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Optimization of power management in an hybrid electric vehicle using dynamic programming

Laura V. Pérez [*,1], Guillermo R. Bossio [1], Diego Moitre, Guillermo O. García [1]

Facultad de Ingeniería, Universidad Nacional de Río Cuarto, Córdoba, República Argentina

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Abstract

Hybrid electric vehicles are those powered from two different sources. Typically, they are equipped with an internal combustion engine, and also with an electrical storage system, such as a bank of batteries or ultra-capacitors. While braking, these vehicles may convert kinetic energy to electrical energy and send it back to the electrical storage system (regenerative braking). The whole vehicle system may be abstracted to one consisting of two energy sources, one of them rechargeable and the other consumable, that feed or receive energy from an energy consumer. A centralized control strategy is required to define the instantaneous power flows among these three main components. In this work, we derive the power split between the two sources such that fuel consumption is minimized, while the vehicle performs a given velocity cycle. Bounds on the power flows from both sources are considered. There is also a constraint of an integral nature that arises from the fact that the energy of the electrical storage system must remain between proper limits, in order to avoid physical damage. The problem is posed as a finite horizon dynamical optimization problem with constraints and solved by a dynamic programming (DP) approach. The hybrid electrical vehicle being developed in the University of Río Cuarto, Argentina is taken as the case study.

Keywords: Cost optimal control; Dynamic programming; Road vehicle control

1. Introduction

Hybrid electric vehicles (HEVs) are those whose architecture includes two or more energy sources and associated energy converters. Typically, they are equipped with an internal combustion engine with an associated fuel tank (FT) and an electric motor with an associated electrical storage system (ESS), such as a bank of batteries or ultra-capacitors. These vehicles take advantage of the higher efficiency of electrical traction, while overcoming its main disadvantage: its low range (a consequence of the low energy density of current ESSs). The addition of a fuel converter compensates for this fact, since fuel has an energy density two or three order of magnitude larger. HEVs are expected to be less polluting, have lower fuel consumption and a range similar to that of conventional vehicles.

The storage elements and energy converters can be arranged following different topologies. Fig. 1 shows the "series" configuration. In this case, the electric motor moves the wheels and is fed by the ESS. The engine, which is in turn fed by the chemical storage system, i.e., the fuel tank, drives an electrical generator. This generator provides electrical energy

* Corresponding author. Tel.: +54 358 4676255; fax: +54 358 4676246.
E-mail addresses: lperez@ing.unrc.edu.ar (L.V. Pérez), gbossio@ing.unrc.edu.ar (G.R. Bossio), dmoitre@ing.unrc.edu.ar (D. Moitre), ggarcia@ing.unrc.edu.ar (G.O. García).
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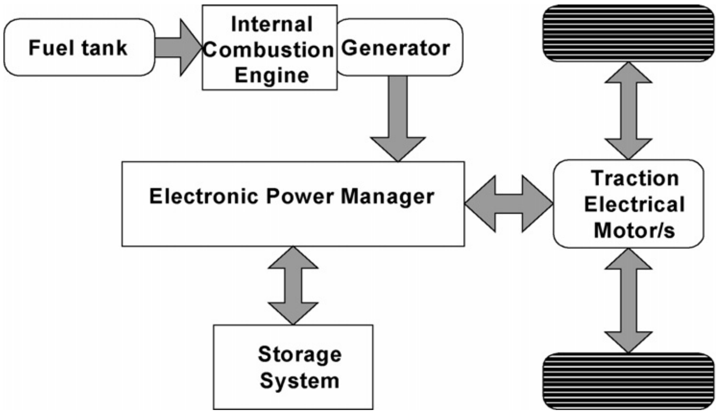

Fig. 1. Scheme of a series HEV.

to the traction motor when the driver power demand exceeds that delivered by the batteries. If the power generated by the engine–generator system exceeds what is needed, then it is diverted to recharge the ESS.

Hybrid power-trains share with electrical ones the additional advantage of regenerative braking. This means that electric motors, when used for traction, are able to become generators during braking. Hence, the vehicle kinetic energy, which otherwise is burnt in the brake drums in the form of heat, can be converted into electrical energy and sent back to the batteries. For that reason, Fig. 1 shows double arrows from the wheels to the storage system.

An electronic power manager determines at each instant, the amount and direction of power flow in each one of the paths. This higher-level control is known as “supervisory control”. At a lower level, power electronic devices will control each one of the power converters of the system to satisfy the supervisory controller commands.

As has been said, there may be other topologies. The addition of power from the two sources may be mechanical instead of electrical, etc., but regardless of the particular configuration, the coordination between them and the system operational and physical limitations force trade-offs. So, to make full use of the benefits of HEV, optimizing the supervisory control strategy is necessary. Optimization will depend on the objective pursued, on the control action selected and on the constraints considered.

Our research group is developing an HEV series aimed for city work. It is in city work where the advantages of HEVs are most noticeable because of the sequence of acceleration and deceleration intervals. This work is a first step towards the definition of an optimal strategy for the supervisory control of the vehicle. The control objective is to minimize fuel consumption while the vehicle performs a scheduled velocity cycle.

Clearly, these control problems include combinations of linear and non-linear, discrete and continuous, algebraic and dynamical systems. Hence, most of the reported optimal supervisory control strategies use either intelligent control techniques, such as rule-based, fuzzy logic and neural networks, or optimal control approaches, such as those in Delprat et al. [5,6] and Steinmauer and del Re [10]. Within the same approach, Zaremba et al. [11], Brahma et al. [2,3] and Sciaretta et al. [9] use a discrete approach and a DP algorithm. In this work, we follow Brahma et al. [2,3] in solving our supervisory control problem. The drawback in this approach is that the treatment of constraints of integral form complicates the computations. This kind of constraint appears because of the need to preserve the batteries from depletion or overcharge, and/or if a “charge sustaining” operation of the vehicle is imposed. Brahma et al. propose heuristic methods based on penalization terms added to the objective function. We apply their approach to our case and propose an alternative method based on checking the constraints as the algorithm proceeds. The method is also suboptimal but strictly ensures the safe operation of the ESS.

The paper is organized as follows. Section 2 gives to the statement of the problem; Section 3 summarizes the DP approach to solve this dynamic optimization problem; Section 4 shows some results; finally, Section 5 contains our conclusions and intended future work.

2. Statement of the problem

To define the supervisory control, a control objective, a control action (or independent variable), a state variable (or dependent variable) and system constraints have to be established. These elements may interchange roles and hence