GRID-SUPPORTING BATTERY ENERGY STORAGE SYSTEMS IN THE LOW-VOLTAGE DISTRIBUTION GRID

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ABSTRACT

The integration of renewable energy sources into the distribution grid may cause more profound voltage deviations and overloading of grid elements. In certain countries (for example, Belgium), a lot of photovoltaic systems are connected to the low-voltage distribution grid at household residences. These renewable energy sources may cause excessive voltage increase at times when also the load is low (for example, during a weekday in summer). If the voltage increases above a certain limit, the photovoltaic systems are forced to stop injecting the energy into the grid. Battery energy storage systems can be installed to solve such a problem. Furthermore, battery energy storage systems can be applied for other goals throughout the grid; for example, electricity cost optimization and peak shaving at the household, feeder, or transformer level. Control systems for providing such services are developed in a multilayered approach: from real-time control of the semiconductor components switching to the long-term optimization in grid planning.

Keywords: battery energy storage system, distribution grid, peak shaving, grid service

INTRODUCTION

Background

Low-voltage distribution grids are, in many places, suffering from increased loading since their inception, typically decades ago. The integration of local distributed generation offsets some of this load during certain periods of time, but it may also increase the occurrence of excessive voltage deviations at other moments, e.g., in low load situations.

Controlled intelligently, grid-coupled energy storage can be beneficial to multiple stakeholders in the electricity system [1]. If the storage efficiency and lifetime are sufficiently high, effective electricity costs for a Battery Electric Storage System (BESS) owner are lowered by charging when electricity cost is low and re-injecting when prices are high.

BESSs are expensive in terms of the investment in storage capacity. In practice, optimization methods are applied to achieve the most economic solution, whether it is for immediate benefits (e.g., through arbitrage on an electricity market), or longer-term benefits (e.g., avoiding grid investment). The outcome of such optimization is a charge and discharge schedule for the BESS.

Control Loops and Layers

The distribution grid contains a variety of control loops on different timescales. In this subsection, different control layers are clarified to facilitate the discussion in the full paper on the optimality of the grid services. Table 1 gives a schematic representation of the discussion in the coming paragraphs.

Grid planning studies take into account the ever-changing nature of the loads and distributed energy resources to make assertions about, amongst others, the future optimal configuration and strengthening of the grid. This information is then used – feedback in the control loop – to decide what changes to make and when to make them.

On an operational timescale other things are controlled. Off-load tap changers may be manually adapted once a year. This allows for the compensation of long-term voltage decrease because of increased loading of the grid. Also, in some grids, the connection of the feeder parts with each other or with the transformer can be reconfigured, something which is usually done to reassure security of supply in case some grid component fails.

Electricity costs on a wholesale market have a certain time resolution; for example, for the Belpex in Belgium this is one hour [2]. Any device that takes pricing into account in its behavior will have a corresponding control strategy at this timescale.

Devices that are bidirectionally coupled to the grid through power electronics have a control system that determines the switching of the semi-conductor components, which may happen at frequencies on the order of 10 kilohertz. Through this switching, current waveforms at the ms scale are generated to coincide with those of the grid.

Table 1. Distribution grid timescales and control loops.

timescale	control loop
decade	Grid strengthening
year	Off-load tap change Replacement of a transformer Feeder reconfiguration
day	Charging/discharging schedule of BESS
hour	Electricity cost On-load tap change
ms	Grid coupling by PV system or BESS
µs	Switching components

When a BESS is, for example, applied for voltage support, the distribution system operator (DSO) may avoid in the medium to short term the costly replacement of underground cables, as determined by a grid-planning study. Because of the relatively high cost of a BESS and to avoid over-investment, applying optimal siting and sizing methodology for the different objectives is crucial for a viable grid integration of the BESS [3]. A charging and discharging schedule for voltage support is determined in a window of days/weeks, but periodic modifications can take into account new information. In this BESS, grid-coupling paradigms with voltage and/or frequency droop, e.g., developed in Reference 4, are applied to facilitate local-scale and large-scale power system integration. Ultimately, it is only the physical switching of the semiconductor components that allows the current to flow from the battery to the grid and back.

OPERATIONAL CONSTRAINTS AND OBJECTIVES

A distinction is made between technical and economical objectives. An example of an economical objective for a BESS is electricity cost minimization, which corresponds with the well-known “buy low, sell high” strategy, also known as arbitrage. The pursuit of a technical objective offers benefits that may or may not be quantified as easily. If a household sometimes notices overvoltage problems and its photovoltaic (PV) system disconnects from the grid, the energy that could have been produced is wasted. This energy could then have been stored at that time and used later. However, for example, consider a DSO. The EN 50160 norm [5], applicable in Belgium, for voltage deviations in low-voltage grids dictates that for 95% of the week, deviations have to be within +/-10% of the nominal value. The DSO could install a BESS in a grid if more problems are detected than what is acceptable. The benefit now is that other grid-improving investments can be postponed.

A model is used to provide energy services at the lowest cost [6]; see Table 2 for the schematic overview. Technical constraints of the system are boundary conditions for the optimization for the energy service objective. Batteries have a certain storage capacity, storage efficiency, self-discharge, cycle life, shelf life, and charge and discharge rates. The power electronic interface to the grid has a certain efficiency, lifetime, and power rating. These parameters also determine the depreciation cost of cycling the battery.

The costs of owning and operating the BESS are determined by an economic cost model [7]. The total cost is determined as the sum of the fixed and the variable costs. The cost deprecation component is taken into account in the variable costs, as it depends on the operation of the system. Maintenance, investment, and the depreciation of the power electronics are taken into account in the fixed costs.

Table 2. BESS operation.

BESS Operation					
Technical constraints		Economic cost model		Energy service objective	
Battery	Power electronics	Fixed	Variable	Technical	Economical
				Peak shaving Voltage support	Arbitrage

BESS DEVELOPMENT

A 4.3-kilowatt hour grid-coupled BESS for peak shaving application is developed. The BESS consists of an inverter, offering AC/DC and DC/DC conversion, and two battery modules in series, each composed of 48 lithium iron phosphate ($LiFePO_4$) cells with a capacity of 15 Ah. These modules are each actively balanced and contain temperature sensors and per cell voltage measurement for computer readout (RS232). A battery protection module (BPM) checks the voltages and temperatures autonomously and signals if problems are detected. A programmable logic controller can open a circuit breaker, isolating the batteries, if necessary conditions are met. The programmable inverter is controlled in real time from the Matlab/Simulink environment.

The BPM avoids damaging the batteries during development; however, in normal operation it will not arrive in a fault situation because the boundary conditions are implemented redundantly in the Simulink control scheme. A rule-based control scheme avoids exceeding voltage, current, and state-of-charge limits of the battery [8]. A multistage constant current charging algorithm is implemented, because of its lifetime maximizing property [9]. The final control layer implements peak shaving. In the full paper, the performance of the BESS will be detailed. The application of peak shaving, with both positive and negative power limits, will be demonstrated in a case with residential load and PV generation and compared with a benchmark optimization.

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BIOGRAPHICAL NOTE

Conference presenter: Frederik Geth received the M.Sc. degree in electrical engineering from the Katholieke Universiteit Leuven (K.U.Leuven), Leuven, Belgium, in 2009. Currently, he is working as a research assistant with the division ESAT-ELECTA. His research interests include optimal storage integration in distribution grids, batteries for (hybrid) electrical vehicles, and mitigating the impact of the charging of (hybrid) electrical vehicles on the low-voltage distribution grid.