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Optimal energy management strategy for battery powered electric vehicles

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HIGHLIGHTS

- The power usage for battery-powered electrical vehicles with in-wheel motors is maximized.
- The battery and motor dynamics are examined emphasized on the power conversion and utilization.
- The optimal control strategy is derived and verified by simulations.
- An analytic expression of the optimal operating point is obtained.

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ABSTRACT

Due to limited energy density of batteries, energy management has always played a critical role in improving the overall energy efficiency of electric vehicles. In this paper, a key issue within the energy management problem will be carefully tackled, i.e., maximizing the power usage of batteries for battery-powered electrical vehicles with in-wheel motors. To this end, the battery and motor dynamics will be thoroughly examined with particular emphasis on the power conversion and power utilization. The optimal control strategy will then be derived based on the analysis. One significant contribution of this work is that an analytic expression for the optimal operating point in terms of the component and environment parameters can be obtained. Owing to this finding, the derived control strategy is also rendered a simple structure for real-time implementation. Simulation results demonstrate that the proposed strategy works both adaptively and robustly under different driving scenarios.

1. Introduction

In response to renewed pleadings for energy efficiency and environment protection, the electric vehicles (EVs), as a promising substitute for the conventional ones, have received much more attention than ever before. However, due to limited energy density of batteries nowadays, energy management has always been the central and critical issue in the control of EVs. Although the term ‘energy management’ may have various meanings in different contexts, all share the common goal of improving the energy efficiency and maximizing the utilization of stored energy in the batteries equipped on the vehicle.

In order to achieve the purpose of energy management, extensive research work has focused on energy control by analyzing the component characteristics, especially for battery-powered EVs. For example, Capasso and Veneri verified the applicability of lithium-based batteries for EV applications [1]. Xiong et al. and Hu et al. proposed adaptive state-of-charge estimation methods based on real-time measurements on the battery terminal voltage and current [2,3]. Zhong et al. developed a method for state-of-charge estimation of the battery pack which accounted for the difference among the cells [4]. Besides the in-depth analyses of battery performance, the study of other key components of the EV system, such as power converters and motors, also abounds in the literature. Pahlevaninezhad et al. proposed a Control-Lyapunov-Function based approach to regulate the input power of the inverter so that higher energy efficiencies and larger stability margin could be attained [5]. Faiz et al. designed a direct torque control law for induction motors used in EVs with the improved overall efficiency and reasonable dynamic response [6]. Although physical

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characteristics of a specific component were fully explored in all those work, the analysis was only performed in a somewhat isolated manner and the coupling effects between different components were neglected.

In parallel to component level analysis, much of attention in the energy-control area has been directed to hybrid energy system design by integrating, for example, ultra-capacitors into the energy storage system of EVs. The defining features of the ultra-capacitor are its high power density and long life cycle [7]. By combining the complementary characteristics of the battery and the ultra-capacitor, a superior dynamic behavior can thus be achieved. Along this direction, the research has been carried out in full length. For example, Dougal et al. analyzed the performance improvement of the hybrid energy system when the ultra-capacitor was connected in parallel with the battery directly [8]. Lu et al. explored a new topology to interface the battery and ultra-capacitor, and proposed the corresponding energy management schemes [9]. Kuperman et al. and Garcia et al. focused on the power flow control of the hybrid energy system. An embedded control topology was proposed to guarantee that the extra power during peak time will be provided by the ultra-capacitor while keeping the battery current unchanged [10,11]. Lukic et al. compared different topologies in terms of efficiency and stability and showed that an active combination of the battery with ultra-capacitor was a promising approach [12]. Under this active topology, Laldin et al. designed an optimal power split path in real time based on the prediction of future load demand and the energy loss model for all system components [13]. The similar problem was approached from another perspective in the work done by Wang et al., in which the way of hybridization between the battery and the ultra-capacitor was determined by solving an optimization problem for the total fuel economy of the energy system [14]. Besides, there are also fuzzy approaches proposed in the literature. Wang et al. designed the fuzzy logic based on the power requirement of EVs [15]. Hannan et al. presented a multi-source model and designed a rule-based power sharing strategy according to the energy source states and load conditions [16].

