



The optimization of a hybrid energy storage system at subzero temperatures: Energy management strategy design and battery heating requirement analysis



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HIGHLIGHTS

- A novel battery degradation model (effective in a wide temperature range) is proposed.
- Dynamic programming approach is used to optimize the system at subzero temperatures.
- The battery heating requirement is analyzed using the convective heating method.
- Four factors, which influence the heating analysis, are considered.

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ABSTRACT

This paper presents a thermal analysis of a semi-active battery/supercapacitor (SC) hybrid energy storage system (HESS), which is used in electric vehicles (EVs), at subzero temperatures. In subzero temperature environments, EVs suffer a dramatic driving range loss due to the energy and power capability reduction of LiFePO₄ batteries, as well as severe battery degradation due to Li plating. This will increase the system operation cost because the battery pack needs to be changed frequently. Based on a novel degradation model of LiFePO₄ batteries, which is validated over a wide temperature range, a near-optimal energy management strategy of the HESS for on-line use is proposed using the dynamic programming (DP) approach, which minimizes the operation cost (the electricity and the battery fade costs) over a typical China Bus Drive Cycle (CBDC). The convective heating method is integrated into the DP process. Finally, the required heating of the HESS at subzero temperatures over multi-CBDC is analyzed by evaluating the system operation cost. Simulation results show that the heating process becomes increasingly necessary with increased driving range, battery price, and heating efficiency, as well as decreasing environment temperature.

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1. Introduction

Hybrid energy storage systems (HESSs), which combine electrochemical batteries and supercapacitors (SCs), have been widely used in hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs) [1–5]. The core reason of adopting the SC is to prolong the life span of the Lithium battery, therefore the system life cycle cost can be reduced due to the reduction in frequency of the battery pack replacement [1–10].

To effectively protect the battery by using the SC, three main factors should be seriously considered: the HESS topology, the SC size, and the energy management strategy (EMS) [6].

Regarding the HESS topology, the semi-active HESS, which only employs one DC/DC converter, is a good tradeoff between performance and system cost in comparison with the fully-active and passive HESSs [7–9]. In addition, most control strategies can be implemented with the semi-active topology. Given these advantages, a semi-active HESS, which uses a bidirectional DC/DC converter to decouple the SC from the battery/DC bus, is adopted in this paper. The HESS EMS can be categorized as having an “on-line” strategy or an “off-line” strategy. The on-line strategy, such as the “all or nothing” control strategy [10], the rule-based

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control strategy [11], the filtration-based strategy [12], the model predictive control strategy [13], and the fuzzy logic control strategy [13], can be easily implemented in practical applications. However, these on-line strategies are usually empirically designed, therefore they cannot achieve the global optimization performance. In terms of off-line strategies, Vinot and Trigui [14] used Pontryagin's minimum principle to reduce the root mean square value of the battery current. By using the dynamic programming approach (DP), based on a dynamic battery degradation model, an integrated optimization problem for deriving the best SC size and the best EMS of a semi-active HESS is solved in [6]. According to the DP results, a near-optimal rule-based strategy for on-line use is also determined [6].

We accomplish some initial researches on the HESS optimization. To be specific, a novel semi-active HESS topology, which only adopts a small DC/DC converter to reduce the system cost, is proposed in [7]. Based on the characteristics of the novel topology, the SC size is optimized by using genetic algorithm to achieve the Pareto solutions [7]. Focusing on a typical topology of semi-active HESS, which is also used in this paper, we finish the integrated optimization by using DP approach [6]. The EMS and the SC size are optimized simultaneously at 15 °C. Finally, a rule-based EMS is derived from DP results [7]. After that, we compare four on-line EMSs, which includes the filtration-based EMS, the rule-based EMS, the model predictive EMS, and the fuzzy logic EMS [13]. The simulation results show that the rule-based EMS has a satisfactory performance because it can reserve most of the operation features shown in the DP process. In [9], four semi-active topologies are compared, and the comparison result shows that different topologies can be used in different applications to fulfill different requirements, such as control simplicity, life cycle cost, initial cost, and DC bus voltage variation. However, our previous published papers only focus on the HESS performance at 15 °C. The variation of the battery temperature is small and can be neglected in this situation. In addition, the heating process of the battery does not need any consideration because the battery performance is excellent at 15 °C.

