Battery Energy Storage System For Primary Frequency Regulation

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Abstract

This paper presents a technical and financial evaluation for a MW sized Battery Energy Storage System (BESS) for primary frequency regulation in a power grid.

In a first step, the specification of the BESS is calculated. Numeric simulations based on historic frequency data are used to determine the minimum possible battery capacity for primary frequency regulation. As a result the investment cost for the BESS is minimised. Assuming a contracted reserve power P_{BESS} [MW], the numerical simulation shows that a minimum capacity of $0.62*P_{BESS}*h$ [MWh] can fulfil the requirements of the European grid code.

In a second step, the underlying operation strategy of a multi-string topology (battery charge/discharge conditions, battery state of charge limits, emergency actions, etc.) is explained.

Following the technical considerations, a monetary value analysis of a 2MW Lead-acid-BESS for the specific application of frequency control is presented. To determine the overall economic viability, the revenues from provision of reserve power and the overall capital and operating costs over the BESS life time are compared in a net present value calculation. It is found that for current European market conditions a capacity-optimized BESS can be a profitable solution.

The frequency data that serve as an input for the numerical simulation and the economic data are specific to the European power grid and market. The methodology however, can be applied to any other power grid in any market place.

1 Introduction

Electric power grid operators guarantee the balance between electrical load and generation at any instant by using reserve power to respond to changes in the grid frequency. Maintaining a stable grid frequency is essential for a secure and high-quality power supply. The control power (also known as spinning reserve) is commonly acquired from generating units that are on-line but operate considerably below their full capacity. This way the output power can be ramped up or down rapidly. Three classes of reserve power exist which are defined by their time scale to become available. In the case of the so called primary reserve, a fast response within seconds is crucial in order to provide power on short notice when a load or generator experiences an unexpected outage.

Previous research results and practical installations [1]-[3] have shown that Battery Energy Storage Systems (BESS) can be used efficiently for the provision of the primary reserve. The storage concept works by recycling energy, i.e. the battery absorbs energy when the frequency is above the nominal value and injects energy back into the grid when the frequency is below the nominal value. However, a method for the determination of the minimum BESS capacity for a certain contracted reserve power has not been addressed yet. For that reason batteries were often over-dimensioned and the total BESS cost was high, impeding economic profitability. Furthermore, an optimized operating algorithm for a BESS that is used for frequency regulation has not been devised. Inadequate operation of the BESS can lead to uncertainty in the exact battery state of charge (SoC) and also to accelerated aging of the battery cells. This again impedes the profitability of a BESS for primary frequency regulation.

The main objective of the work presented in this paper is to maximize the profit for the potential BESS owner participating in the ancillary service market. Since the main cost driver is the battery capacity the optimization will essentially be equivalent to minimizing the battery capacity. This goal is to be achieved by developing an intelligent operation strategy for the BESS.

The outline of the paper is as follows: Section 2 describes the principles of primary frequency control in Europe; Section 3 and 4 present the BESS capacity minimization and corresponding BESS operating strategy and Section 5 explains the economic valuation of a BESS for primary frequency regulation.

2 Frequency control reserves in UCTE

The UCTE - Union for the Co-ordination of Transmission of Electricity (synchronous interconnection of central European countries) – has defined and established three types of reserve in order to guarantee the required generation-load balance. Depending on the timescale after which the regulatory power has to be available to the grid, the three reserves are classified as primary reserve (or spinning reserve, 10 seconds), secondary reserve (10 minutes) and tertiary reserve (>15 minutes).
Here, our investigation will focus on the fastest reserve power, primary regulation. In this case, the deviation of the grid frequency will cause controllers of all generators taking part in primary control to respond within a few seconds in order to stop a frequency drop/rise. Requirements for primary reserve in the UCTE are shown in Table 1 [4].

