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Energy Management for a Hybrid Solar Vehicle with Series Structure

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Abstract: A study on optimal energy management on a Hybrid Solar Vehicle (HSV) with series structure is presented. Previous results obtained by optimal design analysis for HSV confirmed the relevant benefits of such vehicles with respect to conventional cars in case of intermittent use in urban driving (city-car), and that economical feasibility could be achieved in a near future. In order to develop a supervisory control for a HSV prototype under development at University of Salerno, a study on the performance achievable by an intermittent use of the ICE powering the electric generator is presented. In particular, the effects of engine thermal transients on fuel consumption and HC emissions are studied and discussed. The optimal ICE power trajectory is found by solving a non-linear constrained optimization that suitably accounts for fuel mileage and state of charge, also considering solar contribution during parking mode.

Keywords: Engine Modeling, Engine Control, Optimization, Hybrid Vehicles, Solar Energy.

1 INTRODUCTION

In the last years, increasing attention is being spent towards the applications of solar energy to electric and 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 [1], [2], [3], [4], [5]. In fact, thanks to a relevant research effort [6], [7], [8], [9], 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 a certain scepticism 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 more careful analysis of the energy involved demonstrate that this perception may be misleading. In fact, there is a large number of drivers utilizing daily their car for short trips and with limited power demand. For instance, some recent studies conducted by the UK government report that about 71 % of UK users reach their office by car, and 46 % of them have trips shorter than 20 minutes, mostly with only one passenger (i.e. the driver) [10]. In those conditions, the solar energy collected by solar panels on the car along a day may represent a significant fraction of the energy required for traction [13].

In spite of their potential interest, solar hybrid cars have received relatively little attention in literature [5]. Some prototypes have been developed in last decade in Japan [1], [2], at Western Washington University [3], [4] and at the Queensland University [11]. Although these works demonstrate the general feasibility of such an idea, detailed presentation of results and performance, along with a systematic approach to solar hybrid vehicle design, seem still missing in literature. 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 [12], [13] to the control of a hybrid solar vehicle prototype, now under development at the University of Salerno. This activity is being conducted in the framework of the UE funded Leonardo project I05/B/P/PP-154181 “Energy Conversion Systems and Their Environmental Impact” [17]. The on going research is also extended to the study of real time control of solar panels (MPPT techniques and their implementation) and to the development of converters specifically suited for automotive applications [18].

2 THE SOLAR HYBRID VEHICLE MODEL

Different architectures can be applied to HEVs: series, parallel, and parallel-series. In case of solar hybrid vehicles the series structure seems preferable [5], due to its simplicity, as in some recent prototypes of EV [22] and HSV [11]. It is also worth noting that the series structure will potentially act as a bridge towards the introduction of hybrid fuel cell powertrains.

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 the 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.

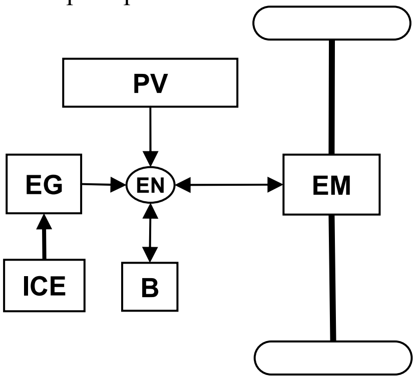

Fig. 1 - Scheme of the series hybrid solar vehicle.

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 has been used [13]. 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, integrating a longitudinal vehicle model based on a dynamic vehicle simulator [15]. The required driving energy depends on vehicle weight and aerodynamic parameters, which in turn depend on the sizing of propulsion system components and on vehicle dimensions, related to solar panel area. Battery, electric motor and generator are simulated by the ADVISOR model [16].

2.2 Vehicle weight

The parametric weight model of the HSV can be obtained adding the weight of the specific components (PV panels, battery pack, ICE, Generator, Electric Motor, Inverter) to the weight of the Conventional Vehicle (CV) equipped with ICE (W_{CV}) and by subtracting the contribution of the components resized or not present in the HSV (i.e. ICE, gearbox, clutch, as detailed in a previous work [12].

Considering the lay-out described in Fig. 1 , the required nominal battery power is:

$$P_B = P_{EM} - P_{EG} \tag{1}$$

In Eq. (1) 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 installed on cars at the current technology stage. Therefore the number of battery modules is evaluated as:

$$N_B = \frac{P_{EM} - P_{EG}}{P_{B,u}} \tag{2}$$

where $P_{B,u}$ is the nominal power of a single battery module.

