Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application

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Abstract - This paper presents a sizing methodology and optimal operating strategy for a battery energy storage system (BESS) to provide a peak load shaving. The sizing methodology is used to maximize a customer’s economic benefit by reducing the power demand payment with a BESS of a minimum capacity, i.e. a system with a lowest cost. The BESS optimal operating strategy is based on dynamic programming and is aimed to minimize the energy cost while satisfying battery physical constraints.

Index Terms - Peak load shaving, battery energy storage system, optimal capacity, dynamic programming.

I. INTRODUCTION

Stressed and less secure power system operating conditions have encouraged both power utilities and large industrial power consumers to look for bulk energy storage systems. Applications such as spinning reserve, load levelling and peak shaving have been identified as the first candidates for bulk energy storage [1]. The peak shaving application is particularly attractive for large industrial plants. The plant’s electricity bill consists of energy payment and power demand payment. The latest corresponds to the highest power demand during a specific time range (typically from 15 minutes to 1 hour) and often reaches a level of 50% of the plant’s electricity bill.

The battery energy storage system (BESS) can be used to reduce this peak demand and thus reducing the plant’s electricity bill by discharging a stored energy during load peaks (Fig.1). The economic benefit of the peak shaving application is directly measurable by comparing power demand load taxes for large industrial customers with realistic installation and maintenance costs of BESS. Previous research and practical installations (in Japan, USA) [2] have technically shown that BESS can be effectively used for peak load shaving application.

The optimal BESS sizing has been addressed in [2-7]. However, it is mainly limited to the load levelling application. The objective of this paper is to develop a BESS sizing methodology that provides an optimal BESS dimension (rated capacity \( B_{\text{cap}} \) [kWh] and power \( B_{\text{pwr}} \) [kW]) to maximize the customer’s economic benefit by reducing the power demand payment. An optimal operating strategy based on dynamic programming minimizes energy payment and reduces a battery deterioration for a given customer load profile.

The outline of the paper is as follows: Section 2 describes principles of load peak shaving; Section 3 gives a brief overview of concerned BESS technologies; Section 4 explains the BESS sizing methodology and optimal operating strategy. Section 5 presents simulation results.

II. PEAK SHAVING

Often industrial customers run apparatuses and devices that require significant amount of power over relatively short time intervals during a day. Extra cost in keeping up with the peak demand (generation and transmission/distribution) is passed to the customers in the form of demand charges. Industrial users are therefore charged according to the energy consumption and according to their highest power demand, usually averaged on 15 minutes period. Demand charges can make up as much as one-half of a facility’s electricity bill.

Peak shaving has been practiced for many years by using on-site diesel generators and gas turbines. However, today large industrial plants can install the BESS capable of discharging for short periods of time during the peak hours and charging during the low demand periods at night hours, hence reducing the peak demand charge (Fig.1).

Power peak is a relative notion that needs a reference value. The power peaks on the load curves are defined as the area above the reference value. \( P_{\text{shave}} \) will denote the reference value and should not be over passed (Fig.2). \( B_{\text{pwr}} \) is the required maximum power to shave and \( \Delta T \) is called the discharge time. The area above \( P_{\text{shave}} \) is the BESS capacity \( B_{\text{cap}} \). The relationship between \( B_{\text{pwr}} \) and \( B_{\text{cap}} \) is represented as (1).

\[
B_{\text{cap}} = B_{\text{pwr}} \cdot \Delta T \tag{1}
\]
III. BATTERY ENERGY STORAGE SYSTEM

All commercially available BESS have a similar system design: batteries, power conversion system (PCS), and a step-up transformer (Fig.1).

Two types of batteries have been considered in this study.

A. Lead-acid BESS

Among all batteries, lead-acid is the most mature. Key features of lead-acid technology have a high degree of maturity, high efficiency and lowest initial storage cost of all batteries. The main drawback of lead-acid BESS is a limited life cycle (Table 1).

B. Vanadium redox flow BESS

The most mature flow battery is the Vanadium redox (VRF). VRF batteries have a longer life cycle of modules (Table 1). The cost of a flow battery is divided into a module cost per kW and an electrolyte cost per kWh. The VRF has a low module cost, but relatively high electrolyte cost.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>CHARACTERISTICS OF DIFFERENT BATTERIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of maturity</td>
<td>***</td>
</tr>
<tr>
<td>Storage cost, €/kWh*</td>
<td>200-500</td>
</tr>
<tr>
<td>Cycle life</td>
<td>1000</td>
</tr>
<tr>
<td>Total efficiency AC-AC, %</td>
<td>72-78</td>
</tr>
</tbody>
</table>

*lower cost is for a discharge time of 3 h and higher cost is for 0.3 h.

