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An improved charging/discharging strategy of lithium batteries considering depreciation cost in day-ahead microgrid scheduling

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ABSTRACT

An energy storage system is critical for the safe and stable operation of a microgrid (MG) and has a promising prospect in future power system. Economical and safe operation of storage system is of great significance to MGs. This paper presents an improved management strategy for lithium battery storage by establishing a battery depreciation cost model and employing a practical charging/discharging strategy. Firstly, experimental data of lithium battery cycle lives, which are functions of the depth of discharge, are investigated and synthesized. A quantitative depreciation cost model is put forward for lithium batteries from the perspective of cycle life. Secondly, a practical charging/discharging strategy is applied to the lithium battery management in MGs. Then, an optimal scheduling model is developed to minimize MG operational cost including battery depreciation cost. Finally, numerical tests are conducted on a typical grid-connected MG. Results show that the depth of discharge of storage is scheduled more rationally, and operational cost is simultaneously saved for MG under the proposed management strategy. This study helps to improve the cost efficiency and alleviate the aging process for lithium batteries.

1. Introduction

Microgrid is a promising form to integrate distributed generators (DGs), including wind turbines (WT) and photovoltaic (PV), which plays an important role in dealing with the energy crisis, the environmental degradation, and the power shortage problems [1]. Due to the characteristics of intermittency and uncertainty, the integration of WT and PV into MGs brings great challenges to the scheduling and operation. In order to alleviate the power fluctuation of the renewable energy, MGs are generally equipped with an energy storage system (ESS), which not only contributes to maintain the safe and stable operation of MG, but also plays a role in load shifting [2,3].

Compared to the conventional grid, one of critical issues in MG is the storage management. An energy management system is necessary in MG for the coordination of various DGs, ESS and even the load. Several methods have been reported focusing on the MG energy management with the objective of minimizing the operation cost and environmental impact [4–8]. The heuristic control strategy is one of common methods used for ESS charging/discharging control in MGs [4,5]. Decisions are made based on the current information, which is particularly appropriate for real-time dispatch. In [6], an optimization model based on Mesh Adaptive Direct Search is established for MG energy management. A fuzzy logic expert system combined with linear programming is proposed for battery scheduling in [7]. The framework can cope with uncertainties in MG. The battery depth of discharge (DOD) can be scheduled at a convenient degree by the fuzzy logic technology. In [8], a probabilistic approach for MG operation management is proposed under the uncertain environment. In the objective function, the operation cost of storage device is included. Similar to the cost model of a controllable generator, the storage cost is composed of bid price and start-up/shut-down cost, which still has room for improvement.

With respect to ESS economical operation, research has been carried out in [9–14]. In [9], a two-layer management approach is proposed for day-ahead economical scheduling and real-time dispatch. In the model, ESS cost consists of the charging/discharging cost and the cost related to the cycle life loss. However, the cycle life of a battery depends closely on the DOD, charging strategy, and so on [10,11]. In [12], a penalty cost as a function of storage DOD is added to MG operational cost. It acts as a soft constraint to prevent a large DOD of the storage. A more reasonable cost model is given on the basis of the decline in state of health (SOH) of ESS in [13]. The SOH directly affects the ESS lifetime.

