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HYBRID OPTIMAL THEORY AND PREDICTIVE CONTROL FOR POWER MANAGEMENT IN HYBRID ELECTRIC VEHICLE

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Abstract. This paper presents a nonlinear-model based hybrid optimal control technique to compute a suboptimal power-split strategy for power/energy management in a parallel hybrid electric vehicle (PHEV). The power-split strategy is obtained as model predictive control solution to the power management control problem (PMCP) of the PHEV, i.e., to decide upon the power distribution among the internal combustion engine, an electric drive, and other subsystems. A hierarchical control structure of the hybrid vehicle, i.e., supervisory level and local or subsystem level is assumed in this study. The PMCP consists of a dynamical nonlinear model, and a performance index, both of which are formulated for power flows at the supervisory level. The model is described as a bi-modal switched system, consistent with the operating mode of the electric ED. The performance index prescribing the desired behavior penalizes vehicle tracking errors, fuel consumption, and frictional losses, as well as sustaining the battery state of charge (SOC). The power-split strategy is obtained by first creating the embedded optimal control problem (EOCP) from the original bi-modal switched system model with the performance index. Direct collocation is applied to transform the problem into a nonlinear programming problem. A nonlinear predictive control technique (NMPC) in conjunction with a sequential quadratic programming solver is used to compute suboptimal numerical solutions to the PMCP. Methods for approximating the numerical solution to the EOCP with trajectories of the original bi-modal PHEV are also presented in this paper. The usefulness of the approach is illustrated via simulation results on several case studies.

Keywords. Hybrid Optimal Control, Nonlinear Model Predictive Control, Hybrid Electric Vehicles, Power management, Nonlinear Modeling

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1 INTRODUCTION

In a hybrid propulsion system, power distribution from two or more energy sources/storages coordinate to deliver the performances demanded by the drivers while considering fuel efficiency and operational constraints. In a parallel hybrid electric vehicle (PHEV), the power demand can be delivered by the main power converter and/or the energy-storage device. Such energy storage devices could be batteries with or without supercapacitors [1, 2]. Examples of main power converters are internal combustion engines (ICEs), fuel cells [3–7], etc. In any case, as illustrated in [8–11], the power distribution among the main PHEV subsystems is computed at the supervisory level. The model of the PHEV at the supervisory level in this investigation is represented as a bi-modal switched system, as opposed to models with higher number of modes.

The description of the PMCP for constructing the model-based control strategies consists of the PHEV dynamical model, and a performance index (PI), both of which are formulated at the supervisory level. Approaches to solve the PMCP in the literatures can be categorized according to computational requirements as the real-time implementable type, and the global optimal type. The dynamic programming (DP) approaches compute optimal solutions over the driving cycles [8, 9, 12]. The curse of dimensionality of DP is well known. Thanks to recent advances in optimization, approximation approaches have been developed and alleviate this problem [13–15]. Since full knowledge of the driving cycles is still required, control using DP is not real-time implementable. Nevertheless, the results can be used as benchmarks for comparing the degree of optimality under replicated driving conditions.

Real-time implementable control strategies for the HEV, not optimal over driving cycles, usually undergo fine-tuning on the actual vehicles for desired performances under various assumptions and driving conditions. The list includes but is not limited to classical instantaneous/static optimization, adaptive equivalent fuel consumption minimization strategy (A-ECMS) [10], simplified rule based , fuzzy logic based [1, 16, 17], and neural network based [4].

The Nonlinear Model Predictive Control (NMPC) technique can provide suboptimal solutions with respect to