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Multi-objective optimization of charging patterns for lithium-ion battery management

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A B S T R A C T

Lithium-ion (Li-ion) battery charging is a crucial issue in energy management of electric vehicles. Developing suitable charging patterns, while taking into account of various contradictory objectives and constraints is a key but challenging topic in battery management. This paper develops a model based strategy that optimizes the charging patterns while considers various key parameters such as the charging speed, energy conversion efficiency as well as temperature variations. To achieve this, a battery model coupling both the electric and thermal characteristics is first introduced. Three key but conflicting objectives, including the charging time, energy loss and temperature rise especially for internal temperature, are formulated. Then, multi-objective biogeography-based optimization (M-BBO) approaches are employed to search the optimal charging patterns and to balance various objectives with different combinations. Optimization results of four M-BBO approaches are compared, and the Pareto fronts for battery charging with various dual-objectives and triple-objectives are analysed in detail. Experimental results confirm that the developed strategy can offer feasible charging patterns and achieve a desirable trade-off among charging speed, energy conversion efficiency and temperature variations. The Pareto fronts obtained by this strategy can be adopted as references to adjust charging pattern to further satisfy various requirements in different charging applications.

1. Introduction

Hybrid electric vehicles (HEVs) and electric vehicles (EVs) have long been viewed as a promising solution worldwide to replace the conventional internal combustion engine (ICE) based vehicles, and in recent years, the campaign for mass roll-out of EVs has gathered momentum in a bid to tackle the global challenges on sustainable energy and climate changes [1]. UK and France have recently committed to ban all new petrol and diesel cars and vans from 2040, while China has proposed a new policy that would require all manufacturers to sell a minimum of 8% "new energy vehicles" starting in 2018. Compared with the ICE vehicles, EVs have better energy conversion performance due to the flexible control of motor working points [2]. In the meantime, a wide range of energy storage systems (ESSs) with different features have been explored to power the EVs.

Commonly used ESSs for EVs include flywheel, super-capacitor and battery [3]. Flywheel is a promising storage unit which maintains the kinetic energy by a flywheel rotation. Its main advantages include long lifetime, fast power response and wide temperature permission. However, its gyroscopic force and safety can be hardly guaranteed for EV applications [4]. Super-capacitor, owing to its high power density and long cycle life, can play a crucial role in the development of ESSs to power EVs. However, the low energy density limits its application to be a main ESS element to provide whole electricity energy for EVs [5]. In practice, battery which can be charged from the renewable power generated from solar, water or other forms of sustainable energies, has now become the most popular ESS for EV applications [6]. Both flywheel and super-capacitor are often selected as the secondary ESS to complement the power supply of the battery to improve the overall performance of the EVs [7]. Among various types of batteries (e.g. lead acid, nickel-cadmium (Ni-Cd)/nickel-metal hydride (Ni-MH) and metal/air), Li-ion battery is preferably adopted as the main power supply in EVs due to its excellent features in terms of high energy density and financial superiority [8]. For Li-ion batteries, a well-designed battery management system (BMS) is a key to guarantee the battery safe operation and to improve energy conversion.

Battery charging is a crucial aspect in the BMS, yet it is also a primary bottleneck for large-scale application of EVs [9]. In addition to the

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charging speed, the charging pattern has significant impacts on the energy conversion efficiency and battery safety [10]. Therefore, developing suitable battery charging pattern that can consider both important objectives and hard constraints is a key functionality in battery management for electric vehicles.

A number of battery charging approaches have been researched in the literature. Conventional methods can be primarily categorized as the constant current (CC) pattern, the constant voltage (CV) pattern and the constant current-constant voltage (CCCV) pattern. For the CC pattern, a predefined small constant current is injected into the battery through the whole charging process to prevent sharp increase on both battery terminal voltage and battery temperature. This method was first and commonly applied to charge Ni-Cd/Ni-MH batteries, and it is also suitable for charging Li-ion batteries [11]. However, it is difficult to predefine a proper charging current rate for the purpose of equilibrating both battery capacity utilization and charging speed. For the CV pattern, a predefined constant voltage is utilized to charge battery until the final charging target is reached. The advantage of using the CV pattern is to avoid over-voltage and irreversible side reactions, to further prolong the battery cycle life. This pattern, however, requires a high current at the beginning of the charging process, which is easy to cause the battery lattice collapse, battery poles broken or powder build-up. It is also difficult to pre-determine the appropriate constant value of charging voltage to balance charging speed, capacity utilization and electrolyte decomposition. The standard CCCV pattern is a hybrid method for the battery charging applications. In this pattern, battery is charged with a constant current firstly until the terminal voltage rises up to the maximum safe-threshold, and then a constant voltage is utilized to charge the battery, entailing the continuous step-down of the charging current. This CV phase is terminated until the charging current decreases to a value below the predefined terminal condition or a predefined capacity target is reached. Compared with the sole CC charging pattern, the CCCV pattern includes the CV phase, which can improve the capacity utilization during the charging process. The capacity loss caused by the large electrochemical polarization in CC phase will be effectively compensated by the CV phase. Currently, the CCCV pattern has become a widely used charging approach for Li-ion batteries. But the selection of charging current rate in the CC phase is still a big issue in the CCCV pattern. Therefore, to optimize the charging pattern has become a thriving research topic in the field of battery applications.