TABLE 1 Requirements for Primary Frequency Control Reserve in the UCTE

Total volume	3000 MW
Start Fully activated End	3-5 sec ≤30 sec ≥15 min
Minimum single bid	≥1-2 MW (limited by the ability of the TSO to measure the delivery of the reserve power)
Maximum single bid	≤40-50 MW (to limit the effect in the case of a unit failure)
Payment mechanism	Power availability payment (no payment for the delivered energy)

The UCTE rules [4] specify the nominal frequency to be 50 Hz and a non-critical frequency window of 50Hz±20 mHz. This tolerance window avoids active primary control at near nominal frequency. As soon as the frequency deviates to values higher than 50.02 Hz, the system supplying primary reserve has to absorb power (reduce the power output in the case of generating units). Should the frequency deviate to values below 49.98 Hz it has to supply power (left hand side of Fig. 1).
The power - frequency (p-f) characteristic that determines the required power as a function of the grid frequency is linear outside the non-critical frequency window (right hand side of Fig.1). The full primary reserve P_n has to be activated when the frequency deviation Δf reaches ±200 mHz.

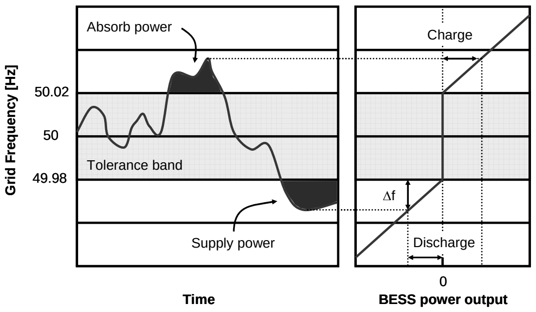

Figure 1: Frequency profile (left) and Power-frequency characteristic of the primary frequency controller in accordance to the UCTE grid code (right).

The p-f characteristic can be used to translate a measured frequency profile into a required output/input power profile for the BESS (Fig.2). The requirement for the BESS is to handle such a charge/discharge profile without overcharging the batteries and also without ever being empty. The question here is: for a given BESS power P_{BESS}, what is the required capacity in MWh, needed for being able to deliver this profile with a high availability?

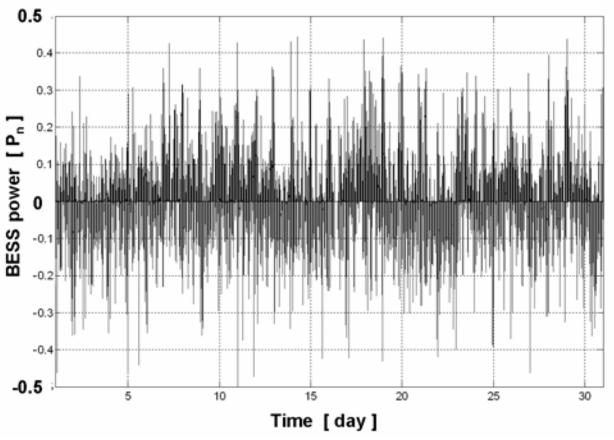

Figure 2: Primary reserve power curve, calculated from frequency data measured in April 2005. From a frequency quality perspective this was an average month. Power supplied to the grid is negative (BESS in discharge mode). Power absorbed from the grid is positive (BESS in charge mode).

3 Dimensioning and overall specification of the BESS

The main objective of the optimization is to maximize the profit for the potential BESS owner acting at the ancillary service market. Since the main cost driver is the battery capacity the optimization will be essentially equivalent to a minimization of the battery capacity.
To determine the minimal BESS capacity we have modeled the BESS operation by applying a specific operating algorithm to measured frequency data of the UCTE grid. The minimal conceivable BESS capacity for the contracted primary reserve P_{BESS} is limited to 0.25 P_{BESS} *h, since the BESS has to provide primary reserve for at least 15 min (Table 1). The realistic minimum will need to be higher because primary control events can follow each other at short intervals so that there is not enough time to recharge the BESS. For this reason, the recharge strategy for the BESS has a strong influence on the optimization result.
Another issue with a strong influence on the result is the topology of the BESS. We propose to use so called emergency resistors as an essential component of an optimal BESS for primary frequency control. They help to reduce the needed capacity of the battery by dissipating energy during rare events when an extreme positive frequency excursion occurs while the BESS happens to be fully charged. The system has to be designed to use them as rarely as possible. This goal enters as another condition into the optimization. It would be neither an environmental nor an economic optimum to avoid emergency resistors completely.