Batteries can be viewed as a simple energy tank which output power does not depend on the state of charge (SoC). The rate of discharge does not affect the available capacity and the overall efficiency of a charge/discharge cycle is typically 72% to 78%. However, in reality the power available from a battery depends on its SoC, and this power is limited by several factors which contribute to the use of battery in a safe way that conserve the life time.

The cost of BESS units per power unit is a strong function of their (energy) capacity, i.e. the maximum discharge time. To calculate the total BESS cost (over the complete lifetime) we add the cost of PCS to the net present value (NPV) of cost of each battery type including required cell replacements [1]. Lead-acid BESS is the most economic solution for a discharge time up to 1.25 h, and then VRF shows the lowest cost.

IV. METHODOLOGY

The objective function $F_{obj}$ is a benefit obtained from the peak shaving application during the period $T_e$, and should be maximized (2).

$$\max\text{Benefit}\left|\begin{array}{c} T_e \\ \text{Savings (Size,"operating schedule")} - \text{Costs (Size,"operating schedule")} \end{array}\right|_{T_e} \tag{2}$$

where the Size stands for the BESS capacity and power. The Costs include BESS installation, operating and maintenance (O&M) costs. The Savings depend on the reduced power demand quantity and the BESS operating schedule (3).

$$\text{Savings}\left|_{T_e} \text{Electr. bill}_{\text{without BESS}} - \text{Electr. bill}_{\text{with BESS}} \right|_{T_e} \tag{3}$$

Usually, for industries, the electricity bill is divided into two parts, one for the energy and one for the power or demand magnitude (4).

$$\text{ElectricityBill}_{T_e} = \int_{T_e} P(t) \cdot EFee(t) \cdot dt + \sum_{T_e} \left(\overline{P}_{\text{max}} \cdot PFee\right) \tag{4}$$

where $\overline{P}_{\text{max}}$ is the averaged demand (usually over 15 min). The first term of the right side is the amount of consumed energy times the energy fee. The second term is the power demand. A period in which a maximum demand will be chosen is defined as the Demand Evaluation period (DEP). The maximum demand is multiplied by the demand charge. If this maximum demand exceeds the contracted limit an extra penalties are charged to the customer.

The criterion defining the optimal solution is purely economical and measures the global annual, or monthly, electricity bill reduction. The objective function does not include any ecological factor. The main ecological problem, here, would be to balance the reduction of power losses with the energy expenses for the construction, operation and elimination of the BESS.

Without knowledge of operating schedule, it is not possible to express $F_{obj}$ as an algebraic function. The nature of the variable “operating schedule” is completely different from that of the battery size. Therefore, in this optimisation problem, there are two sub-problems: the battery size optimisation...
(Bcap and Bpwr) and the operating schedule optimisation. They are inter-dependant and cannot be solved at the same time.

A. BESS size optimization

The objective function (2) can be simplified and expressed as a function of \( B_{pwr} \) (5).

\[
\text{Benefit} = B_{pwr} \times f(\Delta T, T_e)
\]

(5)

It is assumed that the BESS fixed and O&M costs are known for different types of battery technologies and can be expressed as a function of \( B_{pwr} \). Thus, the benefit is a linear function of the shaved power \( B_{pwr} \), and hence, more power is shaved, more money is earned by the BESS owner. The benefit is proportional to the value of \( f \) which depends on: \( T_e \), \( \Delta T \), a battery life cycle, a number of cycles per year, and a power demand fee.

The size optimisation issue can be solved with the “extrema” method where the objective function is calculated for a set of input values (the size to be optimized). Once this objective function is obtained for all the possible input values within their feasibility range, the extrema of that function are derived numerically or graphically.

When the shaved load is not constant over a specific period a required battery rated capacity has to be determined appropriately. A method to dimension the lead-acid battery as a function of any load is presented in [8].

The function \( f \) illustrates a weight of benefits compared to the total customer electricity bill, which is defined as the effective bill reduction. To obtain these results, we additionally assume that the customer load curve and the battery charging schedule are known in advance.

B. BESS optimal operating strategy

The determination of the optimal operating schedule consists on taking the correct sequence of decisions to possibly obtain the best exploitation of the battery, according to desired criteria (minimizes the energy cost, and the battery replacement cost, i.e. minimize the amount of cycles per day). Here, the state variable is the battery SoC and the criterion is the energy cost of each transaction from one SoC to another.