Whether it be control methods for the individual components or power split mechanisms for hybrid systems, it can be noted that most of the work above were targeted at minimizing the power loss in power sharing for a given power demand. This demand is usually either obtained priori or estimated in real time. On the contrary, another point of view in this area has been concerned with the maximization of the travel distance for a given amount of stored energy [17]. Instead of determining the power sharing profile at each instant, it aimed to find an optimal velocity profile that would maximize the travel distance. As a first step, this work built a simplified yet complete EV model. Based on the terrain information and the operating efficiency of the in-wheel motors, the optimal velocity profile can be found using the dynamic programming or other optimization algorithms. The originality of this work lies in that it offers a new perspective to treating the energy management problem.

However, the approach in Ref. [17] is plagued by two major issues that can undermine the optimality of its solution. First, the battery and motor are statically viewed as the energy storage and energy consumption components, and the dynamic behaviors associated with those two components are totally ignored, not to mention the energy flow associated with those dynamic behaviors. Because of this intrinsic model discrepancy, the optimal velocity profile obtained may not produce the corresponding optimal power flow profile as expected in a real-world test. To make things worse, the optimal velocity profile itself might not even be reproducible due to the coupling effects and dynamic constraints. Relevant to the first issue, the second one is that since everything is viewed statically, the technical details of control implementation, especially the control of the DC–DC converter, remain untouched. The lack of this essential part of contents makes the proposed strategy incomplete or inconvincible to some extent.

In this paper, a more systematic and refined approach is proposed for energy management of EVs with in-wheel motors and a single power source, i.e., batteries. Two major issues mentioned above in previous work will be carefully tackled. The discussion will begin with the component analysis by examining the battery and motor dynamics respectively. The vehicle dynamics will also be accounted for in our work and special attention will be paid to the power and torque couplings between motor and vehicle dynamics. The energy management problem will then be reformulated as an optimal control problem with input constraints. With the help of justified simplifications, we can finally find an analytic solution to this energy management problem, which can serve as an important guideline to energy control of battery-powered EVs. After that we will move on to the control implementation of the proposed energy management strategy. Specifically, we will provide the details of the PI controller design for the DC–DC converter in this work which accounts for both the dynamic response and noise rejection.

One significant contribution of this work is that, with justifiable simplifications, we identify the dependence of the optimal operating point on the component and environment parameters in an analytic form. This not only provides a guideline on the driving mode in different road conditions, but also offers insights to the physical mechanism behind the optimality for further theoretical investigation. Owing to this finding, the derived energy management strategy is also rendered a simple and compact structure that facilitates the real-time implementation. Simulation results for two case studies will be demonstrated and analyzed. It can be shown that the proposed strategy works both adaptively and robustly under different driving scenarios.

The rest of the paper is organized as follows. A brief introduction to the vehicle architecture considered in our study is provided in Section 2. In Section 3, the component model for the battery and the motor are derived step by step. Based on this model, the control strategy is developed accordingly. The simulation is demonstrated in Section 4, including the initial condition settings, simulation results, and post analysis. Finally the conclusion of the proposed work and possible future improvement are summarized in Section 5.

2. Background

In this paper, the energy management strategy will be developed for an electric vehicle driven by two rear in-wheel motors. The vehicle topology is shown in Fig. 1. The battery power is delivered to the motors through the DC–DC converter, which is controlled by an energy management unit (EMU) on the vehicle.

Notice that in this work the ultra-capacitor is not included as a part of the power source system like other hybrid systems. Undoubtedly adding ultra-capacitors can improve the transient dynamics of the vehicle at acceleration and can take care of the energy recovery at regenerative braking much better. However, in the authors' opinion, the study of power transportation and power usage is of more fundamental importance from the energy management point of view. In this regard we restrict our focus to these key aspects and temporarily set aside the discussion of the *ancillary* function of the ultra-capacitor, which will be an extension of this work and addressed in our future work.

3. Proposed energy management method

The ultimate goal of energy management is to maximize the power usage of the battery on the vehicle. To this end, two aspects