Operating rules for the BESS with SoC max/min limits:
The goal of the operating strategy is not to keep the battery 100% charged but to keep it in a range between two defined state of charge (SoC) levels. This enables the BESS to absorb more power if needed and reduces the use of resistors. If the target level for the state of charge is chosen slightly below 100% we keep some charging reserve, so that for most of the positive frequency excursions the use of the emergency resistors can be avoided. Additionally, there is a procedure incorporated into the control algorithm which allows selling relatively small amounts of energy on the intra-day market. The main goal of the selling procedure is not to gain a profit but again to keep the SoC parameter below a defined upper limit SoC_{max}.
The complete set of operating rules is the following:

- Discharge the battery when $f < f_{min} = f_{nom} - 20\text{mHz}$ (proportional to Δf).
- Charge the battery when $f > f_{max} = f_{nom} + 20\text{mHz}$ (in case SOC=100%, dissipate energy in emergency resistors)
- If $SoC > SoC_{max}$, discharge the battery (sell energy on the market with discharge power <12% of P_{BESS}).
- If $SoC < SoC_{min}$ and $\Delta f < |20\text{mHz}|$, recharge the battery (maximum recharge power <5% of P_{BESS}).
- Battery is idle when $\Delta f < |20\text{mHz}|$ and $SoC_{max} > SoC > SoC_{min}$

Operating rules with SoC limits make it possible to utilize the resistors only a few times per month for typically 10000 charge/discharge operations (pulses) of the BESS during that month, hence justifying the term “emergency resistors”.

Optimizing BESS capacity:
The detailed description of this calculation was recently published elsewhere [5], here we only give a brief description of the idea. Conceptually, the optimal BESS capacity is not calculated directly, but is rather a result of a cost-revenue calculation: What is calculated is the Net Present Value (NPV) of profit which is a mathematical function that depends – among other parameters – on the BESS capacity (see chapter 5). The main goal is to maximize the NPV of profit. The idea is to find the maximum NPV of profit by using the operating rules as described above and the set of input parameters as shown in table 2. This is done for a range of allowed values for input variables:
In a first step, the NPV of profit is repeatedly calculated by changing the values of the variables (see table 2). The second step is to take into account the energy losses in the resistors. Having no mathematical formulation for a penalty factor of using resistors we restricted the resistor losses to a maximum 10% of the total energy uptake into the BESS. As a result, the method provides the optimal BESS capacity of 0.62 P_{BESS} *h. The corresponding SoC profile using the frequency data of an exemplary month is depicted in Fig. 3.

TABLE 2: The BESS Parameters and Variables used in the optimization are based on a 2 MW lead acid BESS.

Parameters	BESS power = reserve power	2 MW
	Frequency profile	UCTE (Central European power grid), April 2005
	P-f characteristic, MW/mHz	0.011, non-critical window of ±20mHz
	BESS efficiency	70 %
	Life cycle	4 years (battery cells) / 20 years (PCS)
	Reserve prize (revenue)	120 €/kW/year
	Discount rate	6 %
	BESS cost function	Battery (installation): 250 k€/MWh PCS: 150 k€/MW Civil works: 120 k€
	Recharge tariff	60 €/MWh
	Sell energy tariff	50 €/MWh
Variables	SoC max (sell energy)	SoCmin < SoCmax < 100%
	SoC min (buy energy)	0% < SoCmin < SoCmax
	Recharge power	Varied in the range 0÷5, later fixed to 3% of P_{BESS}
	Sell power	Varied in the range 0÷12, later fixed to 3% of P_{BESS}

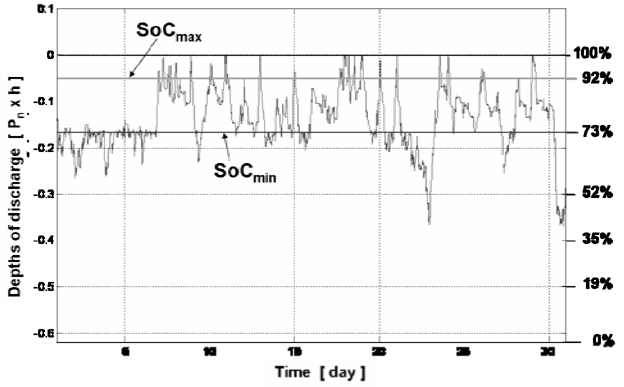

Figure 3: Calculated state of charge profile (SoC) of the BESS. Based on frequency data measured during April 2005. The BESS capacity is assumed to be 0.62 P_{BESS} *h.