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Nomenclature

i, n_G	index and number of controllable units
k, n_{ST}	index and number of LB groups
t_1, t_N	start and end time of scheduling horizon
ΔT	length of a scheduled time step (15 min)
$P_i^G(t)$	output of the ith controllable unit at time step t (kW)
$P_{i,\min}^G, P_{i,max}^G$	minimum and maximum output of the ith controllable unit (kW)
$B_i^G(t), B_{st,i}^G(t)$	binary status and start-up variables of the ith controllable unit
$P^{Buy}(t), P^{Sell}(t)$	power purchase/sale from/to the utility grid at time step t (kW)
P_{max}^{PCC}	power exchanging limit at PCC (kW)
$P^{PV}(t), P^{WT}(t)$	scheduled power output of PV and WT (kW)
$P_{fore}^{PV}(t), P_{fore}^{WT}(t)$	forecasting power output of PV and WT (kW)
$P^L(t)$	load in MG at time step t (kW)
DOD^{ST}	depth of discharge of LB (%)
ΔL^{ST}	LB life loss in a charging/discharging cycle (%)
ΔU^{ST}	LB depreciation cost in a charging/discharging cycle (RMB)
N^{ST}	actual cycle life of LB (cycle time)
n_{seg}	number of piecewise linear segments of LB depreciation cost function
DOD_j^{ST}	continuous variable at the jth DOD segment (%)
B_j^{ST}	binary variable at the jth DOD segment
DOD_{Sj}^{ST}	start point of the jth DOD segment (%)
α_j, β_j	slope and Y-intercept of the jth segment of LB depreciation cost function
$SOC^{ST}(t)$	SOC of LB at time step t (%)
ΔSOC^{ST}	variation of the SOC (%)
$SOC_{max}^{ST}, SOC_{min}^{ST}$	upper and lower bounds of SOC (%)
$SOC_j^{ST}(t)$	continuous variable at the jth SOC segment (%)
$SOC_{Sj}^{ST}, SOC_{Sj+1}^{ST}$	start and end point of the jth SOC segment (%)
$SOC_{op}^{ST}(t)$	optimized SOC of the LB (%)
SOC_{mov}^{ST}	the up or down moving distance of the SOC curve from its primary scheduled SOC (%)
SOC_{mid}^{ST}	the middle level of SOC (%)
$P_{CH}^{ST}(t), P_{DIS}^{ST}(t)$	charging and discharging power at time step t (kW)
$P_{CHmax}^{ST}, P_{DISmax}^{ST}$	maximum charging/discharging power of LB (kW)
$B_{CH}^{ST}(t), B_{DIS}^{ST}(t)$	binary variables related to LB charging and discharging status at time step t
$P_{CH,j}^{ST}(t), P_{DIS,j}^{ST}(t)$	charging and discharging power at the jth SOC segment (kW)
$P_{CHmax,j}^{ST}, P_{DISmax,j}^{ST}$	maximum charging/discharging power at the start of the jth SOC segment (kW)
$B_{CH,j}^{ST}(t), B_{DIS,j}^{ST}(t)$	binary variables related to the charging and discharging status at the jth SOC segment
$\eta_{CH}^{ST}, \eta_{DIS}^{ST}$	LB charging and discharging efficiency (%)
$P_{max}^{ST}, E_{max}^{ST}$	rated power and energy capacity of LB (kW and kW h)
E_{hou}^{ST}	hourly charged/discharged electricity (kW h)
f_1	objective function of the traditional method (RMB)
f_2	objective function of the proposed method (RMB)
$f_{fuel,i}^G(t)$	fuel cost of the ith controllable unit (RMB/h)
$f_{main,i}^G(t)$	maintenance cost of the ith controllable unit (RMB/h)
$f_{st,i}^G(t)$	start-up cost of the ith controllable unit (RMB)
$f^{Buy}(t)$	energy purchase cost from the utility grid (RMB/h)
$f^{Sell}(t)$	energy sale revenue to the utility grid (RMB/h)
$f_{hou}^{ST}(t)$	hourly O&M cost of LB (RMB/h)
f_{cap}^{ST}	LB capital cost (RMB)
C_O, C_M	constants of LB O&M cost (RMB/kW h, RMB/kW h^2)
C_P, C_W	constants of LB capital cost (RMB/kW, RMB/kW h)
$U_{st,i}^G$	start-up cost of the ith controllable unit (RMB)
U^{Buy}, U^{Sell}	power purchase and sale price from/to the utility grid (RMB/kW h)
C, d, m	coefficients of the three-parameter function for a kind of S–N curve
$\gamma\%$	the proportion of LB controllable depreciation cost in its total capital cost (%)
a_i, b_i, c_i	coefficients of the quadratic polynomial function for the unit fuel cost (RMB/h, RMB/kW h, RMB/kW h^2)
d_i	coefficient of the unit maintenance cost (RMB/kW h)

However, the relationship between ESS lifetime and the DOD is not exactly depicted by these models. Accordingly, this problem is investigated in this paper to improve the management of ESS. The operation, maintenance and depreciation costs of ESS are considered for its economical management. A battery cycle life model is proposed, based on which the depreciation cost in each charging/discharging cycle is modeled as a function of DOD. Then, an optimal scheduling model is developed to minimize MG total operational cost. The scheduling model is beneficial for the DOD management of ESS in MG.

Lithium battery (LB) storage is the least costly solution for large-scale stationary applications among various categories of ESS at present [15]. In addition, LB has been widely applied to practical MG demonstration projects for its superior characteristics, including relatively mature technology, large power density, and no memory effect. Thus, this paper focuses on the LB management in MG. Moreover, a practical control strategy is modeled based on a typical charging/discharging strategy, which provides a proper operation condition for LB.

This paper is organized as follows. In Section 2, the architecture of the proposed MG scheduling model is presented. In Section 3, expressions of the cycle life and the corresponding depreciation cost, functions of DOD, are established for LB. A charging/discharging management strategy is discussed in Section 4, followed by the demonstration of a detailed optimal scheduling model for MG in Section 5. Case studies are discussed in Section 6 and the conclusions are summarized in Section 7.

2. Architecture of the proposed MG optimal scheduling model

The framework of MG generation scheduling is briefly introduced firstly. In general, MG day-ahead scheduling is to develop generation schemes with minimum operational cost based on the forecasting of load demand and renewable energy (e.g. PV, WT) [16]. This paper focuses on the charging/discharging management for LB storage in day-ahead MG scheduling. The proposed architecture of the MG scheduling model is shown in Fig. 1.