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Overview of Methods for Battery Lifetime Extension

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Keywords

«Batteries», «Battery charger», «Lifetime», «Battery Management Systems (BMS)», «Energy storage».

Abstract

Lithium-ion (Li-ion) batteries are widely used in transportation, aerospace, and electrical. How to extend their lifetime has become an important topic. In this paper, the methods for battery lifetime extension in terms of thermal management, charging/discharging optimization, and power and energy management control strategies are reviewed. Firstly, this paper summarizes and classifies the methods proposed in recent years to extend battery lifetime. Secondly, the advantages and drawbacks of each method are compared in detail. Finally, the advancement of various methods is summarized and prospect for future research direction on battery lifetime extension is provided.

Introduction

Lithium-ion (Li-ion) batteries are the key energy storage technology to powering various applications (i.e., electric vehicles, robots, drones, etc.) due to their advantages such as high energy density, high efficiency, and low self-discharge [1], [2], [3]. However, the lifetime of Li-ion batteries is not unlimited, as they inevitably experience degradation of their performance parameters because of the different aging phenomenon [4], [5].

Battery degradation is a complex process governed by electrochemical reactions. The battery degradation process is highly nonlinear and influenced by multiple factors, including both manufacturing aspects and operating conditions [2], [6], [7]. High discharge currents, impulse currents, low or high operating temperature, will reduce the battery capacity and increase the internal resistance, subsequently, shortening their lifetime [8], [9]. Thus, the battery aging increases operational costs, reduce the service life, and affects the safe operation of the equipment [10], [11]. From the battery perspective, extending battery lifetime will decrease the required installation battery capacity to drive the system and consequently lower the price and weight of the power source [12]. Furthermore, the recycling of Li-ion batteries has no ideal solution yet, and premature failure will lead to a large number of used Li-ion batteries that cannot be properly handled [6].

Generally, a battery reaches the end of life when the capacity degrades more than 80% of its initial value [13], [14]. Different battery lifetime extension methods were proposed in the literature. At this stage, the methods to extend battery lifetime are mainly focused on engineering and electrochemical approaches. Engineering approaches are mainly to improve three battery aspects, e.g., thermal management, optimal battery charging/discharging strategies, and power and energy management strategies. The electrochemical approaches are mainly focusing on the improvement of cathode and anode materials. This paper focuses on presenting and analyzing the engineering approaches for battery lifetime extension. The aforementioned three main methods are compared with respect to their improvement in battery lifetime. The final paper will propose an algorithm to compare the characteristics of these methods and an outlook for further research will be provided.

Thermal Management

To obtain optimum performance, the operating temperature of the Li-ion batteries should be around 20°C - 25°C [15]. Thermal management is therefore required to avoid fast performance degradation of Li-ion batteries, maximize their lifetime and ensure safe operation (avoiding thermal runaway). In [15], a simple parallel battery-supercapacitor hybrid architecture with a dual-mode discharge strategy is used, which provides instant temperature management, where the supercapacitor is used as an energy buffer during battery idling periods. This method reduces the capacity attenuation to 14.88%. In [16], an online core temperature estimation algorithm based on a lumped thermoelectric model was developed for onboard AC auto heaters. This method compensates for the influence of parameter uncertainty by implementing an extended state observer. The core temperature estimation error of the proposed method is only within 1.2°C, and the self-heating time and energy consumption are reduced by 50%.

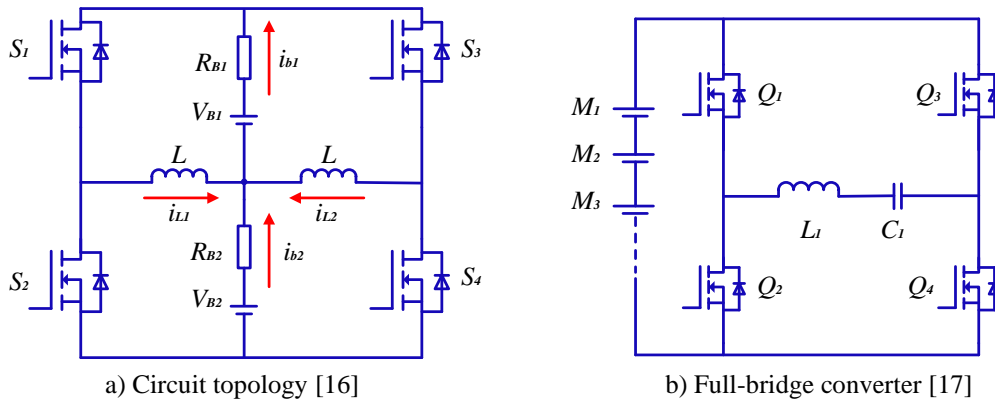


Fig. 1: Structures of battery thermal management.

