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Charging, power management, and battery degradation mitigation in plug-in hybrid electric vehicles: A unified cost-optimal approach

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ABSTRACT

Holistic energy management of plug-in hybrid electric vehicles (PHEVs) in smart grid environment constitutes an enormous control challenge. This paper responds to this challenge by investigating the interactions among three important control tasks, i.e., charging, on-road power management, and battery degradation mitigation, in PHEVs. Three notable original contributions distinguish our work from existing endeavors. First, a new convex programming (CP)-based cost-optimal control framework is constructed to minimize the daily operational expense of a PHEV, which seamlessly integrates costs of the three tasks. Second, a straightforward but useful sensitivity assessment of the optimization outcome is executed with respect to price changes of battery and energy carriers. The potential impact of vehicle-to-grid (V2G) power flow on the PHEV economy is eventually analyzed through a multitude of comparative studies.

1. Introduction

1.1. Motivation and control challenges

The transportation system is currently highly dependent upon nonrenewable fossil fuels [1]. Electrified vehicles are among the most effective technologies to alleviate such unsustainable dependency [2–7]. As an important alternative-energy solution, plug-in hybrid electric vehicles (PHEVs) adopt downsized internal combustion engines (ICEs) with increased fuel economy, while furnishing flexible energy storage to accelerate the utilization of renewable energy in the electrical power system [8]. PHEVs, therefore, assume an essential role in decreasing fuel consumption, pollutant emissions, and carbon footprint. The expensive large-scale battery packs and other mechatronic subsystems, nonetheless, pose a severe challenge to cost competitiveness of PHEVs, which is strongly concerned by vehicle purchasers/operators. To combat this challenge from a control perspective, three main control tasks in PHEVs, i.e., charging regulation during parking, power

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management during driving, and battery degradation mitigation, are particularly relevant. Conventional methods merely handle a single task and thus have limited efficacy. In this paper, we propose an innovative optimal control scheme to examine the three tasks in a synergistic manner, with the primary objective to maximize PHEVs economy.

1.2. Literature review

1.2.1. Charging control of PHEVs

PHEVs charging is necessary to meet the requirement of on-road driving, whilst influencing the grid operation, e.g., grid load following and stabilization [9], and increasing grid network efficiency [10]. With the development of measurement and communication, PHEV charging protocols are increasingly adjusted adaptively in a smart grid context with real-time information on electricity price, carbon dioxide emissions, and so on. As such, a wealth of optimal charging methods has been reported, such as the cost-optimal charging via convex programming (CP) [11], dynamic programming (DP) [12], or linear programming (LP) [13]. The pseudo-spectral method was also used to optimize tradeoffs between charging time and energy loss [14].

1.2.2. On-road power management of PHEVs

On-road power management strategies of PHEVs considerably impact their fuel economy and are generally divided into the charge-depleting/charge-sustaining (CD–CS) and blended methods [15]. In the CD–CS solution, PHEVs first work in a pure electric mode until the preset limit of battery State-of-Charge (SOC) is arrived, and then switch to a charge-sustaining hybrid mode. In the blended solution, on the other hand, the ICE and battery pack constantly interact each other (their powers are continually mixed), provided that the trip information is known. A plethora of optimization methods has also been utilized to determine the optimal power management control, e.g., DP [16], equivalent consumption minimization strategy (ECMS) [17], Pontryagin's Minimum Principle (PMP) [18], model predictive control (MPC) [19], hybrid optimal control algorithm [20], and CP [21].

1.2.3. Combined charging and on-road power management of PHEVs

All the foregoing efforts analyzed separately either charging control or on-road power management in PHEVs. There is, nevertheless, a fact that the two control tasks are intimately coupled [22]. In order to probe their interplay, DP was applied to simultaneously optimize the charging and on-road power management of a PHEV, with global optimality attained at the expense of computational speed [23]. To boost computational efficiency, an integrated CP framework was established in [24] as well.

1.2.4. Battery degradation mitigation of PHEVs

Battery degradation is inevitable in the realistic operation of PHEVs, so that battery cost and lifetime are seriously concerned by users. In the pursuit of enhanced battery durability, several studies presented a first assessment of the implication of on-road power management to battery health in hybrid electric vehicles (HEVs) by incorporating semi-empirical aging models [25–27]. Such implication in PHEVs was rarely investigated. Fuel consumption and battery health of a power-split PHEV were optimally traded off via stochastic dynamic programming (SDP) in [28], where an electrochemical model emulating anode-side solid-electrolyte-interphase (SEI) growth was employed to capture a certain source of battery aging. The complexity of the electrochemical model and SDP, however, may lead to a tremendous computational burden, thwarting real-time vehicle control. The effect of charging patterns on battery health was also evaluated [29,30].

1.3. Notable contributions

The interactions among charging control, on-road power management, and battery degradation mitigation in PHEVs were, nonetheless, inadequately examined in the aforementioned papers. An intriguing question naturally remains unanswered: how are the three control tasks coordinated (or unified) to accomplish the best economy of a PHEV?

The overarching purpose of this paper is to address this question by delivering three salient contributions fundamentally different from existing work. First, we put forward a novel CP-based optimal control scheme to minimize the daily operational cost of a PHEV, which covers expenditures of electricity charged from the grid, fuel consumed during on-road driving, and battery aging. The proposed scheme can quickly and efficiently examine the synergy of the three tasks. Second, we perform a simple but useful sensitivity analysis of the optimal control solution with respect to price changes of battery and energy carriers. Finally, we preliminarily explore economy influence of adding vehicle-to-grid (V2G) function to PHEVs, through a comparison with the standard scenario without such an addition.

1.4. Paper organization

The rest of this paper proceeds as follows. Section 2 introduces the PHEV powertrain modeling. The unified cost-optimal control scheme is described in Section 3. Results and discussion are given in Section 4, followed by conclusions drawn in Section 5.