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Energy management strategy for plug-in hybrid electric vehicles. A comparative study

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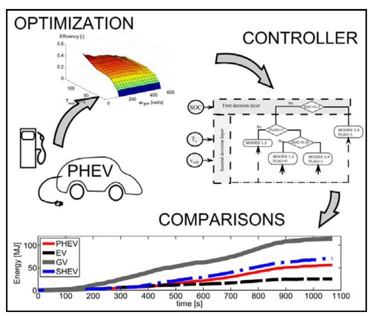
HIGHLIGHTS

- The accuracy of the proposed strategy of control is evaluated through simulations.
- Results are compared with respect to vehicles equipped with different powertrains.
- The modeled vehicle combines energy savings and greater autonomy.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents the development of an energy management strategy of a Plug-in Hybrid Electric Vehicle (PHEV). In this case, a rule-based optimal controller selects the appropriate operation mode. Furthermore, advantages and drawbacks of such vehicles are compared with respect to other vehicles powered by the most popular powertrain architectures. Simulations are carried out for three predefined drive cycles repeated over different geographic regions with varying CO_2 intensities. The results reveal that the proposed controller is able to switch the vehicle's operating mode according to previous established criteria.

1. Introduction

An attractive research is that related to hybrid electric vehicles (HEVs), where more than one on-board power source is employed. In recent years HEVs are becoming very popular. Government and industry in development countries have teamed up to invest billions of euros in partnerships intended to reduce dependency on fossil fuels. Problems derived from mobility, nowadays, mainly focus on pollution, low internal combustion engines performance, noise and depletion of fossil fuels. These problems justify the numerous efforts aimed at developing a new generation of vehicles. In this sense, automobile companies such as Toyota, Honda, Chevrolet, Mazda and Ford, have invested a lot of efforts and money in developing hybrid cars. There are many advantages of HEVs over conventional petroleum-based vehicles, some of these are: (i) fuel economy: since petroleum consumption is reduced drastically by using an electric motor [1]; (ii) less pollution: mostly the vehicle is powered by "green" energy (battery) [2]; (iii) saving money: some governments offer tax incentives for buying hybrid/electric vehicles [3]; and (iv) the battery is recovered, using part of the kinetic energy when the vehicle decelerates, through regenerative braking [4].

Despite all these advantages exposed, some inherent issues of HEVs should be considered. For the concrete case of Plug-in Hybrid Electric Vehicles (PHEVs), a massive demand would produce an

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important impact on the electric distribution grids [5,6], including the integration of recharging infrastructures [7]. Furthermore, the characteristics of the power generation mix determine the efficiency and grade of emission of CO_2 of a PHEV in overall terms [8]. Consequently, the ability of EVs and PHEVs to reduce the CO_2 emissions from personal mobility is considerably decreased in highly CO_2 intensive countries [2,9]. An interesting approach for the development of PHEVs is that these vehicles are considered to actuate as accumulators of electricity. That is useful to balance the mix of power generation, and addresses an increased use of green energy sources. In this sense, PHEVs allow store the surplus electricity such a wind power during the night for later uses [10,11].

There are many powertrain configurations for hybrid electric vehicles [12,13]. Each configuration depends on the state of three components: a petroleum-based engine, a generator and an electric motor. A key point related to hybrid electric vehicles is how to select the status of each component (engine, generator, motor) since depending on this decision the power system will work, and hence more energy would be saved or wasted [14]. Therefore the energy management strategy has a fundamental role in hybrid vehicles.

There are several ways to address the problem of energy management control. For instance in [15] a rule-based controller is presented. The rules depend on the power demand, the driver's acceleration and the State of Charge (SOC) of the battery. Then taking into account the value of such variables a powertrain configuration is adopted. In [16], a rule-based controller is designed and simulated for a two-modes power-split hybrid electric vehicle, whose powertrain is modeled using the bond-graph technique. A similar approach to rule-based control has been followed using fuzzy logic technique [17]. Another popular approach is to employ genetic algorithms [18]. Recently more advanced control techniques based on optimal control has emerged [19,20]. In the paper [21] a model predictive control strategy (MPC) has been applied to energy management for hybrid vehicles. At each sampling time the powertrain operation point is chosen minimizing a desired criterion, in this case the fuel consumption. In [22], a nonlinear constrained MPC is utilized to obtain the power split between the combustion engine and electrical machines and the system operation points at each sample time.