In [17], a sine-wave heating circuit for automotive battery self-heating is proposed for subzero temperatures. An interleaved-parallel topology is introduced to derive a high-frequency sine-wave heater based on resonant LC converters to self-heat the automotive batteries at low temperatures without the need for external heaters. The heating speed of the heater reaches 6.45 °C/min. The heating speed increased by 2.5 times that of the basic heater. The mentioned thermal management methods are presented in Fig. 1. In [18], a battery thermal management strategy based on dynamic programming was proposed. By predicting the future battery power of connected and autonomous hybrid electric vehicles, the best air and liquid cooling/heating power can be achieved with minimal power consumption, thereby regulating the battery temperature. The strategy based on iterative dynamic programming can reduce battery thermal management energy consumption by 14.8%. In [19], an intelligent model predictive control strategy suitable for plug-in electric vehicles is proposed. This strategy is based on a neural network vehicle speed predictor and a target battery temperature adaptor based on the Pareto boundary. The energy consumption of intelligent model predictive control is 24.5% and 14.1% lower than the energy consumption of the switch controller and the traditional model predictive control, respectively. A comparison of thermal management methods for extending battery lifetime is summarized in Table I.

Table I: Comparison of thermal management methods for extending battery lifetime

Method	No.	Performance	Ability to extend battery lifetime

Parallel battery-supercapacitor hybrid architecture	[15]	Reduces the capacity fade up to 14.88%.	Medium
Online core temperature estimation algorithm	[16]	Energy consumption is reduced by 50%.	High
A sine-wave heating circuit	[17]	Heating speed increased by 2.5 times.	Medium
Iterative dynamic programming	[18]	Energy consumption is reduced by 14.8%.	Medium
Intelligent model predictive control strategy	[19]	Energy consumption is reduced by 24.5% and 14.1% than the switch controller and the traditional model predictive control.	Medium

Optimal Battery Charging Strategies

1. Introduction to pulsed current charging

Pulse charging means intermittently charging the battery in pulses during charging. Such an intermittent charging cycle can make the battery fully chemically react, so it can greatly reduce the polarization of the charging process, improve the charging efficiency of the battery, and have a cooling effect, which can extend battery lifetime [20]. Pulsed current can prolong the battery lifetime because it provides the rest time for the complete internal chemical reaction of the battery cell and suppresses the increase in resistance. There are two basic pulse current modes for pulse current charging, namely positive pulse current (PPC) and negative pulse current (NPC) [21]. The variables of PPC mode include frequency, duty cycle and amplitude. For the NPC mode, the main influence are the number and amplitude of the negative pulse current and the relaxation time on the life and charging performance of the Li-ion battery is considered. The six PPC modes of Li-ion batteries are shown in Fig. 2. The six NPC modes of Li-ion batteries are shown in Fig. 3.

