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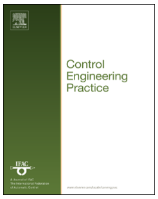

A stochastic method for the energy management in hybrid electric vehicles☆

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ABSTRACT

There are many approaches addressing the problem of optimal energy management in hybrid electric vehicles; however, most of them optimise the control strategy for particular driving cycles. This paper takes into account that the driving cycle is not *a priori* known to obtain a near-optimal solution. The proposed method is based on analysing the power demands in a given receding horizon to estimate future driving conditions and minimise the fuel consumption while cancelling the expected battery energy consumption after a defined time horizon. Simulations show that the proposed method allows charge sustainability providing near-optimal results.

1. Introduction

The performance of hybrid electric vehicles (HEV) is determined to a great extent by the control strategy, and then HEV control has been widely studied during last years as can be checked in Sciarreta and Guzzella (2007) and references within. Most of those works address it through the optimal control theory, searching for the control policy that provides the minimum fuel consumption while satisfying other energetic constraints. Dynamic Programming (DP) (Mosbech, 1980; Sundström, Ambühl, & Guzzella, 2010), Pontryagin Minimum Principle (PMP) (Ambühl, Sundström, Sciarretta, & Guzzella, 2010; Chasse & Sciarretta, 2011; Serrao, Onori, & Rizzoni, 2011) or Model Predictive Control (MPC) (Borhan, Vahidi, Phillips, Kuang, & Kolmanovsky, 2009; Kermani, Delprat, Guerra, Trigui, & Jeanneret, 2012) techniques have been applied to the Energy Management Problem of HEVs, hereinafter EMP. *Ad hoc* methods such as the Equivalent Consumption Minimisation Strategy (ECMS) (Paganelli, Ercole, Brahma, Guezennec, & Rizzoni, 2001) have been developed to address the EMP, demonstrating similar performance to the methods purely derived from the optimal control theory. In any case, as far as the application of optimal control techniques requires information on the future driving conditions it is necessary to include in the control strategy some kind of driving cycle prediction if those techniques are intended to be applied online.

Vehicles are highly dynamic systems and their power demands depend on many factors (driver style, road, traffic, weather, passengers agenda, etc.). There are two main sort of methods to estimate future driving demands: those based on external sensors such as Global Position System (GPS) or Intelligent Transportation System (ITS) (Gong, Tulpule, Marano, Midlam-Mohler, & Rizzoni, 2011) and those based on past information to predict future driving conditions in a stochastic fashion. Amongst this second kind of methods, some authors propose to estimate future power demands with a Markov chain which provides the probability of a set of discrete power demands depending on its current value. Once the future power demands are estimated, the problem can be solved by MPC (Ripaccioli, Bernardini, di Cairano, Bemporad, & Kolmanovsky, 2010) or by stochastic DP (Liu & Peng, 2008). This paper introduces a control strategy based on the ECMS formulation with a probabilistic estimation of future driving conditions.

According to the previous ideas, the paper is presented as follows: Section 2 contains the description of the case study. For the sake of simplicity, a series HEV is presented as an example to apply the proposed strategy. Nevertheless, the method can be easily adapted to address other powertrain architectures. Section 3 is devoted to the problem formulation. Then, in Section 4 the proposed strategy for the energy management of HEVs is introduced and formal and applied aspects regarding the prediction of the vehicle operating conditions and driving pattern identification are addressed. Section 5 evaluates the presented method by means of an application example in which its performance is compared with the optimal solution of the problem. Finally, the extension

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Table 1
Description of the main vehicle features.

Vehicle mass	2000 kg
Engine power	75 kW
Generator power	60 kW
Motor power	150 kW
Battery power	160 kW
Battery energy capacity	6.38 MJ (1.77 kWh)

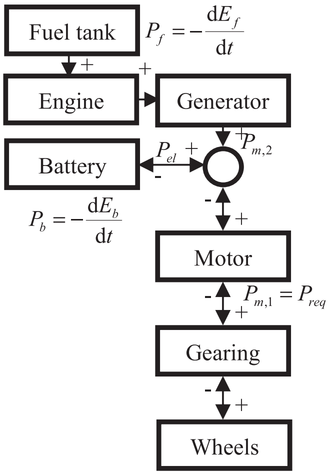

Fig. 1. System layout, nomenclature and sign criteria for series hybrid architecture.

of the proposed method for parallel HEVs is presented in the Appendix. The obtained results show that the proposed strategy is able to provide robust solution to the EMP without information about the driving cycle to be optimised.