However, EVs suffer from significant driving range loss in sub-zero temperature environments due to the resulting reduced energy and power capability of Li-ion batteries. In addition, the battery degradation also becomes severe due to lithium plating [15]. As a result, the EV operating cost will increase due to the high cost of replacing the battery during the life of the vehicle [11]. Therefore, all conclusions in our previous papers may significantly change due to the temperature decrease. In addition, Ouyang et al. [16] also pointed out that charging procedures at low temperatures severely shorten the cycle life of lithium ion batteries due to lithium deposition on the negative electrode. Omar et al. [17] and Tippmann et al. [18] proved that the battery age far more at low temperatures than at room temperatures even at low charge/discharge rates. Low temperatures are unavoidable in practical applications, hence some effective methods should be proposed to prevent the battery from the significant capacity degradation. For example, pulse heating can efficiently heat the battery to mitigate the effects of low temperatures [15,19]. Ji and Wang [15] also compared four preheating methods (self-internal heating, convective heating, mutual pulse heating, and AC heating) in terms of capacity loss, heating time, system durability, and cost. But the higher rates of charge/discharge will increase the lithium deposition meanwhile [20]. As a result, the heating process cannot ensure the optimization of the battery performance at low temperatures. Although the severe degradation of LiFePO₄ batteries have been pointed out by above literatures, regarding to the low temperature case, a quantitative analysis of the battery performance under practical driving cycles and the heating requirement analysis of the battery are still missing in the existing literatures.

The performance analysis of the HESS at subzero temperatures (especially the heating requirement of the battery) is a novel issue which no existing literature addresses. Actually, there are several problems to be addressed when the HESS is used at low temperatures. To be specific, (1) How much is the additional battery degradation under subzero temperatures as compared to normal temperatures? (2) Is the EMS obtained at normal temperatures still optimal under subzero temperatures? (3) Is a heating process necessary for the HESS under subzero temperatures? (4) Which factors should be considered in the heating necessity analysis? All these novel issues should be discussed to optimize the HESS performance at subzero temperatures.

This paper analyzes the heating requirements of a semi-active HESS at subzero temperatures based on a novel LiFePO₄ battery degradation model, which is verified to be effective over a wide temperature range by experimental data. To be specific, the HESS operation cost, including the battery degradation cost and the electricity cost over one typical China Bus Driving Cycle (CBDC), is minimized at different subzero temperatures by using the DP approach. In the DP analysis, various levels of constant heating power, supplied by the HESS itself, are considered and compared. In consequence, a near-optimal on-line EMS, whose parameter corresponds to the environment temperature and the heating power, is proposed in this paper. Any heating process will increase the HESS operation cost along only one CBDC because the heating process increases the electricity cost and battery utilization (the SC cannot support the heating power continuously). The battery fade cost is therefore increased. In fact, the battery heating process can be split into two stages, which are the heating stage and the beneficial stage. In the heating stage, the battery temperature increases, but both the electricity and battery fade costs are increased when compared to non-heating cases. In the beneficial stage, the battery temperature is maintained within a steady range in which the battery can effectively operate. In this case, the HESS cost can be shown to be dramatically reduced in comparison with non-heating cases. The battery heating requirement should be comprehensively analyzed over both stages due to the opposite characteristics of the two stages. However, the DP approach is not effective with regards to real-time implementation due to its high computational cost. Thus the proposed on-line EMS is used to analyze the heating requirement along multiple CBDCs. Simulation results show that the heating process becomes increasingly necessary with an increase in EV driving range, battery price, and heating efficiency, as well as a decrease in environment temperature. In general, when the number of driving cycles exceeds 12 and the environment temperature is lower than 0 °C, battery heating can bring significant benefit to the EV in comparison with the non-heating case. The comprehensive analysis of the heating requirement also provides some conclusions about whether the heating power is effectively used to decrease the system operation cost. The input–output trade-off, which corresponds to the heating power and the operation cost reduction, is carefully addressed in this paper.

2. Hybrid energy storage system modeling

As shown in Fig. 1, the semi-active HESS adopted in this paper employs a bidirectional DC/DC converter to decouple the SC from the battery/DC bus. The DC bus voltage is equal to the battery voltage as they are directly connected. The convective heating method, which employs a resistive heater and a fan, is used in this paper due to its effective and fast heating performance [15]. The heating resistor converts electric power to heat, and the fan creates a convective flow to enhance the heat transfer from the heater to the battery cell [15]. For simplicity, battery cells are assumed to have uniform temperature distribution.

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