Energy 118 (2017) 446–455

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Decentralized price-driven grid balancing via repurposed electric vehicle batteries

B. Faessler [a, b], P. Kepplinger [a], J. Petrasch [a, *]

[a] Josef Ressel Center for Applied Scientific Computing in Energy, Finance, and Logistics, Vorarlberg University of Applied Sciences, Hochschulstrasse 1, 6850 Dornbirn, Austria

[b] Faculty of Engineering and Science, University of Agder, Jon Lilletuns vei 9, 4879, Grimstad, Norway

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form
1 December 2016
Accepted 4 December 2016

Keywords:
Grid balancing
Vehicle batteries
Repurposed
Battery storage
Distributed storage
Optimization

ABSTRACT

The share of electricity generated from intermittent renewable sources, e.g., wind and solar grows rapidly. This affects grid stability and power quality. If the share of renewable power generation is to be increased further, additional flexibilities must be introduced.

Aggregating small, distributed loads and energy storage facilities is a good medium-term option. In this paper, the suitability of decentralized and on-site optimized storage system consisting of repurposed electric vehicle batteries for grid balancing is investigated. Battery operation is controlled via an optimization procedure, which relies on a one-way communicated pseudo-cost function (PCF). Day-ahead electricity stock market prices are used as the PCF.

Based on one year simulations, a sequential quadratic programming (SQP) approach is compared to a dynamic programming (DP) and an integer linear programming (ILP) approach with respect to runtime and control objective. All approaches lead to very similar results, however ILP leads to the shortest runtimes. ILP is then used to investigate the grid balancing potential using last decade's hourly day-ahead prices. Higher market data resolutions featuring quarter-hours introduced in 2014 lead to higher earnings. For hourly day-ahead prices the optimal capacity-to-power ratio of the battery is approximately 6 h while for quarter-hourly prices it is about 3 h.

1. Introduction

Global warming and dwindling fossil resources have sparked a strong growth in renewable power generation. Some industrialized countries have set very ambitious targets for increasing the proportion of renewables in electricity production [1]. For example, Germany plans to generate 80% of its electricity from renewable sources by 2050 [2]. However, fluctuating sources of renewable energy such as wind and solar severely affect grid operation [3,4]. Supply and demand imbalances are traditionally compensated for by large-scale buffer storage systems, e.g. pumped storage hydro power plants. These grid balancing strategies are limited by infrastructural considerations [5]. Therefore, developing additional, modular strategies for grid balancing are necessary [3,6].

Aggregating small, distributed loads and energy storage facilities constitutes a promising approach. Such a strategy would reduce the need for new power plants [7]. In this context, demand side management (DSM), which is known as a portfolio of measures to balance the electrical grid on consumption side [6], has been extensively discussed [8]. In DSM, controllable, flexible loads and energy storage facilities reduce, increase or shift energy consumption in order to line up electric energy usage with generation [6]. The most important strategies used are peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shaping [9]. To motivate consumers to change their consumption from the nominal pattern to respond according to the actual electric energy generation, a specific tariff or program has to be provided [10]. Han et al. [11] distinguish between incentive- and time-based demand response (DR). In Ref. [10], they further divide incentive-based DR in classical and market-based DR. In case of classical DR, consumers agree to give-up the control of certain devices or react by limiting their consumption based on payments or preferential prices. Market-based DR allows consumers to bid with their loads and energy storage facilities on an appropriate marketplace. Time-based DR depend on received event signals e.g. price which stimulates devices to react with their

* Corresponding author.
E-mail address: joerg.petrasch@fhv.at (J. Petrasch).

http://dx.doi.org/10.1016/j.energy.2016.12.013
0360-5442/© 2016 Published by Elsevier Ltd.