On the basis of conventional charging patterns, research proposals with various charging objectives have been developed to improve the charging performance of the Li-ion batteries in recent years. Shortening the charging time is crucial in improving the convenience of EVs. Numerous intelligent technologies such as fuzzy logic [12,13], model predictive control [14,15], Pseudo-spectral [16], and Taguchi-based approach [17,18] have been successfully utilized to search the suitable charging patterns, with the purpose of increasing charging speed primarily. Although these technologies can significantly reduce battery charging time, to choose the right tuning parameters in these methods is however a big challenge and needs to be carefully designed. Other researches have also considered the energy loss or energy conversion efficiency as a key objective in battery charging. Huang et al. [19] proposed a fast charging strategy for Li-ion battery based on the residual energy evaluation, which is able to decrease the charging time with high charging efficiency. The presented strategy can assess the internal residual energy and conduct high-rate charging in a proper condition, so charging time will be shortened with less energy loss. Chen et al. [20] presented an optimal charging strategy based on a first-order RC electric model to improve energy conversion efficiency of Li-ion battery. The dynamic programming (DP) method was adopted to minimize the energy losses of both the battery and the charger. Better energy conversion efficiency was achieved without affecting the charging speed during the charging process. Wu et al. [21] proposed a multi-stage charging approach which considers the charging speed and energy loss as the optimization objectives for Li-ion battery charging. A designed DP algorithm was adopted to search the charging current of objective function. Comprehensive optimization problem of charging time and energy loss can be solved by adjusting the weighting factors in algorithm.

Further, temperature is also a key indicator for battery charging because battery safety and performance are significantly affected by the temperature variations within the battery [22]. Jiang et al. [23] investigated the polarization voltage under various charging rates for Li-ion batteries. Then an acceptable charging current pattern based on the polarization voltage characteristics, which considers polarization time constants is proposed for real time charging. The proposed charging pattern is capable of equilibrating the charging time and temperature rise. Pramanik and Anwar [24] proposed an optimal charging method for Li-ion battery based on the 1-D electrochemical model. Battery bulk temperature is designed as a control component in the performance index in order to achieve fast charging. Simulation results show that the proposed charging method can increase the charging speed while maintaining the battery temperature within limits. Zhang et al. [25] proposed the optimal charging patterns to balance the charging speed and the temperature rise for Li-ion batteries based on the battery thermal models. The polarization is selected as the constraint and the genetic algorithm (GA) is applied to search the optimal current patterns.

Some other researches simultaneously consider the battery charging speed, energy conversion and temperature variation as the objectives to design the charging pattern. Vo et al. [26] proposed a hybrid strategy to search the current pattern for Li-ion battery charging. The battery state of charge (SOC) is estimated by a designed switching gain sliding mode observer, and the optimal charging pattern is determined by the Taguchi approach. Results reveal that the designed strategy has good charging performance including fast charging speed, little energy loss and narrow temperature variation. Abdollahi et al. [27] presented a linear quadratic solution to optimally charge the Li-ion battery. A combination of cost function including time-to-charge, energy loss and temperature rise is formulated and the effect of different function weights on the current and voltage profiles are analysed to develop the optimal charging pattern. Even though all of the three objectives are considered in these researches, some parameters such as the internal resistance in the battery model are assumed to be constant in order to achieve successful computation by the proposed method. However, this will unavoidably reduce the efficacy due to the fact that the battery internal resistance will change frequently during the charging process [28]. In addition, only the surface temperature rise of battery is considered in these researches, but the variation of battery internal temperature is ignored.

Temperature difference between the battery surface and interior can be significantly large in some EV operations (sometimes greater than 12 °C in a standard driving cycle [29,30]). The internal temperature of the battery may rise to a critical point faster than the surface temperature. Battery overheating will trigger thermal runaway, accelerate battery aging and even cause severe safety problems such as fire and electrolyte leakage. Therefore, the temperature variations of both battery surface and interior should be taken into account especially when the battery is charged in high power applications. In other word, it is also crucial to consider the internal temperature in forming the charging objectives for high power charging of battery. Our early research [31] proposed a cost function which combines three objectives including the charging time, energy loss and temperature rise for battery charging. Although trade-off has been successfully achieved by optimizing the CCCV pattern, the results are still less satisfactory in some cases due to the lack of deep analysis of the contradictory objectives. Further, the weight for each term in the cost function was manually adjusted and the optimization problem was transformed to a single-objective optimization. The effective range of charging current cannot be properly studied within the framework proposed in [31]. Further,