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Electrical operation behavior and energy efficiency of battery systems in a virtual storage power plant for primary control reserve

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ABSTRACT

A rising interest in battery systems for various applications needs a deep understanding of the system performance for technical and economical optimization. The electrical system behavior and the energy efficiency of two different Li-ion battery systems are presented in this paper. Both systems are designed for operation in a virtual storage plant with respect to the primary control reserve. The efficiency of both systems is analyzed including the battery, the power electronics and auxiliary units. Based on the overall energy efficiency of the electrical storage systems, a model is developed to show the impact on the operation and standby behavior. This model is transferred in a simulation framework investigating the application of battery systems towards primary control reserve. Real frequency data of continental European transmission system are used to simulate the behavior of the two systems in order to determine energy losses during operation. Primary control reserve is one possible application as grid support service for battery systems and is under current discussion. In this new field of battery application energy losses are a limiting factor for economic and technical qualification. The simulation identifies strengths and weaknesses of the investigated systems based on the determined efficiencies, and the results support an optimized operation strategy.

1. Introduction

In a progressive developing society with increasing energy consumption, a need of flexibility and also with respect to ecologic values a global change of energy supply is required. A significant increase of the share of renewable energy in the coming years is expected [1]. Renewable energy supply and energy demand do not correlate inevitably. One way to solve this non-congruence is to store the energy. Therefore different storage technologies exist, e.g. battery storage systems with lithium ion battery cells.

Assuming a decrease of the number of central power plants for base load supply decentralized electrical power supply systems may play a dominant role in the future [2]. In order to manage these changes, storage solutions may contribute to support the necessary grid services which were previously provided by conventional power plants. For dispersed generation a larger number of small units will come into focus with new capabilities and uncertainties in operation. In any event the electrical grid has to be stabilized in short- and long-term time frames. For the short term application the primary control reserve is the symmetric control strategy to stabilize the grid to 50 Hz.

In order to stabilize electrical grids via primary control reserve lithium ion battery storage systems [3,4] can be used. The lithium ion technology is a promising storage technology due to high charge and discharge capabilities, high energy density and low self discharge. It is important to reach the highest possible efficiency in order to avoid the loss of energy, independent of the storage technology. Battery systems for primary control reserve are complex compared to standard stationary battery system for low power applications. Additional protection and controller units are necessary. However, additional devices consume additional energy and thus reduce the system efficiency. Therefore an economic successful operation of battery systems necessitates a detailed investigation of the efficiency behavior.

Primary control reserve cannot be provided by each system available on the market. The threshold performance for primary control reserve power is 1 MW. Thus, small systems such as in residential applications could only participate in the primary control reserve market as a pool of small systems called virtual power storage plant. In this case new possibilities arise. If different kinds of energy storage systems are integrated in this virtual storage plant, an optimization could be done with respect to advanced operation strategies. In this case it is also necessary to determine the efficiency depending on the power of each system. Auxiliary and standby losses are included in the efficiency in

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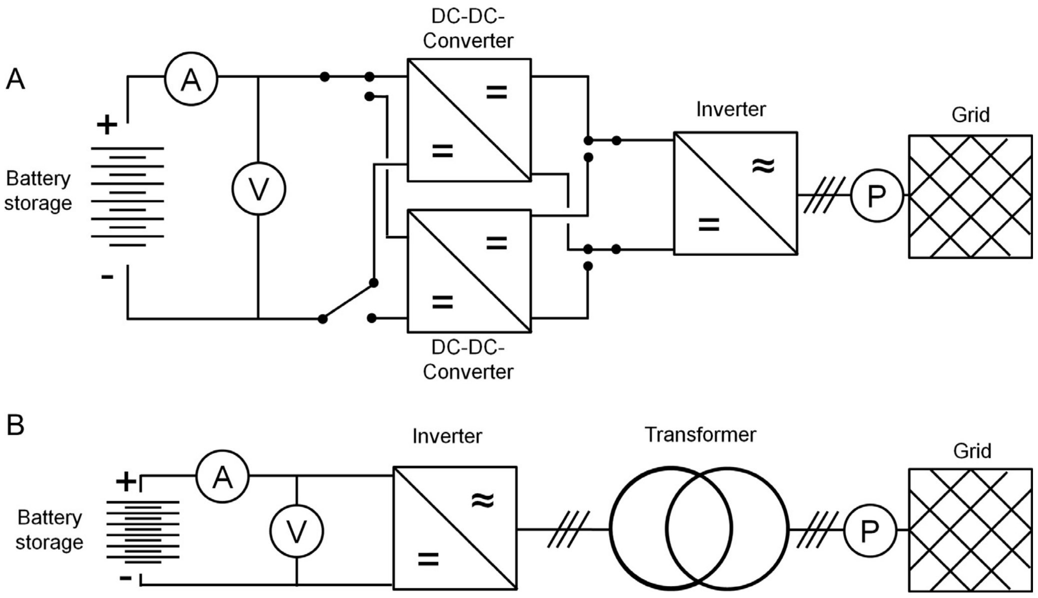

Fig. 1. Circuit diagrams of two different topologies of Battery-storage systems for primary control reserve including voltage, current and power measurements. (a) Battery-storage system with two DC-to-DC-converters with different maximum power and one DC to AC inverter and (b) battery-storage system with one DC to AC inverter and one transformer.

order to optimize each system within the power plant and to reduce energy consumption by supporting the grid.

In this paper two storage systems based on lithium ion technology are investigated relating to their application in the primary control reserve power market. The energy efficiency behavior and the energy losses are investigated and mathematical correlations are derived which were used to model both systems. The energy losses were determined under operation with respect to the primary control reserve.

2. Theory & experimental setup

Two different battery storage systems based on lithium ion technology for grid primary control reserve were investigated. Both systems have a maximum power of 20 kW, but consist of different system topologies. The equivalent circuit diagrams of both systems are shown in Fig. 1. System A had a direct current (DC) voltage level between 150 and 180 V with lithium ion cells, 25 A h each. The cells were graphite based on the anode side and NMC-oxide (lithium nickel manganese cobalt oxide) based on the cathode side. Three battery modules were installed in series whereby each module consisted of 15 cells in series connection and three in parallel (15s3p) with an energy content of 12 kWh. Two DC-to-DC converters for different power ranges were installed to set the DC link voltage to a higher level for the inverter to convert DC to a three-phase alternating current (AC) with a phase to phase voltage of 400 V. System B had a DC voltage level between 420 V and 560 V. Lithium ion cells with a graphite based anode and a NCA-oxide (lithium nickel cobalt aluminum oxide) based cathode were used, each cell having a capacity of 45 A h. The battery system consisted of 10 modules in series connection, where each module includes 14 cells in series. The energy content of the system was 20 kWh. One inverter was installed to convert DC link voltage to three phase AC voltage. Due to the level of the DC intermediate circuit voltage being too low to reach the phase to phase AC grid voltage of 400 V, a wye connected transformer was installed for direct grid connection. An overview of system A and system B is provided in Table 1.

Table 1
Rated power and energy of system A and B.

	System A	System B
Rated power/kW	20	20
Rated energy/kWh	12	20

The measurement points for voltage (V), current (A), and active power (P) are indicated. Both systems were investigated on the DC side via current sensors and voltage measurement and on the AC side via a 3 phase power measurement device (ECS-PM3-80) to determine the system parameters for characterization such as efficiency, auxiliary losses, standby losses and grid power. The DC voltage on both systems was measured with a LEM current transducer HTR 100-SB connected to a Keithley 2010 multimeter. The DC voltage was measured by the internal battery management system.

One of the key performance indicators of a storage system is the energy efficiency. Losses occur in the inverter, the battery, the transformer and in the auxiliary units.

$$\eta_t(P,\mathrm{SOC}) = \eta_b \eta_{el} \tag{1}$$

According to Eq. (1) system efficiency is divided into battery efficiency and electrical efficiency including everything other than the battery.

Essentially, the definition of efficiency of the total system η_t is the relationship between the energy supplied and the energy needed from the grid to re-establish the same state of charge (SOC) prior to the discharge (Eq. (2)).

$$\eta_t(P,\mathrm{SOC}) = \frac{\int_{\mathrm{SOC2}}^{\mathrm{SOC1}} |P_{g,d}|\,\mathrm{d}t_d}{\int_{\mathrm{SOC1}}^{\mathrm{SOC2}} |P_{g,c}|\,\mathrm{d}t_c} \tag{2}$$

In this equation $P_{g,d}$ is the power at the grid access point during the discharging and $P_{g,c}$ is the power at the grid access point during the charging process. For the time t the same indices are used. The limits of integration SOC1 and SOC2 describe the states of charge between which the measurements were carried out in order to determine the efficiency. The starting SOC was also the SOC at the end of the measurements in order to fulfill the definition.

For the determination of the energy storage efficiency it was also necessary to determine the auxiliary and standby losses, because these effects reduced the stored energy depending on storage time. These losses were included in η_{el} during operation and separately considered during the standby or 'Off' mode and they are listed in Section 3 in an overview.

2.1. Determination of system efficiency at a fixed SOC

In order to reduce the efforts to determine the system efficiency according to Eq. (2) an alternative approach to full charge/discharge cycles is proposed. For primary control as grid support service