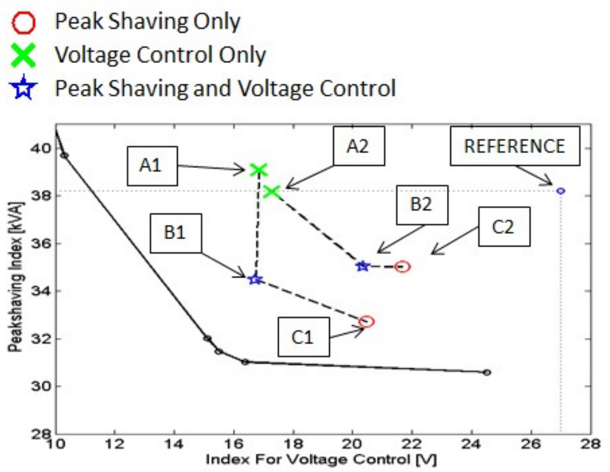

Figure 5: Trade-off peak shaving vs. voltage control, optimal benchmark solution and three real-time strategies.

In TABLE **2**, the BESS configurations for the different control strategies presented in Figure **5** are given, with the optimal configuration for the ex post strategy in parentheses.

Compared to the reference scenario without BESS, the 'voltage control only' strategy accomplishes a great reduction in voltage deviation for low costs without increasing the peak shaving index. For higher costs (larger than 3200 €/a) the improvements saturate and the peak shaving index increases. This is because without a battery to store energy, only load balancing over the three phases can reduce the peak shaving index. Furthermore, reactive power used for voltage control worsens the peak shaving index in some time steps. The 'peak shaving only' strategy decreases the peak shaving index and indirectly also the voltage deviations. A larger maximum cost allows for a larger battery, which allows for more peak power to be stored.

The combined 'voltage control and peak shaving' strategy proves that both voltage deviations and power peaks can be reduced by combining both strategies.

VI CONCLUSIONS

Peaks in power delivery and voltage deviations are two crucial issues in operating the low voltage grid with an increasing amount of PV. A BESS can offer peak shaving and voltage control services using active and reactive power at a strategic location in the grid.

For the real-time control of a BESS, prediction based methods have been proposed in literature, which are based on a forecast of load profiles [9]. In this paper, strategies are presented that allow real-time control for these services without the need for load profile forecasts.

Through the use of performance indices for the peak shaving and the voltage control, different control strategies are compared. It is shown that both the peak shaving and voltage control services can be combined in one controller. A graphical representation of the performance in **Figure 5** shows that the three real-time strategies approach the optimal solution, compared to the reference scenario without BESS. A distribution grid operator can obtain a desired objective by selecting one of the proposed strategies along with the corresponding configuration of the BESS.

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