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 *Tab. I.*

$$PtW_{HSV} = \frac{P_{ICE,CC}}{W_{body,CC}} \tag{3}$$

$$P_{EM} = PtW_{HSV} \cdot W_{HSV} \tag{4}$$

	CV	HSV
P_{ICE} [kW]	75	46
Fuel	gasoline	gasoline
P_{EG} [kW]	0	43
P_{EM} [kW]	0	90
N_B [/]	0	27
A_{PVH} [m^2]	0	1.44
W [kg]	1250	1465

Tab. I – Vehicle Technical Data.

3 ENERGY FLOW MANAGEMENT AND CONTROL IN A HYBRID SOLARVEHICLE

Hybrid Solar Vehicles have of course many similarities with Hybrid Electric Vehicles, for which many studies on the optimal management and control of energy flows have been presented in last years [6], [7], [8], [9], [22]. Nevertheless, the presence of solar panels and the adoption of a series structure may require to study and develop specific solutions for optimal management and control of an HSV.

In fact, in most electric hybrid vehicles a charge sustaining strategy is adopted: at the end of a driving path, the battery state of charge should remain unchanged. With a solar hybrid vehicle, a different strategy should be adopted as battery is charged during parking hours as well. In this case, a different goal can be pursued, namely restoring the initial state of charge within the end of the day rather than after a single driving path [13].

Moreover, the series configuration suggests quite an efficient solution, namely to operate the engine in an intermittent way at constant operating conditions. Of course, the maximum gain in terms of fuel consumption occurs when the ICE power corresponds to the most efficient value. In such case, the engine-generator system may be designed and optimized to maximize its efficiency, emissions and noise at design point, while in current automotive engines the maximum efficiency is usually sacrificed to the need of assuring stable operation and good performance in the whole operating range. The techniques developed for HEV, mostly adopting parallel or series/parallel structure, tend to treat the engine as a continuous system working in the whole range of operating conditions. This approach is also followed in some recent studies to HSV, based on the application of Dynamic Programming and Model Predictive Control [21]. In case of engine intermittent operation, the effects exerted on fuel consumption and emissions by the occurrence of thermal transients in engine and catalyst should be considered. These effects are neglected in most studies on HEV, where a steady-state approach is usually used to evaluate fuel consumption and emissions.

A preliminary analysis of HSV energy management has been presented by considering a single period for ICE operation within the driving cycle module, at specified position (i.e. at the end of driving cycle) [13]. This approach allows to take into account the key aspects related to control, in a framework where the main target was to estimate the effects of different vehicle and powertrain variables on energy flows. This procedure has been integrated in the vehicle dynamic model, also considering weight and costs, and used to study optimal vehicle design.

In order to develop a supervisory control to be implemented on the vehicle, a more accurate analysis of the optimal ICE power distribution over an arbitrary driving cycle has to be performed.

4 EFFECTS OF ICE INTERMITTENT OPERATION

The intermittent operation of the ICE produces the occurrence of thermal transients both in engine and in catalyst, so influencing fuel consumption and emissions. These effects should be analyzed and taken into account for energy flow management and control, also in order to develop suitable solutions for vehicle thermal management. In this paper, the aspects related to engine thermal transients and HC emissions are considered.

A study on the optimal ICE power trajectory has been performed by solving the following constrained optimization problem:

$$\min_X \int \dot{m}_{f,HSV}(X)dt \qquad (5)$$

subject to the constraints:

$$\Delta SOC_{day}(P_{EM}, P_{ICE}(X), P_{SUN}) = 0 \qquad (6)$$

$$SOC > SOC_{\min} \qquad (7)$$

$$SOC < SOC_{\max} \qquad (8)$$

The decision variables X include, for each ICE-on event, starting time, duration and ICE power level, while the number N of ICE-on phases has been assigned, in order to analyze its influence on the results.

The first constraint allows to restore the initial state of charge within the end of the day, also considering parking phases. It requires the integration of the vehicle dynamic model over the day. P_{EM} is known from the assigned mission profile, while also net power from sun is considered known. P_{ICE} depends on the decision variables X.

It is worth noting that the proposed control strategy is based on the knowledge of the vehicle route, thus being unsuitable for real-time control. Nevertheless the proposed approach is consistent with the purpose of the paper, that is aimed at analyzing the effects of engine operation on fuel efficiency. This task will be helpful for the future development of supervisory HSV control, extending to HSV the approach based on provisional load estimate recently applied to HEV real-time control [9].

The minimum and maximum allowed values for SOC are imposed considering battery reliability, while the limit on maximum SOC during driving phases is due to the exigency to assure a battery capacity sufficient to store the expected solar energy during parking time. Further constraints are introduced to limit the ICE power within the operating range and to avoid ICE operation phases overlapping.

The driving cycle is composed of 4 modules of ECE-EUDC cycle, as shown in Fig. 2.

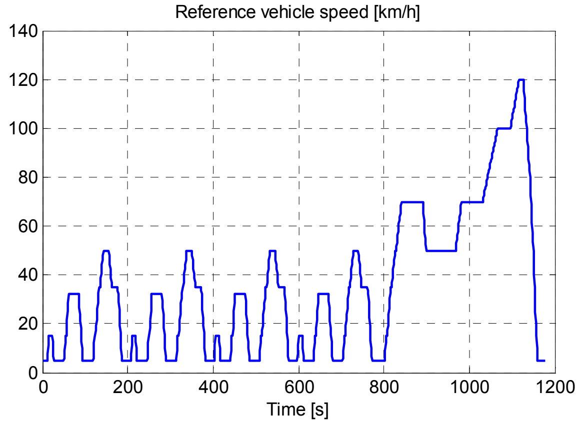

Fig. 2 – Module of the ECE-EUDC driving cycle.

4.1 Modeling of engine thermal transient

The effects of thermal transients have been accounted for assuming that: (i) the ICE power does not reach instantaneously its reference value and (ii) the specific consumption depends not only on ICE power but also on the actual engine temperature.

The coolant temperature T has been assumed as engine reference temperature. The time variation of T has been estimated as a first order process by the following equation:

$$T(t) = T_{ss} + (T_{in} - T_{ss}) \cdot e^{-\frac{t}{K}} \qquad (9)$$

The values of steady state temperature T_{ss} and of the time constant K have been assigned according to the following table, based on some experimental tests performed at the test bench:

ICE operation	T_{ss} [°C]	K [s]
ON	82	150
OFF	27	600

Fuel consumption (Eq. 10) is estimated by correcting the steady-state values, corresponding to thermal equilibrium conditions, by a factor depending on the ratio between the actual and steady-state values of engine temperature.

$$P(t) = P_{ss} \cdot f\left(\frac{T}{T_{ss}}\right) \qquad (10)$$

$$SFC(t) = SFC_{ss}(P) \Big/ f\left(\frac{T}{T_{ss}}\right) \qquad (11)$$

4.2 Modeling of HC emissions

HC emissions are of major concern when frequent engine start/stop maneuvers are performed, as in the case of the ICE intermittent use proposed for HSV operation. Therefore, appropriate estimation of HC emissions during engine thermal transient could be useful to optimize energy management strategies also with respect to HC impact.

A simple model for HC emissions has been developed, based on the observation of experimental data measured on the engine test bench during a cold-start transient on a 4 cylinder SI engine 1.2 liters. The experimental trajectory, plotted in Fig. 3, shows that HC tail pipe emissions exhibit a dramatic decrease during the first 20 seconds, starting from a very high HC concentration mainly due to fuel enrichment and eventually misfiring in the early stages of engine operation. Afterwards, the HC trend follows the catalyst thermal dynamics and approaches almost negligible concentration after about 400 s.

According to this behavior and to experimental evidences derived from literature analyses [14], [19], in the first 20 seconds HC emissions are modeled as first order process, as follows:

$$HC(t) = HC_{ss} + \left(HC_{in} - HC_{ss}\right)e^{-\frac{t}{\tau}} \qquad (12)$$

The initial value HC_{in} is computed by correcting the experimental value detected during the cold start test (about 1000 ppm) by a factor accounting for the actual engine temperature:

$$HC_{in} = HC_{in\_cold} \cdot f\left(\frac{T_{in}}{T_{in\_cold}}\right) \qquad (13)$$

this way the model can predict HC emissions even in case of engine warm start. The correcting factor has been evaluated as function of a fuel delivery efficiency that expresses the ratio between actuated and effective Air to Fuel Ratio (AFR) [14] Actually, the fuel delivery efficiency accounts for the wall wetting process and the effect of fuel enrichment on HC formation mechanism. Of course, assuming fixed engine speed, load and spark advance, the correcting factor mainly depends on the engine thermal state [14], [20].

The steady state value HC_{ss} is computed by a look-up table expressing the dependence of HC concentration from engine temperature. Hence, when the early transient has been extinguished (i.e. after the first 20 s), the HC emissions are evaluated as function of the engine thermal state, regardless to gas composition and temperature and to catalyst thermal state.

Actually, the experimental data were measured imposing stoichiometric mixture and fixed spark advance, engine speed and load along the whole warm-up maneuver. Therefore, if a similar transient is imposed for each engine start operation then gas composition and temperature are not affected by anything else than engine temperature. Consequently, also catalyst efficiency can be associated to engine temperature, even if its thermal dynamics differs from the engine.

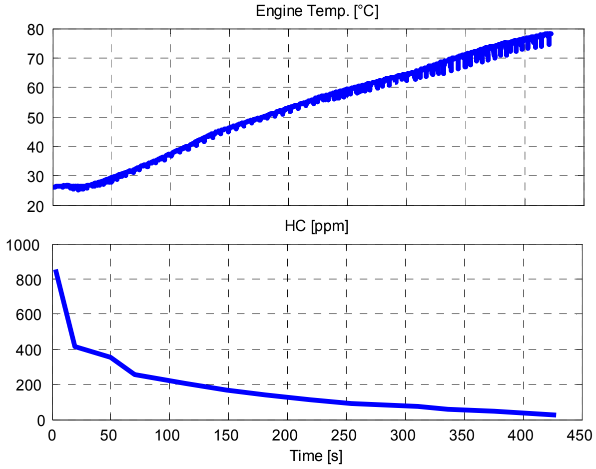

Fig. 3 – Measurements of engine temperature and tail-pipe HC emissions along a cold-start maneuver on the engine test bench.

The results of a simulated engine start maneuvers are shown in Fig. 4 in case of cold and warm operation. The figure evidences that the amounts of HC tail-pipe emissions differ in the two cases, due to the different temperature transients that in turn influence the catalyst light off time.

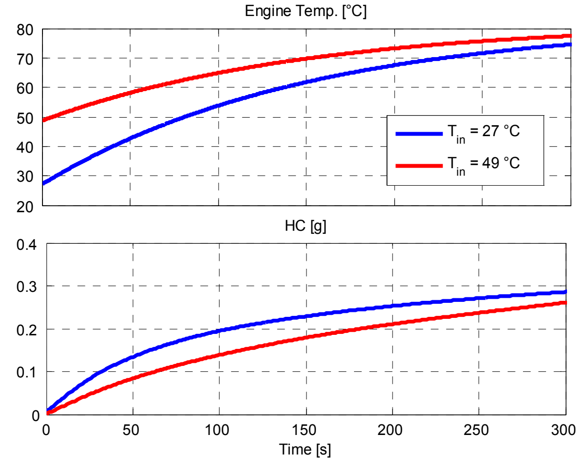

Fig. 4 – Simulated engine temperature and tail-pipe HC emissions in case of cold (27 °C) and warm (49 °C) engine start maneuver.

5 SIMULATION RESULTS

The simulations were performed by solving the constrained optimization problem, as defined in Eqs. (5-8), for the HSV configuration described in Table I. It is worth mentioning that such configuration corresponds to the one that maximizes fuel economy, as indicated by the authors themselves in a previous work [13]. The ICE intermittent operation was analyzed for a number of ICE-on phases N ranging from 1 to 8, thus allowing to extensively assess the effect of several engine start/stop maneuvers on both fuel consumption and emissions.

Fig. 5 shows the dependence of fuel consumption and HC emissions on N. It emerges from the figure how fuel consumption initially decreases towards a minimum value, in correspondence of N=3. This is explained by the tendency, with higher number of ICE-on phases, to operate the engine as close as possible to its most efficient operating point (i.e. 22 kW, which is approximately ½ of maximum power as reported in Table I). Then, due to the negative effect of thermal transient on ICE efficiency, taken into account by Eqs. (10) and (11), the advantage related to the higher number of ICE operation vanishes, thus causing fuel consumption to increase.

On the other hand, HC emissions show an undesirable increasing trend when more ICE-one events are considered. This happens because of the initial large amount of HC released when ICE is turned on, as a consequence of the rich air-fuel mixture delivered to the engine for fast warm-up. Nevertheless, after the first ICE-on event, the relatively slow decay in engine temperature (see Fig. 7) causes this effect to reduce at following engine starts (see Fig. 4). Particularly, Figure 7 shows that in case of N=3 the engine is turned on for the second and third time at temperature as low as 40 °C, whereas in case of N=4 ICE is always turned on at higher temperatures. Moreover, the last ICE-on for N=4 is enabled at temperature around 55 °C, which results in a small HC release in this phase. Therefore, fuel delivery efficiency for N=4 is, on average, higher than the N=3, thus explaining the local minimum of HC emissions occurring in correspondence of N=4.

