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Optimal management of stationary lithium-ion battery system in electricity distribution grids

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HIGHLIGHTS

- A battery management model is developed for stationary battery applications.
- The model is tested in a hypothetical case study in Great Britain in 2020.
- Battery usage ensures high wind energy surplus compensation in the distribution grid.
- Efficient battery utilisation is achieved.
- The battery contributes to residual demand smoothing at electricity market level.

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ABSTRACT

The present article proposes an optimal battery system management model in distribution grids for stationary applications. The main purpose of the management model is to maximise the utilisation of distributed renewable energy resources in distribution grids, preventing situations of reverse power flow in the distribution transformer. Secondly, battery management ensures efficient battery utilisation: charging at off-peak prices and discharging at peak prices when possible. This gives the battery system a shorter payback time. Management of the system requires predictions of residual distribution grid demand (i.e. demand minus renewable energy generation) and electricity price curves (e.g. for 24 h in advance).

Results of a hypothetical study in Great Britain in 2020 show that the battery can contribute significantly to storing renewable energy surplus in distribution grids while being highly utilised. In a distribution grid with 25 households and an installed 8.9 kW wind turbine, a battery system with rated power of 8.9 kW and battery capacity of 100 kWh can store 7 MWh of 8 MWh wind energy surplus annually. Annual battery utilisation reaches 235 cycles in per unit values, where one unit is a full charge-depleting cycle depth of a new battery (80% of 100 kWh).

1. Introduction

Lithium-ion energy storage technologies are attracting a great deal of interest in the field of battery[1] research for electric vehicles (EV). The interest in Lithium-ion batteries is based on several technical advantages: high energy conversion efficiency of more than 95% (electrical–chemical–electrical, at 1C[2] and below), a long lifecycle of 3000 cycles (at deep discharge of 80%) and high energy density up to 200 Wh kg^{-1} [1,2]. According to the technology roadmap of European Commission (EC) [3], it is expected that a large number of EVs will be using the electricity grid by 2020. This in turn stimulates research on Lithium-ion technologies, where efforts are focused on increasing technical performance and reducing costs in general. The latter is currently the main drawback [4], but as they overcome this barrier and given the above-mentioned characteristics, Lithium-ion batteries are suitable for large scale use not only in EVs but also in stationary applications.

Potential grid support services of battery technologies are widely studied mainly for grid connected EVs, but also for stationary battery applications. Battery energy storage as a means for facilitating distributed renewable energy sources of electricity (RES-E) penetration is the subject of a study by Leadbetter and Swan [5], who conclude that energy storage systems provide a

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[1] 'Battery' refers to a secondary electrochemical battery.

[2] 'xC' indicates battery charging/discharging current rate, e.g., charging current of 1 C for a 5 Ah battery is 5 A.

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means of increasing grid flexibility and enabling the integration of stochastically variable generation sources by temporarily decoupling this generation from demand. White and Zhang [6] find that the importance of EVs lies in peak demand reduction on a daily basis; however, there is little financial incentive. According to Denholm et al. [7], EV batteries are also able to reduce curtailment under high RES-E generation. In all these studies, batteries are seen as a controllable load, which, when available, can be shifted to accommodate variable RES-E power. For example, a battery could be charged at high RES-E generation and low demand in the distribution grid in order to prevent situations of reverse power flow in the distribution transformer. In order to increase the feasibility of grid connected batteries, it is suggested that load shifting be shared with other grid support services such as frequency regulation [8] and voltage control [9]. Neubauer and Pesaran [10] have studied the secondary use of EV batteries as grid based energy storage applications, which has the potential to become a common component of automotive batteries' lifecycle, essential for use in cost effective energy storage. The abovementioned grid support services of battery systems are supported by the EC as one of the key policy priorities for renewable energy generation, including the development of methods and tools for the network integration of distributed renewable resources [11].

