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Real-time control strategy to maximize hybrid electric vehicle powertrain efficiency

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HIGHLIGHTS

- An off-line local control is proposed for real-time HEV energy management.
- Powertrain efficiencies are studied to produce a unified objective function.
- Penalty function is designed to ensure charge sustaining operation.
- Implementation by storing optimal power share in a two-dimensional control map.
- Proposed control improved fuel economy by up to 20% compared to conventional control.

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ABSTRACT

The proposed supervisory control system (SCS) uses a control map to maximize the powertrain efficiency of a hybrid electric vehicle (HEV) in real-time. The paper presents the methodology and structure of the control, including a novel, comprehensive and unified expression for the overall powertrain efficiency that considers the engine-generator set and the battery in depth as well as the power electronics. A control map is then produced with instructions for the optimal power share between the engine branch and battery branch of the vehicle such that the powertrain efficiency is maximized. This map is computed off-line and can thereafter be operated in real-time at very low computational cost. A charge sustaining factor is also developed and introduced to ensure the SCS operates the vehicle within desired SOC bounds. This SCS is then tested and benchmarked against two conventional control strategies in a high-fidelity vehicle model, representing a series HEV. Extensive simulation results are presented for repeated cycles of a diverse range of standard driving cycles, showing significant improvements in fuel economy (up to 20%) and less aggressive use of the battery.

1. Introduction

Over the past decade there has been an increasing awareness of climate change and growing concerns regarding air pollution and the finite supply of fossil fuels. As a result, the whole automotive sector has seen the start of a historical transition towards the electrification of vehicle fleets. This effort has seen growing collaboration and understanding between manufacturers, regulators and researchers to deliver vehicle technologies that are not only environment-friendly but also commercially viable. This transition is therefore expected to depend significantly on the hybrid electric vehicle (HEV), which is seen by some as a stepping stone while others consider it a solution in its own right [1,2]. It is predicted that by 2020 approximately 18% of new vehicles sold in Europe, and 7% in the US, will be HEVs (while the estimates are 8% and 2% respectively for pure electric vehicles) [3]. It is therefore of significant interest to study how improvements in HEV performance can be made.

Of particular interest is the energy management problem, which involves determining the optimal power allocation between multiple sources in the powertrain. The supervisory control system (SCS) of the vehicle is responsible for addressing this problem with respect to vehicle constraints. The topic has been studied for the past decade and a vast range of SCSs have been proposed in the literature, ranging from rule-based to optimization-based solutions [4–9]. However, most SCSs of the latter nature involve significant amount of computation and therefore they are not implementable in real-time. Nevertheless, these can serve as important benchmarks to identify a globally optimal solution. Past work has generally applied dynamic programming [10,11] in this pursuit but more

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Nomenclature

η_{CS}	charge sustaining objective function
η_{dcdc}	DC–DC converter efficiency
η_{ICE}	ICE efficiency
η_{PS}	PS efficiency
η_{rec}	rectifier efficiency
η_{re}	SS replenishing efficiency
η_{SS}	SS efficiency
η_{tot}	combined efficiency of PS and SS
$\omega_{ICE,opt}$	optimal ICE speed for given load
ω_{ICE}	ICE speed
I_{bat}	battery current
k	charge sustaining factor
M_{eq}	normalized equivalent fuel consumption
m_{eq}	equivalent fuel consumption
m_f	mass of fuel consumed by ICE
P_{bat}	battery power
P_{ch}	scaling factor for PFCS
P_{PL}	PL power
$P_{PS,opt}$	PS power at its optimal operating point
P_{PS}	PS power
P_{SS}	SS power
Q	consumed battery charge
Q_{HV}	lower heating value of diesel
s_c	charging equivalence factor
s_d	discharging equivalence factor
SOC	state-of-charge
T_{ICE}	ICE torque
u	power share factor
u_{opt}	optimal power share factor
v	correction factor for SS efficiency
$V_{bat,OC}$	battery open circuit voltage
V_{bat}	battery voltage
V_{dc}	DC bus voltage
η^*_{SS}	SS discharging efficiency
ECMS	equivalent consumption minimization strategy
EMCSM	Efficiency Maximizing and Charge Sustaining Map
EMM	Efficiency Maximizing Map
EUDC	extra-urban driving cycle
EZ	exponential zone
FTP-75	federal test procedure 75
HEV	hybrid electric vehicle
ICE	internal combustion engine
NYCC	New York city cycle
PFCS	Power Follower Control Strategy
PL	Propulsion Load (inverter, PMSM and vehicle load)
PMSG	permanent magnet synchronous generator
PMSM	permanent magnet synchronous motor
PS	Primary Source (ICE, PMSG and rectifier)
SCS	supervisory control system
SS	Secondary Source (battery and DC–DC converter)
TCS	Thermostat Control Strategy