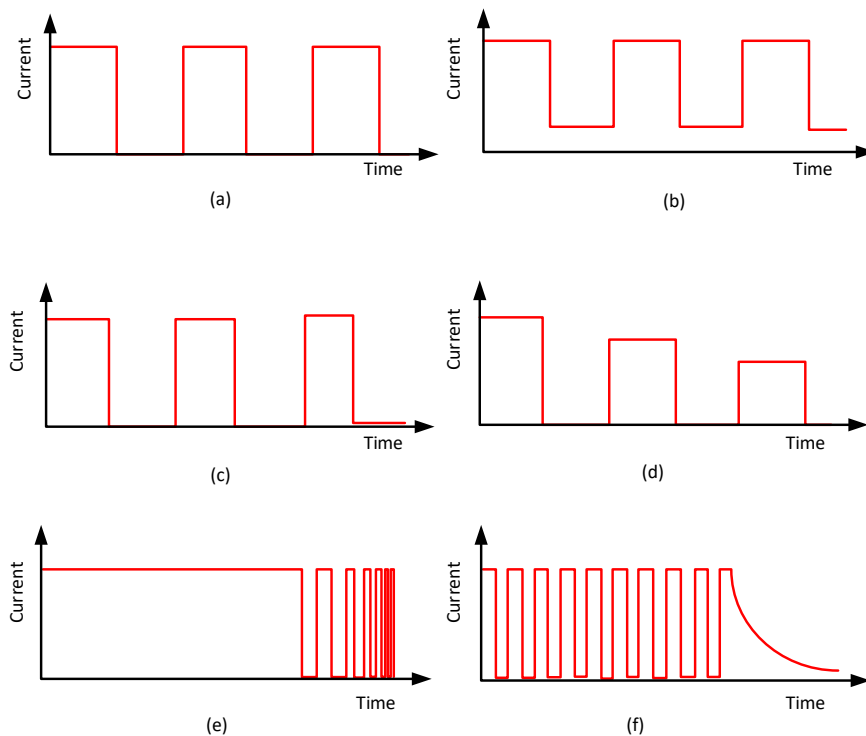


Fig. 2: Six PPC modes for Li-ion batteries: (a) Standard PPC mode, (b) Pulsed Current with Constant Current (PCCC) mode, (c) Pulse Width Modulation (PWM) mode, (d) Pulse Amplitude Modulation (PAM) mode, (e) Constant Current-Pulsed Current (CC-PC) mode, and (f) Pulsed Current-Constant Voltage (PC-CV) mode [21].

The positive and negative pulse charging improves the activity of the positive and negative electrodes, inhibits the formation of concentration polarization, and the repair results are stable, thereby effectively improving the battery lifetime. In [22], to study the effect of high frequency on the capacity decay of Li-ion batteries, a float-charging test was carried out to represent calendar aging, and the results were compared with the capacity decay caused by pulse current. In the 147-day cycle life test, the capacity attenuation rate at 1 Hz and 10 Hz is about 13% and 15%, respectively, while the capacity attenuation rate at high frequencies is much lower. In the experiment of [23], the maximum number of cycles is reached when the duty cycle is 16.6%. At the frequencies of 0.017 Hz, 0.03 Hz, and 0.17 Hz, the cycle life is increased by about 55% compared with the CC-CV strategy, 70% and 130%. As the duty cycle decreases, the cycle life is extended, and higher frequencies have a more positive impact on battery life. In [24], the author used the NPC strategy compared with the CC-CV strategy, and the capacity attenuation can be reduced by 23% after 60 cycles.

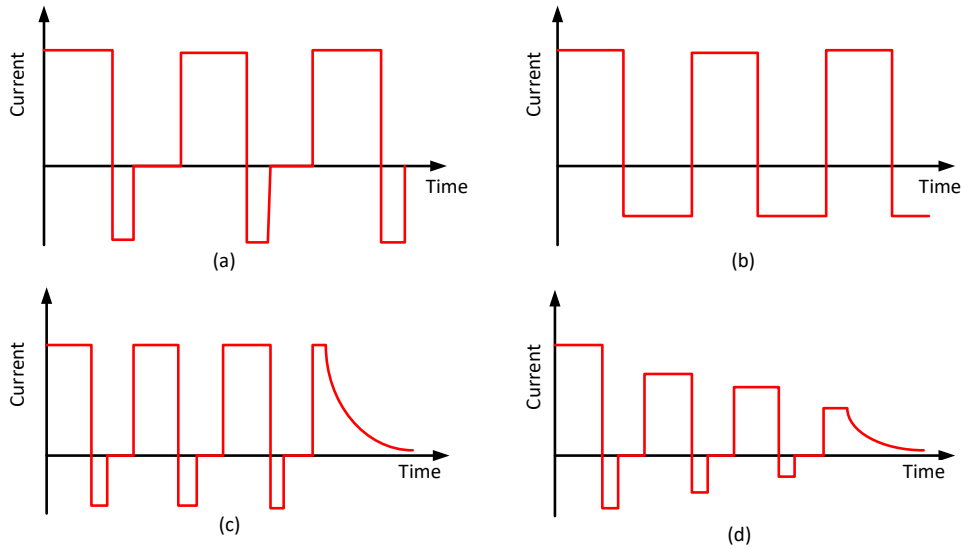


Fig. 3: Four NPC modes for Li-ion batteries: (a) Standard NPC mode, (b) Alternating Current Pulse (ACP) mode, (c) Constant Current-Constant Voltage with Negative Pulse (CC-CVNP) mode, and (d) Multi-Stage Constant Current-Constant Voltage with Negative Pulse (MCC-CVNP) mode [21].