2. Case study

The main objective of the paper is to introduce a new method to estimate future driving conditions that allows applying the ECMS strategy to solve the EMP. In particular, the present paper addresses the EMP in a series HEV as a demonstrative example to show the potential of the proposed optimisation method. It should be noted that the method is general and can be also applied to parallel HEVs as shown in the Appendix. The main characteristics of the selected powertrain are summarised in Table 1 while Fig. 1 shows the powertrain architecture and the sign criteria employed.

Due to the lack of a proper experimental facility, the present study has been made by modelling. Particularly, the approach proposed by Rizzoni, Guzzella, and Baumann (1999) has been used. With this approach, the power demands in powertrain elements are progressively calculated from the vehicle velocity by means of energy balances done with inverted physical causality. Then, the vehicle is assumed to follow a series of steady states in which the power in the vehicle elements is calculated from the vehicle speed, acceleration and the road grade. In addition, for any powertrain element, its efficiency is mapped with rotational speed and torque, while maximum and minimum torques are defined as functions of the speed.

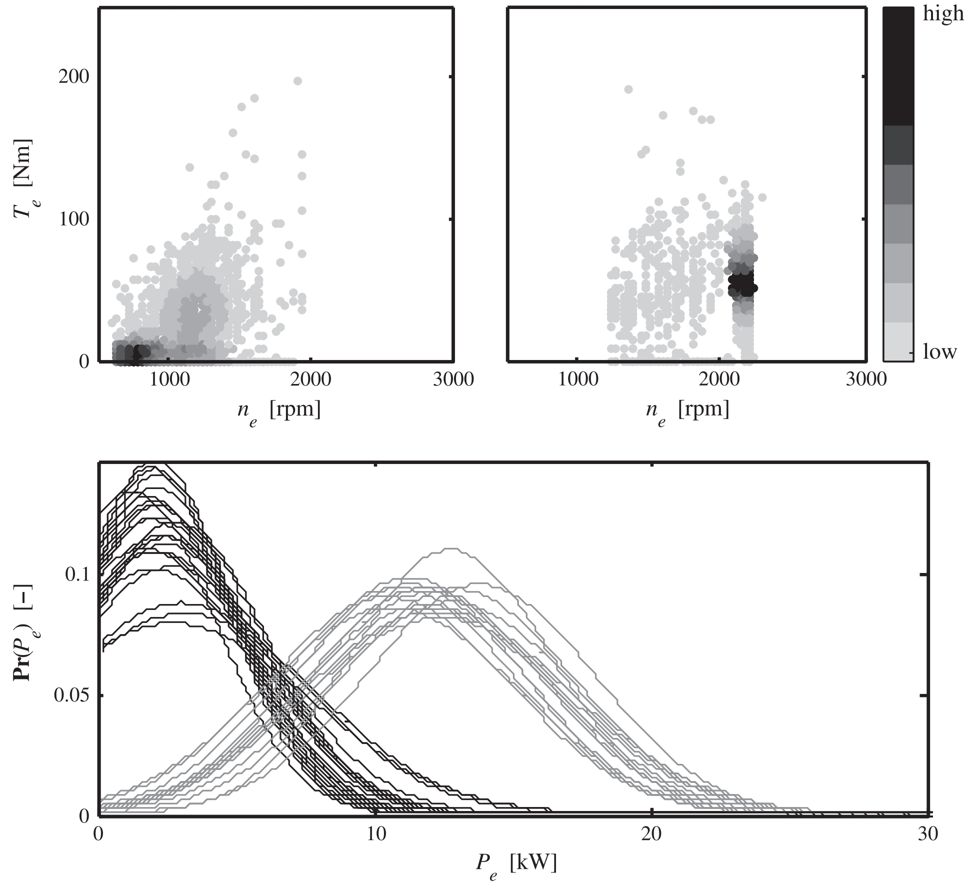

Fig. 2. Upper plots: operating points in the engine speed-torque ($n_e - T_e$) map for urban (left) and extra-urban driving tests (right) and qualitative representation of its frequency $\mathbf{Pr}(P_e)$. Lower plot: Fit of the engine power (P_e) during urban (black line) and extra-urban (grey line) tests to normal distributions.