recently convex optimization [12–14] has emerged as a potent option.

Various types of equivalent consumption minimization strategies (ECMS) have been pursued [15,16] for all types of HEVs, as they are computationally feasible in real-time and have been shown to achieve good fuel economy. However, the success of the ECMS is quite sensitive to the equivalence factor between fuel and battery charge that depends on driving cycle and other changing factors. An alternative approach to minimizing equivalent fuel consumption is to maximize the powertrain efficiency. This has the advantage of not only being more intuitive but also less sensitive to tuning, as the component efficiencies are often readily available unlike equivalence factors. Also, this method is more transparent in the sense that it can be understood where the various losses are occurring in the powertrain. Furthermore, this control method does not rely on future driving information but only on the instantaneous power demanded for the vehicle to follow any given speed profile. Therefore, it can be implemented in real-time at low computational cost.

Past work that has taken the approach of considering the powertrain efficiency has often focused on the optimization of the internal combustion engine (ICE) or the engine-generator set, as a vast majority of the powertrain losses occurs there. Consequently, this often results in the battery dynamics and losses being considered very crudely, if not neglected. Instead the battery is only considered when applying constraints on the control, typically to ensure the SOC remains between a defined upper and lower bound. Some work investigates the overall powertrain efficiency but uses it to derive heuristic control rules rather than an efficiency-maximizing objective function [17–19]. Other work studies the powertrain efficiency in depth to inform the control algorithm (without specifically optimizing efficiency) and then evaluates simulation results rigorously [20,21]. The proposed work takes a holistic approach and investigates the efficiency of the whole powertrain in depth before producing a control map such that the total efficiency is continuously locally maximized during driving (subject to SOC constraints). The implementation of SCSs using control maps has been done in the past as well [22]. These maps are easy to implement and can be read during driving in real-time with very limited processing requirements. Also, as the maps are precomputed off-line, there is practically no time-constraint on the optimization algorithm to maximize the efficiency.

The control strategy proposed in this paper is an evolution of the algorithm presented in [23,24]. The main advances involve improvements in the methodology for determining the powertrain efficiency and condensing of the algorithm into a simpler form without loss of performance. Although the method and structure of the proposed control strategy is applicable to HEVs of any architecture, it has been implemented for a series HEV in this work, using the dynamical vehicle model described in [25]. This high-fidelity physics-based model allows complex transient behavior throughout the powertrain, unlike most models that are based on steady-state operation, and thus provides validity to the obtained results. However, due to the complexity of the vehicle model, it has not been feasible to compute a global optimal control solution for benchmarking purposes. Instead, the proposed SCS has been benchmarked against two conventional series HEV control strategies: the Thermostat Control Strategy (TCS) and the Power Follower Control Strategy (PFCS). These are widely used as benchmarks in literature for series HEVs.

In the next section the vehicle model is introduced and Section 3 analyzes the powertrain to determine the efficiencies of the energy sources. This analysis forms the foundation for the SCSs discussed in Section 4. Results are presented in Section 5 where the performance in terms of power profiles, SOC and fuel economy are discussed. Finally conclusions are given in Section 6.

2. Vehicle model

The SCSs presented in this work are designed and tested in the dynamic vehicle model described in [25]. The model consists of a