2. Optimization of the pulsed current charging

Due to physical limitations on the design of cells, Li-ion batteries typically have a preferred/nominal rate of charging or discharging. Above the rate, the reactions are less efficient and incomplete because of the degradation inside the cells. Many researchers attempted to improve the standard constant-current constant-voltage (CC-CV) method for better charging results to extend battery lifetime. A cycle life study of Li-ion batteries with an aging-level-based (ALB) charging method is presented in [25]; according to this work, the batteries lifetime can be extended by changing the charging current according to the state of health of the battery. Compared with the standard CC and four-stage constant current charging methods, the battery life using the ALB strategy is increased by 3.84% and 2.55%, respectively. However, the charging time increased by 22.5% and 10.71%, respectively. In [26], the authors have proposed a multi-input battery charging system. Pulse chargers allow charging via wall outlets or energy harvesting systems. Compared with the reference constant current and constant voltage, the pulse charger reduces the charging time of 100 mAh and 45 mAh Li-ion batteries by 37.35% and 15.56%, respectively, and increases the charging efficiency by 3.15% and 3.27%.

In [27], the authors use Taguchi orthogonal arrays to search for the best pulse charging parameters that will maximize battery charging and energy efficiency while reducing charging time. Compared with the use of CC-CV charging method, when the rate is 0.5 C, by using the best parameters to operate the pulse charger, it can be determined that the charging time is reduced by 47.6%, and the battery charging and energy efficiency are increased by 1.5% and 11.3%, respectively. In [28], the authors have applied the pulsed charging method to polymer Li-ion batteries. Compared with the CCCV charging method, the pulsed current charging optimized by the Taguchi orthogonal array method can extend the battery cycle life by up to 100 cycles. A comparison of optional charging/discharging methods for extending battery lifetime is summarized in Table II.

Table II: Comparison of optional charging methods for extending battery lifetime

Method	No.	Performance	Ability to extend battery lifetime
The ALB charging strategy with a four-stage constant current (4SCC) charge profile	[25]	The battery lifetimes increase by 3.84% and 2.55%.	Low
Combination of trickle charge (TC) and fast charge charging strategy	[26]	Increases the charging efficiency by 3.15% and 3.27%	Low
Optimized Charging Strategy of Taguchi orthogonal arrays	[27]	Battery charging and energy efficiency are increased by 1.5% and 11.3%	Low
Optimized pulse charging strategy	[28]	Extend the battery cycle life by up to 100 cycles.	Medium

Power and Energy Management Strategies

In battery systems, different power and energy management strategies are necessary depending on the application. The control strategies have a great impact on battery lifetime. For example in [29], the authors study the applicability of five strategies for providing primary frequency regulation and re-establishing system SOC from the perspective of Li-ion battery ESS lifetime. For the analyzed power and energy management strategies, the lifetime expectancy of the Li-ion battery ESS varies between 8.5 years and 13.5 years. The blind and task-ware scheduling methods are proposed in [30] to prolong battery lifetime. The blind method uses a neural network time step estimator to find the optimum time step for batteries at different discharge currents without any contemplation about drawn current patterns. The task-ware scheduling method extends the battery lifetime on average by 31% compared to the blind method. An arrangement of instruction controlled hybrid battery-supercapacitor can enable longer battery life in systems with instruction controlled power gating. A multi-dimensional size optimization framework and a hierarchical energy management strategy are proposed in [31]. The hierarchical energy management strategy can simultaneously optimize vehicle fuel consumption and suppress battery aging. Its upper layer uses the dynamic programming algorithm to optimize fuel economy, and the lower layer applies the linear programming method to improve battery life and the battery aging rate has been reduced by 48.9%.

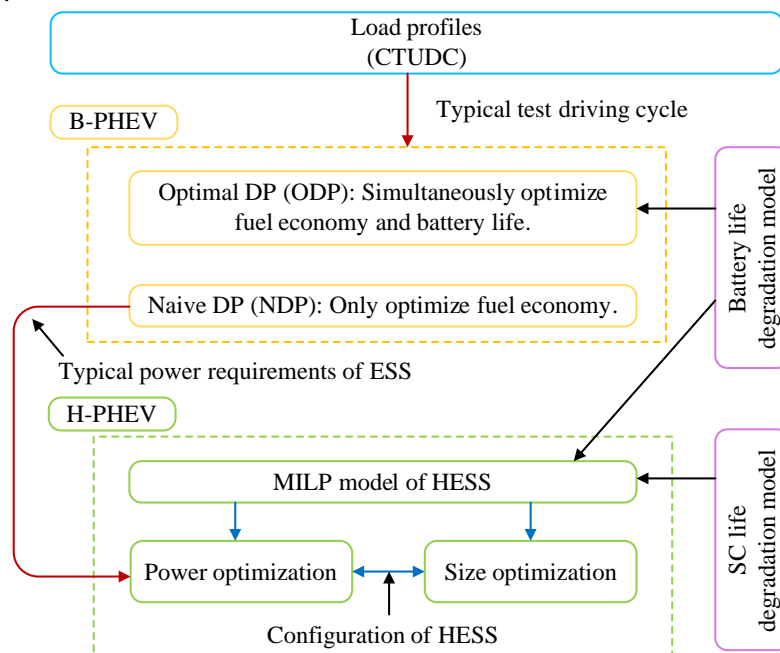


Fig. 4: Simulation methodology for the optimal design of the HESS in a plug-in hybrid electric vehicle [31].