4 Adequate operation algorithm for the BESS based on a multi-string topology

Multi-string operating algorithm

The BESS monitoring and control system uses the frequency measurement and the SoC level as input signals. So far the storage part of the BESS was assumed to be a single large battery which was sufficient for the modeling assumptions. For the further considerations with regard to a technical realization of the BESS the topology is refined as a battery of parallel strings. Each string is connected to a common AC bus via an individual power conversion system.

In order to explain the operation concept, a BESS with three independent battery strings is assumed (Fig. 4). During operation, each string is assigned to perform a dedicated function: At any given moment in time, one string is the so called "*Discharger*", another the "*Charger*" and the third one is the "*Equalizer*". The *Discharger* responds to negative frequency deviations out of the tolerance band of 50±0.02 Hz, i.e. any frequency deviation below 49.98 Hz, and injects the corresponding power into the grid by discharging the battery string. The *Charger* takes up any positive deviation, i.e. for frequencies higher than 50.02 Hz, and absorbs power by charging the string. The *Equalizer* is kept as a reserve capacity and is used to keep the total battery capacity within a predefined state of charge range SoC_{min} and SoC_{max}. For example, the total state of charge is preferably in the range of 73-92%. This means, when the total battery state of charge falls below the predefined lower level of 73% the *Equalizer* will slowly be charged until the prescribed total state of charge range is reached. The recharge operation of the *Equaliser* occurs only during times when the frequency is in the tolerance band, i.e. within 50±0.02 Hz and the recharge power is small (ex. 3% of P_{BESS})

The BESS operates in a mode with these fixed string functions until the state of charge of the *Discharger* drops below a minimum level or until the *Charger* is charged above a maximum level. In case the limit is reached for a single string, then the functions of all strings are changed by permutation. The string that was the *Discharger* becomes the *Charger*, the former *Charger* becomes the *Equalizer* and the *Equalizer* becomes the *Discharger*.

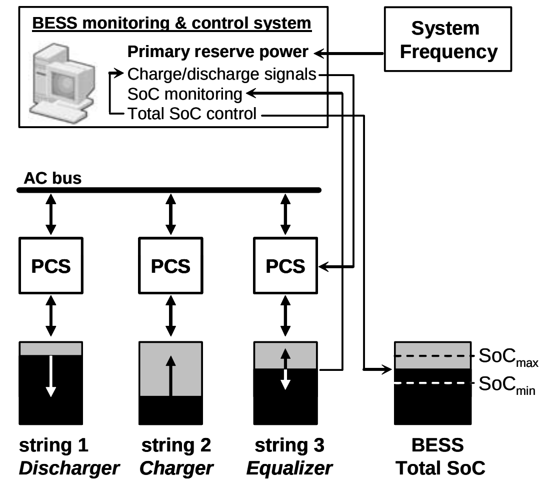

Fig. 4 BESS multi-string layout and operating principle.

There are two main benefits resulting from the arrangement with separate strings. Firstly, the less frequent charge/discharge operations allow a more accurate charge state determination thereby reducing the risk of deep discharges. Secondly each individual string remains in the same operational mode (either discharge or charge) over longer periods. This reduces unwanted premature ageing.

In the case of three strings, each single string can provide only one third of the total BESS power. This corresponds to a maximal frequency deviation of ±80 mHz, a situation that is valid for approximately 98% of the time. In the rare situation of a large frequency deviation, larger than the capability of a single string (larger than ±80 mHz), the *Equalizer* is used in parallel with the *Charger/Discharger* to boost the power output/input. For example, if a negative frequency deviation is so large that the *Discharger* alone can not provide the required power, the *Equalizer* is used as a "backup Discharger". The two strings will be able to deliver 2/3 of the BESS Power, satisfying power requests arising from frequency deviations up to ±140 mHz. Statistically this will cover 99.8% of the time. Further more, during the very rare situations of frequency deviations of more than ±140 mHz, all three strings are used in concert to fulfil the power request. This enables the BESS to deliver its full rated power P_{BESS} and thus guarantee primary frequency regulation at all times.

