A Framework for the Integrated Optimization of Charging and Power Management in Plug-in Hybrid Electric Vehicles

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Abstract— **This paper develops a dynamic programming (DP) based framework for simultaneously optimizing the charging and power management of a plug-in hybrid electric vehicle (PHEV). These two optimal control problems relate to activities of the PHEV on the electric grid (i.e., charging) and on the road (i.e., power management). The proposed framework solves these two problems simultaneously in order to avoid the loss of optimality resulting from solving them separately. The framework furnishes optimal trajectories of the PHEV states and control inputs over a 24-hour period. We demonstrate the framework for 24-hour scenarios with two driving trips and different power grid generation mixes. The results show that addressing the above optimization problems simultaneously can elucidate valuable insights for certain combinations of daily driving scenarios, grid generation mixes, and optimization objectives. For example, in one of the cases considered, the grid produces higher CO_2 per unit energy between 3AM and 8AM. This causes the optimal PHEV state and control input trajectory to refrain from completely charging the PHEV's battery in the early morning, and judiciously combine electricity and gasoline while driving. The paper's main contribution to the literature is a framework that makes it possible to evaluate tradeoffs such as this one.**

I. Introduction

THIS paper examines the problems of optimizing the charging trajectory of a PHEV and optimally managing PHEV power when driving. We solve these two optimal control problems together, thereby accounting for their interdependence. Such combined optimization is essential because a PHEV, unlike a more traditional HEV, is expected to exchange significant amounts of energy with the electric grid. In doing so, PHEVs make it possible to replace some of the petroleum currently being used for propulsion with other sources of energy [1, 2]. To maximize this synergy, our overarching goal is to simultaneously optimize PHEV activity on the electric grid (i.e., charging) and on the road (i.e., power management).

The literature motivates this work by highlighting several non-trivial tradeoffs between PHEV design/control on the one hand and power system optimization on the other. These tradeoffs often necessitate an integrated approach to optimal design and control in PHEVs and the power grid. For example, research by Bashash and Fathy reveals a tradeoff between one PHEV battery degradation mechanism (namely, anode-side resistive film formation) and total PHEV energy cost [3]. Mitigating this tradeoff involves charging the PHEV battery just enough to complete a given driving trip, immediately before the trip [3]. Furthermore, Traut *et al.* show that the PHEV battery size that minimizes lifecycle greenhouse gas (GHG) emissions is not necessarily the maximum battery size [4]. Finally, the literature also explores the use of PHEVs for vehicle-to-grid (V2G) services such as provision of spinning reserves and regulation. These services can reduce GHG emissions [5], enable integration of intermittent renewable power sources, and provide cheaper reserves [6,7]. Depending on the objectives and services that a PHEV provides to the grid, it may not be possible to charge the PHEV's battery optimally or fully [8, 9]. This affects on-road PHEV power management, thereby motivating the combined optimization of PHEV charging and power management.

The literature already presents significant research on optimal PHEV charging and power management, but the problems are considered separately. Optimal charging refers to the problem of finding a State-of-Charge (*SOC*) trajectory that minimizes some environmental or economic objective for a given PHEV over the span of a day [9-11]. The goal is typically to minimize the total dollar cost of electricity consumed by the PHEV, minimize GHG emissions, or provide V2G services to the grid. Optimal power management refers to the problem of delivering power to a PHEV's wheels in the most effective manner. The most common minimization objectives in power management studies are gasoline consumption and dollar costs associated with a given trip [12-15]. Existing studies on optimal charging and optimal power management typically either assume or require the PHEV battery to be full at the onset of any given driving trip. Our work relaxes this assumption to enable a full exploration of tradeoffs and synergies between these two problems, for the first time.

Several optimal control methods have been applied to PHEV charging problems and power management problems. Examples include dynamic programming (DP) [12, 13], predictive control [16, 17], game theory [18], and static optimization methods [3,4,11]. Assuming that grid operation, driving times and driving profiles are known for the day under consideration, we use a Deterministic Dynamic Programming (DDP) approach. This approach explicitly uses Bellman's principle for optimal control, and thus guarantees global optimality. The output of this process is a supervisory control trajectory that can be used to gain

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solution to charge the battery fully before a driving trip. For the initial SOC = 0.3 case, if we imagine that due to some unforeseen reason the consumer could not charge the battery in the evening (hours 18-22), then it is not optimal from a CO_2 perspective to charge the PHEV overnight completely. Rather, it is optimal drive the first trip on gas and charge the battery thereafter. This non-intuitive solution is possible to obtain only due to the consideration of both the charging and power management solution together.

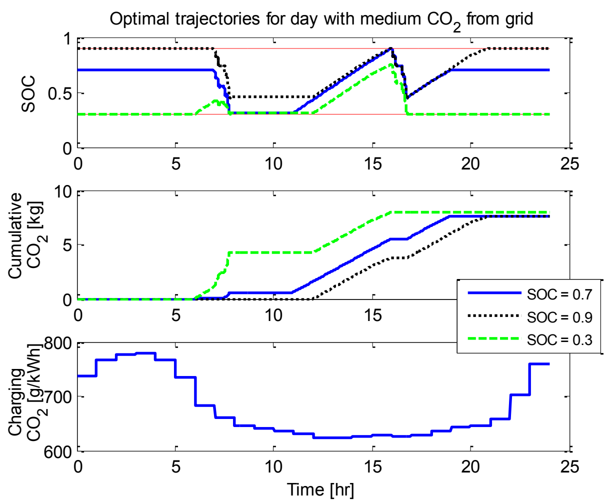

Fig 13. Optimal trajectories for a day with medium CO_2 from the grid for different initial *SOC*

II. CONCLUSIONS

A complete optimal framework which considers the dependence between optimal charging and power management is introduced. It is computationally feasible due to a DP implementation using backward looking system dynamics model. The steps of the framework are explained and applied to 24 hour charging and driving scenarios. Three different cases with days of high, low and medium CO_2 are studied along with two naturalistic driving trips.

The results show that it is necessary to consider a combined approach to optimally charge and drive a PHEV. Our framework is also capable of exploring tradeoffs that might result from usage of a PHEV for grid related services. Depending on the objective and constraints, it is shown that it is not always optimal to fully charge the battery before every driving trip as assumed in the literature.

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