Given the energy technology trends in distribution grids and the importance of feasibility for the widespread implementation of batteries, this article puts forward proposals as to how a Lithium-ion battery system[3] can be best managed for stationary applications. The proposals are aimed at maximum feasibility of battery systems, focussing on the following three priorities (in order of importance):

1) High utilisation of distributed RES-E in the distribution grid

The battery is managed so as to prevent reverse power flows in the distribution transformer. At high RES-E penetration, this may avoid the need for reinforcements of the distribution grid.

2) Efficient utilisation of the battery

Efficient utilisation of batteries leads to a short payback period. This is an important economic incentive from the end energy user perspective, as it could result in high battery deployment in households. Moreover, since battery operation mode is regulated by electricity price, the battery contributes to the smoothing of residual demand (i.e. demand minus RES-E generation) at electricity market level. Demand smoothing is a process in which demand variations are reduced by charging and discharging batteries at times of low and high demand respectively. This operation follows the prices of the electricity market.

3) Smoothing of residual distribution grid demand (i.e. demand minus RES-E generation)

Residual demand smoothing in the distribution grid will lead to peak demand reductions when the electricity price is high and to off-peak demand rises when the price is low. This smoothing is performed for an aggregated residual distribution grid demand at step-down distribution transformer level, which is the product of distribution grid demand minus distributed generation (DG) from RES-E. Dynamic grid support services like frequency and voltage control are beyond the scope of this article.

[3] 'Battery system' refers to battery and power converter.

The proposed approach to management is based on the demand-tracking management model of a battery for stationary applications presented by Purvins et al. [12]. The aim of demand-tracking management is peak demand shaving and demand smoothing. The proposed approach includes additional management priorities and is more accurate, since it takes account of battery aging, which causes reduction of battery capacity and efficiency after any additional charge-depleting cycle. Moreover, the proposed management code would be more efficient for distribution grid applications, as it recalculates optimal battery operating power at hourly intervals, taking into account updated prediction profiles of residual distribution grid demand and electricity market price. The management can be applied for new as well as second-hand battery systems.

Section 2 of the article describes the battery system management model in details. In Section 3, a case study in Great Britain (GB) is presented, starting with demand and wind speed data acquisition and proceeding with wind farm/turbine power calculations, battery system sizing and study results. In Section 4, the payback period of the battery system is calculated at different battery system capital costs and electricity prices. Section 5 contains our overall conclusions.

2. Management methodology

The battery system is managed according the three above-mentioned priorities: high utilisation of distributed RES-E in the distribution grid (1st priority), efficient utilisation of the battery (2nd priority) and residual distribution grid demand smoothing (3rd priority).

In line with the first priority, battery capacity is firstly reserved to be used to prevent reverse power flows in the distribution grid transformer, i.e. the battery stores RES-E energy surplus in the distribution grid and supplies the stored energy to the grid during high residual demand.

The second priority, efficient utilisation of the battery, is achieved by charging the battery during times of low electricity price and discharging during high price periods when possible. The battery thus reaches the highest possible state of charge (SoC) at the end of the low electricity price period. At the beginning of the next high price period, this stored energy is supplied to the grid when possible. The minimum possible SoC is thus reached at the end of the high price period. The highest and lowest possible SoCs are assumed to be 100% and 20% respectively. However, since battery performance is limited by the rated battery system power, management constraints and the length of the low/high price periods, the highest/lowest SoCs will not always be reached. Nowadays, with different electricity price systems, low electricity prices usually apply during the night at times of off-peak demand and high electricity prices during peak demand hours (morning and afternoon peak). In the future, with electricity systems at high RES-E deployment, the electricity price curve may change its characteristics and be partly determined by RES-E generation. In Great Britain, electricity price levels may be strongly influenced by overall country-scale wind farm generation. At the end of 2011, Great Britain already had 6.5 GW installed wind farm capacity [13] and, according to the national renewable energy action plan, will have 27.9 GW by 2020 [14]. High wind generation during midday may reduce residual demand significantly, leading to a change in electricity price from high to low. This electricity price will determine the operation mode of the battery.

Finally, battery system operation (instantaneous) power is variable and this allows for residual demand smoothing at distribution grid level. Thus, during times of high electricity prices, battery capacity is firstly reserved for the reduction of the highest residual