5 Monetary value analysis of a 2MW Lead-acid-BESS

To determine the economic viability of the BESS application for primary frequency control [6], the total Net Present Value of revenue from selling reserve (NPV_{RES}) must be compared with capital, operating, and maintenance (O&M) costs over the BESS life cycle (NPV_{BESS}).

$$Profit = NPV_{\mathrm{RES}} - NPV_{\mathrm{BESS}} \qquad (1)$$

$$NPV_{\mathrm{RES}} = \sum_{t=1}^{T} \frac{Revenue}{(1+r)^t} \qquad NPV_{\mathrm{BESS}} = \sum_{t=1}^{T} \frac{Cost}{(1+r)^t} \qquad (2,\ 3)$$

In these equations T is the BESS life cycle and r the discount rate (here T= 20 years, r= 6%). *Revenue* and *Cost* are annual values.

1) Revenue from providing primary control power

Revenue is the primary reserve availability payment. In this case of *primary* frequency control the TSO pays for the mere availability of control power. There is no utilization payment proportional to the actual amount of energy supplied or consumed. In Europe, the German market for primary frequency reserve has been established in 2001 and has the longest historic records in UCTE. The current average prize for primary reserve is about 120 €/kW/year. The revenues depend on the primary reserve prizes and are subject to uncertainty. Thus, the supply of 2 MW primary control power will bring annually 240 k€ to the owner of the BESS.

Introducing *Revenue* = 240 k€/year into equation (2) results in a net present value of revenue of NPV_{RES} = 2.89 M€ for the supply of primary control power.

As described in chapter 3, the sold energy is an additional source of profit for the owner of the BESS. However, the monthly amount of energy will rarely exceed 0.1 P_{BESS}*h and the revenue is small. Therefore, the revenue from selling energy on intra-day market is neglected in this estimation.

2) NPV of BESS cost for primary control power:
A 2 MW Lead-acid BESS has been selected for this application since it is the most economic solution for this application. We estimate two scenarios: an optimistic and a more conservative one. The optimistic one has the required capacity of 0.62 P_{BESS}*h = 1.24 MWh (as resulting from the modeling) and assumed battery cell life of six years. This BESS has a total installation cost of 860 k€ (see some of the cost components in table 4). Taking into account the fact that lead-acid battery cells may last for six years, three replacements should be scheduled for 20 years lifetime of the BESS. Therefore, we add the NPV of cost of the required battery cell replacements (532 k€) to the BESS installation cost. Further more, including Operation and Maintenance costs results in the total NPV of cost of NPV_{BESS} = 1.57 M€.

The conservative scenario has a design capacity of 0.83 P_{BESS}*h = 1.66 MWh and a battery cell life time of four years (four battery replacements during the 20 years). This results in an NPV_{BESS} = 2.29 M€.

3) Estimated value of BESS for primary control power: **With NPV_{RES} = 2.89 M€ and NPV_{BESS} = 2.29 M€** for the conservative scenario for example, a NPV of profit of 0.6 M€ is obtained (1) and the payback of the BESS for this conservative scenario is about 11 years. The more optimistic scenario with assumed battery cell life time of 6 years shows a payback time of only 4 years and a NPV of profit of 1.3 M€. These estimations show that a BESS designed for a relatively fast discharge is a profitable solution for the supply of primary control power. The prize of primary control power is the most important parameter, which influences the estimated profit and payback time. We assume that there will be a steady increase of primary control power prizes in the future.

Conclusions

The supply of frequency control reserve is important to balance power system load and generation at any instant for a secure and high-quality power grid. Battery Energy Storage Systems are able to satisfy the technical and economic requirements for primary frequency control.

The optimum BESS capacity is 0.62 MWh per 1 MW of reserve power. For a cost effective sizing it is essential to use maximum and minimum state of charge limits, to recharge at moderate rate while the system frequency is within the non-critical window, and to sell some power to the intraday market if the state of charge is on the high side. An economically optimized BESS for primary frequency control includes emergency resistors to dissipate energy during rare events when an extreme over frequency excursion occurs while the BESS is fully charged.

With estimated payback times between 4 and 11 years, a lead-acid BESS is a profitable utility solution at current battery system costs and current market prizes for the provision of primary reserve capacity.

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