The dynamic programming (DP) algorithm prevents to calculate all the possible sequences by selecting relevant sub-sequences at each step (Bellman principle). One of the main interests of using the DP in the optimisation problem is that we can take the physical constraints of the battery into account by using an appropriate model of the battery [8]. The battery is described with an internal resistance that varies as a function of the SoC, and is different for discharge or charge.

Here the main goal is to say if a desired transaction is physically possible for the battery, and if possible, at which rate. The losses will be computed correctly, as a function of the battery discharge rate, thus we can avoid a usage of a flat efficiency. An arbitrary maximum demand is set at the beginning of the DP algorithm. The discharge schedule is then imposed. If the given battery of a rated capacity is not sufficient, the algorithm will indicate it.

The DP algorithm inputs are: the customer load curve, energy fees (\( E_{tax} \)), battery parameters and the value of the shaved power \( P_{shave} \).

V. SIMULATION RESULTS

The developed sizing methodology and optimal operating strategy have been tested with an example of the large industrial customer. The customer’s daily load profile is shown in Fig.4. It illustrates average power demand for each 15 minutes period.

A. BESS size optimization

Fig.5 illustrates a projection of \( f_{benefit} \) in \( \Delta T \) and \( T_e \) coordinates, thus, shows an economic viability of a peak shaving application for a particular customer. Only the curves that correspond to a positive value of \( f_{benefit} \) are displayed. In order to obtain a benefit after \( T_e \) years of exploitation for a certain peak width \( \Delta T \) the corresponding value of \( f_{benefit} \) is multiplied by a desired level of shaved power, \( B_{pwr} \).

It can be seen that in this particular case the peak shaving application is not profitable for discharge time (peak width) > 1 hour. The minimum payback time is 6 years. As these
results are strongly dependant on the BESS fixed and O&M costs, the chart is only a rough estimation and is subject to uncertainty. It is clear that shorter peaks generate higher profit.

Fig.6 illustrates the effective electricity and power demand bill reduction (4) as a function of the BESS size. The annual electricity bill is reduced by 4% (power demand bill by 8%) compared to a situation without BESS.

The recommended size of the BESS is: $B_{cap}=250 \text{ kWh}$ and $B_{pwr}=280 \text{ kW}$. $T_e$ is a system life cycle of 20 years and four replacements of lead-acid battery cells are foreseen during this period. In this case the battery operating schedule has been chosen as simple as possible, by re-charging the battery only during the periods of low load or no-load and without taking into account the physical limits of the battery. The result is significantly different for VRF BESS (Fig.7).

Additional analysis has shown that investment costs are linearly increasing for different BESS types but with a significantly different slope (investments growth in respond to battery capacity growth is smaller than for lead-acid batteries). This is due to the fact that there are fewer replacements. Therefore, we obtain rather a constant $F_{obj}$ as a function of the BESS capacity. However, a global performance is the same than for a lead-acid battery. The effective demand bill reduction also reaches maximum of 8%. The recommended optimal sizes for this case would be a capacity of 750kWh with 280kW rated power.

### B. BESS optimal operating strategy

At the next step, we used a BESS model which takes into account a battery internal resistance [8]. The internal resistance varies as a function of battery state of charge (SoC) and is different for discharge or charge.

The inputs of DP algorithm are the load curve with the energy fees ($E_{tax}$), the battery data and the value of $P_{shave}$. The top chart in Fig.8 illustrates the base customer load profile (blue bars) compared to the shaved customer load profile (red bars). The bottom chart gives the optimal battery operating schedule (green line) and the real battery usage in relation to the maximum available usage at that SoC (black bars). In this scenario, dynamic programming (DP) suggests to recharge the battery between two peaks. In fact the battery size has the minimum possible capacity for a peak shaving application with $P_{shave}=650 \text{ kW}$. The criterion to measure a quality of the path is the energy cost of the battery's charge/discharge operations. DP algorithm cannot help us to directly find an optimal battery size since they are set at the beginning of the algorithm. However, DP algorithm can be very helpful for the global BESS optimisation by using it in a recursive manner.

### VI. CONCLUSIONS

The paper presents a method to find the optimal battery energy storage capacity and power for a peak load shaving application. This method assesses a customer load profile, finds the optimal battery size (power, capacity) which provides an electricity bill reduction.

Dynamic programming was used to obtain the optimal operating (charging) strategy for a selected battery. The operating schedule optimizes the energy costs while satisfying battery physical constraints.

The proposed methods were tested with a real industrial customer load profile and results were discussed.
VII. REFERENCES