The main focus of this report is to develop an energy management strategy in order to improve the fuel efficiency of a hybrid electric vehicle without deteriorating the vehicle performance and reaching the desired references despite of external disturbances. It is assumed that vehicle is steered by a human operator, and the driving cycle is not known a priori under real world operating conditions. The suitability of the proposed strategy of control is measured through a simulator implemented in MATLAB/Simulink. These simulations are carried out for three predefined drive cycles repeated over different geographic regions with varying CO_2 intensities.

The paper is organized as follows. Section 2 deals with the discussion of the key features of the different operation modes available at the considered vehicle, the designed rule-based controller is explained and the methods of evaluation are presented. Simulation results are detailed in Section 3. Finally, conclusions are depicted in Section 4.

2. Methods

2.1. Problem statement

In order to extract the maximum benefit from a PHEV, it is necessary to have a control strategy which is able to manage the different machines involved in its powertrain [23]. Concretely, the powertrain of the considered PHEV in this study is composed of an electric motor (MOT), a generator (GEN) and a gasoline engine (ENG). In particular, we have considered the powertrain architecture of the vehicle GM Voltec [24] (see Fig. 1). In this case, the MOT develops a power up to 140 kW and 370 Nm of torque, the GEN 55 kW and 110 Nm, and the ENG 63 kW and 130 Nm. Electric machines are powered by a battery with capacity of 16 kW h, maximum power of 110 kW and maximum recharging power of 60 kW. The main issue inherent to this kind of vehicles is its power-split device based architecture, which is a planetary gear set. This is responsible to connect the three machines involved in the vehicle's propulsion to the wheels by means of a reduction gear and a differential [25].

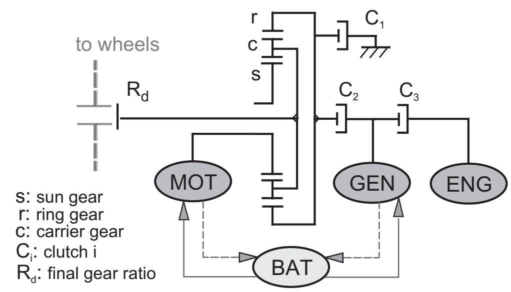

Fig. 1. Powertrain architecture.

2.1.1. Powertrain kinematics

As shown in Fig. 1, the sun gear of the planetary gear set is connected to the electric motor. The planetary ring may be either locked or connected to the generator. Finally, the carrier is connected to the rest of the driveline.

The kinematic relations which occur at the powertrain are described as follows:

$$\rho\omega_r + \omega_s = \omega_c(\rho + 1), \tag{1}$$

where ω_r, ω_s and ω_c are the ring gear, sun gear and carrier angular speed, respectively and $\rho = N_r/N_s = 2.24$ represents the ratio between the number of teeth of the ring and the sun gear. From now on, ω_s equals to the electric motor angular speed (ω_{mot}). Moreover, ω_r equals to the angular speed of the generator (ω_{gen}) or to the angular speed of the engine (ω_{eng}) as will be explained subsequently.

The torque relations imposed by the planetary gear set are:

$$T_s = \frac{T_r}{\rho} = \frac{T_c}{\rho + 1}, \tag{2}$$

where T_s and T_r are torques at the sun and ring gear respectively, and T_c is the torque at the carrier gear, which is connected to the wheels by means of a final gear with ratio $R_d = 2.16$. Hence, the torque at the wheel T_{wh} is obtained as $T_{wh} = R_dT_c$. From now on, the torque on the sun gear equals to the torque provided by the electric motor (T_{mot}) and the torque on the ring gear is the sum of the generator and the engine torques ($T_{gen} + T_{eng}$), with $T_{eng} = 0$ when C_3 is open. Finally, applying the law of conservation of energy leads to:

$$P_c = \omega_cT_c = P_s + P_r = T_s\omega_s + T_r\omega_r, \tag{3}$$

where P_c, P_s and P_r are the powers related to the carrier, sun and ring gear, respectively.

2.1.2. Vehicle dynamics

Attending to the vehicle's motion, its longitudinal dynamics is defined as: