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Effects of engine thermal transients on the energy management of series hybrid solar vehicles

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ABSTRACT

The paper focuses on investigating thermal-transients effects, associated to intermittent use of internal combustion engine (ICE), on fuel economy and hydrocarbon (HC) emissions of series hybrid solar vehicles (HSVs). An offline, non-linear constrained optimization is set-up to individuate the ICE power trajectory that simultaneously minimizes fuel consumption, suitably operates the battery and fully exploits daily solar contribution. The results highlight the importance of including thermal transients in HSV energy management. The combined effects of engine, generator and battery losses, along with cranking energy and thermal transients, produce non-trivial solutions for the engine/generator group, which should not necessarily operate at its maximum efficiency.

1. Introduction

In the last years, increasing attention is being spent towards the integration of solar energy with either electric or hybrid cars. While solar cars do not represent a practical alternative to cars for normal use, the concept of a hybrid electric car assisted by solar panels appears more realistic (Letendre, Perez, & Herig, 2003; Saitoh, Hisada, Gomi, & Maeda, 1992; Sasaki, Yokota, Nagayoshi, & Kamisako, 1997; Seal & Campbell, 1995; Seal, 1995). In fact, thanks to some relevant research efforts, in the last decade hybrid electric vehicles (HEV) have evolved to industrial maturity, and represent now a realistic solution to important issues, such as the reduction of gaseous pollution in urban drive as well as the energy saving requirements.

The use of solar energy on cars has been considered with certain skepticism by most users, including automotive engineers. This may be due to the simple observation that the net power achievable in a car with current photovoltaic panels is about two order of magnitude less than maximum power of most of today cars. But a deeper energetic analysis evidences that this perception may be misleading. In fact, there are a large number of drivers who use car everyday for short trips and with limited power demand. For instance, some recent studies conducted by INRETS (André, Hammarström, & Reynaud, 1999) report that about 71% of European car users drive 61 minutes a day, with 12 minutes average trip length and one passenger for most of the time (i.e. the driver).

On the other hand, a solar panel, if properly located, oriented and controlled, can operate near its maximum power for many hours a day, and in those conditions the daily solar energy collected by solar panels on the car may represent a significant fraction of the energy required for traction (Arsie, Rizzo, & Sorrentino, 2007b).

Despite their potential interest, solar hybrid cars have received relatively little attention in literature until a few years ago (Letendre et al., 2003). Some prototypes have been developed in Japan (Saitoh et al., 1992; Sasaki et al., 1997), at Western Washington University (Seal, 1995; Seal & Campbell, 1995) and at the Queensland University, while the first model of hybrid vehicle assisted by a solar panel, even if finalized to air conditioning, has been launched in 2009 by Toyota. Although these works demonstrate the general feasibility of such an idea, detailed presentation of results and performance, along with a systematic approach to hybrid solar vehicle design, were missing in literature until a few years ago. Therefore, appropriate methodologies are required to address both the rapid changes in the technological scenario and the increasing availability of innovative, more efficient components and solutions. The current study focuses on the extension of the methodologies presented in previous papers (Arsie, Graziosi, Pianese, Rizzo, & Sorrentino, 2005; Arsie, Di Martino, Rizzo, & Sorrentino, 2007a) for the energy management of an hybrid solar vehicle. Particularly the effects of engine thermal transients on fuel consumption and hydrocarbon (HC) exhaust emissions (Cheng & Santoso, 2002; Zavala, Sanketi, Wilcutts, Kaga, & Hedrick, 2007) are accounted for while

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investigating the most suitable powertrain management in case of ICE intermittent operation.

The paper is organized into 4 main sections. After a general description of vehicle model, the issues related to energy management in HSV are addressed in Section 3. Section 4 is devoted to the analysis of ICE thermal transients through detailed description of experiments and modeling approach. Finally, in Section 5 optimization results are presented and discussed.

2. The solar hybrid vehicle model

Different architectures can be applied to HEVs: series, parallel, and parallel-series. The choice can depend on vehicle size, performance and targeted usage. In this case, as for other solar hybrid vehicles (Letendre et al., 2003), the series structure has been adopted. Although the latter exhibits lower global efficiency than parallel, a series hybrid powertrain presents some very interesting features, such as:

- It is simpler, with fewer constraints for vehicle layout.
- There are no mechanical links between generator and wheels, therefore very effective vibration insulation can be achieved.
- It is possible to use in-wheel motors with advanced traction control techniques.
- Engines specifically optimized for steady operation can be used, with high peak efficiency and/or with favorable weight/power ratio (i.e. micro gas turbines).
- Series architecture acts as a bridge towards the introduction of fuel cell powertrains.

Moreover, their main disadvantage (i.e. lower global efficiency, due to electric generator/converters losses and not optimized engines for the specific application) is expected to become less concerning in next future, thanks to a significant research effort in such fields. The growing interest paid by the automotive industry towards the series structure is confirmed by the announced launch of the Chevrolet Volt, a plug-in hybrid electric vehicle to be produced by GM. Unlike most current commercially available electric hybrids, the actual propulsion of the Volt is accomplished exclusively by the electric motor (Bullis, 2007).

In the series structure, the photovoltaic panels (PV) assist the electric Generator (EG), powered by the internal combustion engine (ICE), in recharging the battery pack (B) in both parking mode and driving conditions, through the electric node (EN). The electric motor (EM) can either provide the mechanical power for propulsion or restore part of the braking power during regenerative braking (Fig. 1). In this structure, the thermal engine can work mostly at constant power, corresponding to its optimal efficiency, while the electric motor EM is designed to assure the attainment of the vehicle peak power.

2.1. Solar energy for vehicle propulsion

The estimation of net solar energy captured by PV panels in real conditions (i.e. considering clouds, rain etc.) and available for propulsion is accomplished by a solar calculator developed at the US National Renewable Energy Lab (Arsie et al., 2007b). The maximum panel area can be estimated as function of car dimensions and shape by means of a simple geometrical model. The instantaneous power ($P(t)$) is estimated for assigned vehicle data and driving cycle by integrating a longitudinal vehicle model, expressed by the following Newton law reduced to

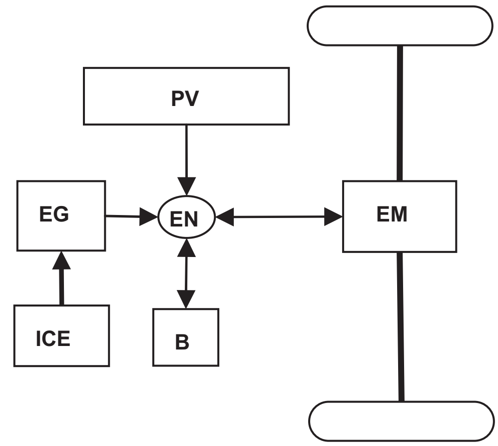

Fig. 1. Scheme of the series hybrid solar vehicle.

vehicle wheels:

$$I\frac{d\varpi}{dt} = T_{EM} - T_R \quad (1)$$

where I is the vehicle inertia, T_{EM} is the EM output torque and T_R is the resistant torque due to aerodynamic and rolling resistance (Arsie, Flora, Pianese, Rizzo, & Serra, 2001).

The required traction energy depends on vehicle weight and aerodynamics, which in turn depend on the size of propulsion system components, vehicle dimensions and solar panel area. Battery, electric motor and generator are simulated by the ADVISOR model (Burch et al., 2009).

2.2. Vehicle weight

The parametric HSV weight model results, on one hand, from the addition of the hybridizing devices (PV panels, battery pack, ICE, generator, electric motor, inverter) onto the conventional vehicle (CV) equipped with ICE (W_{CV}) and, on the other, by properly revaluating the contribution of the components resized or not present in the HSV (i.e. ICE, gearbox, clutch) (Arsie et al., 2007b). Considering the layout described in Fig. 1, the required nominal battery power is

$$P_B = P_{EM} - P_{EG} \quad (2)$$

In Eq. (2) the power contribution from the PV array is not accounted for because of two reasons: the first is the unpredictability of sunshine availability (e.g. rainy days); the second is linked to the relatively small PV nominal power that can be installed on cars at the current technology stage. Therefore the number of battery modules is evaluated as

$$N_B = \frac{P_{EM} - P_{EG}}{P_{B,u}} \quad (3)$$

where $P_{B,u}$ is the nominal power of a single battery module, here set to 1.67 kW for a 12 V, 25 Ah lead-acid module (Burch et al., 2009).

The power of the electric machine (P_{EM}) is computed imposing that the HSV power to weight ratio (PtW_{HSV}), corresponds to a 1250 kg conventional vehicle (CV) powered by a 75 kW gasoline engine, as reported in Table 1

$$PtW_{HSV} = \frac{P_{ICE,CV}}{W_{body,CV}} \quad (4)$$

$$P_{EM} = PtW_{HSV}\, W_{HSV} \quad (5)$$

Table 1 also shows that a battery pack consisting of 27 lead-acid modules was yielded by Eq. (3). Such an energy reservoir