Nomenclature

A	Surface area of the battery pack (m^2)
C	Path dependent costs in DP (€)
c	Pseudo-cost function (€/MWh)
c_p	Specific heat capacity (J/(kg·K))
d	Thickness of battery pack isolation (m)
E_{el}	Electrical energy content (J)
$E_{el}^{(n_s)}$	Scaled electrical energy content (J)
f	Heat removal proportionality constant (W/K)
g_l, g_u	Constraints for lower and upper E_{el} in SQP (J)
h	Connective heat transfer coefficient ($W/(m^2 \cdot K)$)
I_{DC}	Direct charge/discharge current (A)
$I_{DC}^{(n_s)}$	Scaled charge/discharge current (A)
k	Thermal conductivity ($W/(m \cdot K)$)
m	Battery mass (kg)
$m^{(ns)}$	Scaled battery mass (kg)
n	Total number of data point (–)
n_c	Number of battery cells per string (–)
n_s	Number of battery cell strings (–)
P_{AC}	Alternating power (W)
P_{DC}	Direct power (W)
$P_{DC}^{(n_s)}$	Scaled direct power (W)
P_{fan}	Cooling fan power (W)
$P_{fan}^{(n_s)}$	Scaled cooling fan power (W)
P_h	Auxiliary heating power (W)
$P_h^{(n_s)}$	Scaled auxiliary heating power (W)
P_{loss}	Linearized battery losses (W)
P_{Ri}	Dissipated heat transfer rate due to internal resistance (W)
$P_{Ri}^{(n_s)}$	Scaled dissipated heat transfer rate due to internal resistance (W)
$\dot{Q}_{cool}$	Heat transfer rate due to cooling (W)
$\dot{Q}_{cool}^{(n_s)}$	Scaled heat transfer rate due to cooling (W)
$\dot{Q}_{loss}$	Heat loss via insulation (W)
$\dot{Q}_{loss}^{(n_s)}$	Scaled heat loss via insulation (W)
R_c	Internal resistance of single cell (Ω)
R_i	Internal resistance (Ω)
SOC	State of charge (%)
s	Discrete states in dynamic programming (–)
T	Battery temperature (°C)
T_{amb}	Ambient temperature (°C)
t	Time (s)
U_{DC}	Direct terminal voltage (V)
U_T	Thermal transmittance ($W/(m^2 \cdot K)$)
u_{AC}	Decision variable on AC power side (–)
u_{DC}	Decision variable on DC power side (–)
η_{in}	Charge converter efficiency (–)
η_{out}	Discharge converter efficiency (–)
τ	Time interval for analytic solution (s)

demand [11].

Contrary to DSM, distributed loads and energy storage facilities could be introduced to the power grid with the specific aim of balancing the grid.

In any case, these devices that are to be used for grid balancing have to be equipped with communication hardware. While most grid balancing concepts require two-way communication [12] - as price signals, bid data, etc. have to be transmitted between utilities and loads and energy storage facilities [10] - local, autonomous control with unidirectional communication proposed in Ref. [13] has been demonstrated as a robust and cost effective alternative.

With an increasing share of decentralized and fluctuating electricity generation due to sources such as wind and solar the voltage level in the power grid is affected [14,15]. Such sources are often connected to the low voltage grid [16–18]. Active and reactive power control strategies have been discussed and applied to limit the voltage rise [14,15,19].

Battery storage systems are suitable for either large-scale applications or for aggregated approaches. They are practically maintenance-free [20], fast to respond [21], and highly efficient [22]. They have total round-trip efficiencies, including AC-DC converters, ranging from 65% to almost 90% [23]. Various types of battery storage systems have been investigated for balancing electrical grids [24–26]. A range of cell chemistry types have been considered, particularly lithium-ion (Li-ion), sodium sulfur (NaS), ZEBRA ($Na\text{-}NiCl_2$), nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and lead acid (Pb-acid) type batteries [27,28]. Divya et al. [29] state that the application timescales for future battery storage systems may range from seconds to days. Battery storage systems have been already investigated in large-scale applications for primary frequency control [30] and for secondary control [31]. Since lifecycle costs for such systems are higher than, for instance, pumped storage hydro power plants [32], numerous applications seek to aggregate already existing, small battery storage systems. Often, photovoltaic power systems are combined with small battery banks to increase the self-consumption [33]. Since the capacity of such batteries is not entirely used at all times, a DSM motivated approach would further increase the efficiency of usage. Such concepts have been extensively discussed in Ref. [34]. Guille et al. [35] state that on an average, electric vehicles (EV) stay idle for about 22 h a day. Hence, in DSM, the idea of aggregating batteries of EVs for control strategies, a concept which is known as vehicle-to-grid (V2G), seems to be promising and was proposed, among others, in Refs. [29,36–40]. Daimler announced [41] that it plans to re-use their old EV batteries and connect them to the electrical grid, thus building the world's largest stationary storage facility with a capacity of 13 MWh. Using repurposed electric vehicle batteries may help to offset the costs associated with battery-based systems [42]. Batteries are generally not used in EVs once their capacity falls below 70–80% [43] of the initial capacity. However, they are still useful for stationary applications. This second-use approach also reduces the ecological footprint [44].

In the current paper, local, autonomous control with a unidirectionally communicated time-based event signal (pseudo-cost function) [45] (as is often used in DSM), which has been successfully tested for domestic hot water heaters [46], is applied to battery storage systems. In a previous paper [47], the potential of ZEBRA (Zero Emission Battery Research Activities) batteries for autonomous control has been investigated by simulation. In this paper steps are taken towards implementing the approach on a physical battery system by developing an embedded control system with highly efficient simulation and optimization routines. To this end, different nonlinear and linear optimization approaches are compared with respect to computational costs and resulting control optimality. A sequential quadratic programming approach (SQP) is used for non-linear optimization. Dynamic programming (DP) as well as integer linear programming (ILP) are approaches considered for linear optimization. The grid balancing potential is