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Development of an Adaptive Efficient Thermal/ Electric Skipping Control Strategy Applied to a Parallel Plug-in Hybrid Electric Vehicle

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Abstract

In recent years automobile manufacturers focused on an increasing degree of electrification of the powertrains with the aim to reduce pollutants and CO_2 emissions. Despite more complex design processes and control strategies, these powertrains offer improved fuel exploitation compared to conventional vehicles thanks to intelligent energy management. A simulation study is here presented aiming at developing a new control strategy for a P3 parallel plug-in hybrid electric vehicle. The simulation model is implemented using vehicle modeling and simulation toolboxes in MATLAB/Simulink. The proposed control strategy is based on an alternative utilization of the electric motor and thermal engine to satisfy the vehicle power demand at the wheels (Efficient Thermal/Electric Skipping Strategy - ETESS). The choice between the two units is realized through a comparison between two equivalent fuel rates, one related to the thermal engine and the other related to the electric consumption. An adaptive function is introduced to develop a charge-blended control strategy. The novel adaptive control strategy (A-ETESS) is applied to estimate fuel consumption along different driving cycles. The control algorithm is implemented on a dedicated microcontroller unit performing a Processor-In-the-Loop (PIL) simulation. To demonstrate the reliability and effectiveness of the A-ETESS, the same adaptive function is built on the Equivalent Consumption Minimization Strategy (ECMS). The PIL results showed that the proposed strategy ensures a fuel economy similar to ECMS (worse of about 2% on average) and a computational effort reduced by 99% on average. This last feature reveals the potential for real-time on-vehicle applications.

Introduction

Electrified powertrains are one of the key technologies for vehicle energy saving. Combining an Internal Combustion Engine (ICE) and one or more high-efficiency electric machines, Hybrid Electric Vehicles (HEVs) have lower fuel consumption than conventional vehicles. However, effective Energy Management Strategies (EMSs) are required to coordinate the energy distribution among powertrain components and, at the same time, respecting their safe working condition.

Zhang et al. [1] proposed to classify EMSs in two main headlines: (1) offline EMSs, categorized according to the information level of the driving conditions utilized, including global optimization based-EMSs and rule-based EMSs; and (2) online EMSs represented as instantaneous optimization-based EMSs, predictive EMSs, and learning-based EMSs.

Offline EMSs are mainly divided into global optimization-based EMSs and rule-based EMSs. Rule-based EMSs are based on the selection of driving modes. They are typically used in real-time applications thanks to their low computational effort [2-4]. Dynamic programming (DP) and Pontryagin Minimization Principle (PMP) are two of the most common offline EMSs. DP is a mathematical technique to find the global optimum solution in managing the energy sources in hybrid power trains [5-7]. Therefore, it is used as a benchmark tool for other EMSs [8]. It requires prior knowledge of the entire driving cycle and has high computational complexity. PMP is an analytical optimization method that transforms a global optimization problem into an instantaneous Hamiltonian optimization problem [9, 10]. Its main disadvantage is the requirement of the co-state estimation [11, 12]. Kim et al. [13] developed a methodology to calculate the optimal co-state when a driving cycle is given. The simulation results showed that PMP control can achieve near-optimal results compared to DP. The computational time for PMP-based control was a tenth of that for DP-based control.

The Equivalent Consumption Minimization Strategy (ECMS) can be considered a PMP extension for online implementation. It is based on the idea that power is distributed by minimizing the fuel consumption at each instant by converting the electricity consumption into the equivalent fuel consumption [14, 15]. The control variable in EMCS is an Equivalent Factor (EF) that relates the electric energy consumption to the power requirement. Wang et al. [16] developed a real-time

is two orders of magnitude faster than A-ECMS and its average execution time is lower than the typical cycle time of a CAN message for an updated engine torque request. At the expense of slightly worse fuel consumption, the proposed strategy greatly reduces computational costs.

As a future development of this work, the proposed methodology for the estimation of c_0 will be refined to improve A-ETESS performance when it is implemented for a connected and autonomous vehicle. Vehicle connectivity can provide information to train neural networks which can cooperate with the proposed strategy. A detailed clutch model to disengage ICE, in the case of load-less operations, and an enhanced gear shifting strategy will be introduced, as well.

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Acronyms

A-ECMS - Adaptive - ECMS
BA - Battery pack
BSFC - Brake Specific Fuel Consumption
CB - Charge Blended
CD - Charge Depleting
CS - Charge Sustaining
DP - Dynamic Programming
ECMS - Equivalent Consumption Minimization Strategy
EM - Electric motor
EM - Electric machine
EMS - Energy Management Strategy
ETESS - Efficient Thermal/Electric Skipping Strategy
FC - Fuel consumption
HEV - Hybrid electric vehicle
HIL - Hardware in the Loop
ICE - Internal Combustion Engine
LHV - Lower Heating Value
MT - Manual Transmission
PHEV - Plug-in HEV
PIL - Processor in the Loop
PMP - Pontryagin Minimum Principle
RDC - Real Driving Cycle
RDE - Real driving Emission
SoC - State of charge

Symbols

m - mass
ΔE_{batt} - Battery energy variation
$\dot{m}_f$ - Fuel mass rate
s_0 - Equivalence factor
k_{pen} - Adaptive term
P_{batt} - Battery Power

Greeks

η - Efficiency

Subscripts

a - Acceleration
batt - Battery
dem - Demanded
diff - Differential
eq - Equivalent