In [32], the authors propose an energy distribution strategy based on machine learning based on battery temperature and health constraints for a new type of power distribution hybrid bus. The fully continuous depth deterministic strategy gradient is combined with an expert-assisted regulator to enhance "cold start" performance and optimize hybrid electric buses power allocation. The rate of battery degradation is only one-third of the state-of-the-art strategy. To minimize the battery power pressure and extend its service life, [33] proposes an optimal energy management strategy based on particle swarm optimization and combined with the Nelder-Mead simplex method. In order to keep the supercapacitor SOC near its initial value at the end of each driving cycle, based on the dynamic limitation of the battery power of the supercapacitor energy, a PI active control loop is added. Compared with a single power supply based on an ordinary single-cell battery, this strategy can increase battery lifetime by up to 20%. To extend the battery lifetime while fully addressing the redundant capacity and distributed locations, an optimal hierarchical management model for shipboard multi-battery ESS is proposed [34], which iteratively regulating the MSOC of batteries will greatly facilitate their lifetime, which brings extra lifetime extension of 12.7%. Overall simulation methodology for the optimal design of the HESS in a plug-in hybrid electric vehicle is shown in Fig. 4. The lifetime improvement of the aforementioned power and energy management strategies are summarized in Table III.

Table III: Comparison of control strategies to extend battery lifetime

Method	No.	Performance	Ability to extend battery lifetime
Neural network time step estimator	[30]	The lifetime is prolonged by around 31%	High
Dynamic programming algorithm	[31]	The aging rate has been reduced by 48.9%	High
Energy distribution strategy based on machine learning	[32]	The rate of battery degradation is only one-third of the state-of-art strategy.	High
An optimal energy management strategy based on particle swarm optimization and Nelder-Mead simplex method	[33]	Increase battery lifetime by up to 20%	Medium
Multi-battery management	[34]	The lifetime is prolonged by around 12.7%.	Medium

Comparison

Effective thermal management is essential to maintain the battery temperature within the boundary to achieve the best performance of the Li-ion battery. The operating temperature of the Li-ion battery is controlled by the thermal management system, so each battery must work within the threshold temperature range. When the battery temperature exceeds the safety limit, the thermal management system will provide immediate response through the heating and cooling management and control system to ensure safe operation and extend the lifetime of the Li-ion battery. At the same time, the service lifetime of Li-ion batteries is closely related to the safety during battery charging/discharging. In order to improve the overall performance of Li-ion batteries, it is necessary to study advanced charging/discharging strategies to extend the lifetime and performance of Li-ion batteries. For Li-ion battery packs, the core of the power and energy management control strategy is to distribute the power output of the battery, optimize the efficiency, control the battery state of charge to fluctuate within a reasonable range, and try to avoid the Li-ion battery working under unfavorable conditions for life (largely Variable load, start-stop, continuous low load and overload). The advantages and disadvantages of these three aspects are compared as shown in Table IV.

Table IV shows that the structure and control of thermal management are simple, and the application range is wide, but the effect of extending lifetime is not obvious. The optimal charging/discharging strategies have fast execution process, but the effect of extending lifetime is not obvious. The logic and

operation process of power and energy management strategies are complex and computationally intensive, but the impact of extending lifetime is obvious.

Table IV: Comparison of the advantages and disadvantages of these three aspects

Method	Advantage	Disadvantage
Thermal Management	-Simple structure and control - Wide range of applications	- Temperature management equipment will take up more volume
Optimal Battery Charging/Discharging strategies	-Fast execution process	-The effect of extending lifetime is not obvious
Power and Energy Management Strategies	-The effect of extending lifetime is obvious	-Complex logic and operation process - Large amount of calculation

Conclusion

This paper conducts an overview of battery lifetime extension methods from three aspects: thermal management, battery charging/discharging optimization, and control strategies. Among these methods, the improvements in battery topology and control strategy are commonly adopted by the researchers. Through the comparative analysis of this paper, optimizing control strategies is the most effective way to extend the battery lifetime.

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