The above considerations on fuel consumption and HC emissions lead to select N=4 engine starts as the most convenient strategy to be adopted for the selected driving route.

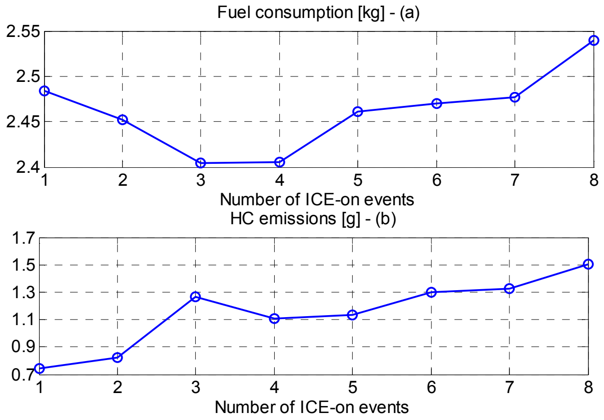

Fig. 5 – Effects of number of ICE-on phases (N) on fuel consumption (a) and HC emissions (b).

Fig. 6a and 6b show the model outputs computed in case of 4 ICE-on events. Particularly, Fig. 6a shows the power contributions from the electric generator (red line) to meet the traction power demand, whereas battery and solar panels (the latter being constant and quite negligible during driving phases) power trajectories were omitted for sake of clarity. It is interesting to note how for N=4 the constrained optimization analyses led to place the ICE-on events in correspondence of the highest power demands. This result can be explained by considering that it allows to reduce low-load, less efficient ICE operations.

Fig. 6b shows that the final state of charge differs from the initial one by the value corresponding to the energy storable through the solar panels during parking hours (here set to 9 hours whereas driving time is 1 hour per day).

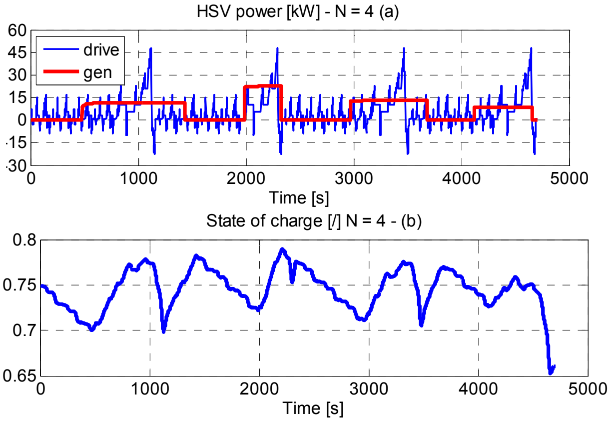

Fig. 6 – Simulated power (a) and state of charge (b) trajectories for the selected driving cycle.

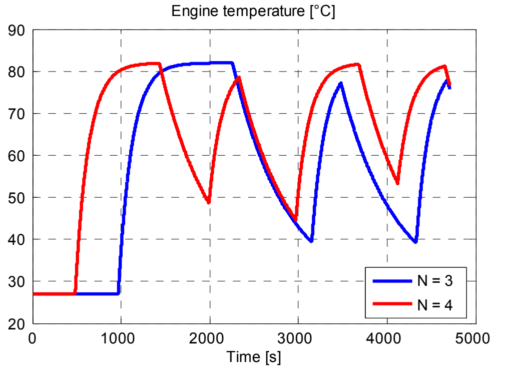

Fig. 7 – Simulated engine temperature trajectory for N=3 and N=4 ICE-on events.

6 CONCLUSIONS

A study on energy flow management in a hybrid solar vehicle with series structure has been presented. In spite of the many similarities, there are some significant differences between HSVs and HEVs: the presence of solar panels, contributing to recharge the battery also during parking phases and the adoption of a series structure, more suitable with plug-in hybrid concept, instead of the prevailing parallel or series/parallel structure in HEVs. These differences suggest that HSV control cannot be simply borrowed by the solutions adopted for HEV. In order to develop a supervisory control for a HSV prototype, a study on the performance achievable by using the ICE at maximum efficiency in intermittent mode is presented. The analysis also considers thermal transient effects on engine power and fuel consumption and HC emissions transient during the engine start maneuver. The optimal ICE power trajectory is found by solving a non-linear constrained optimization that accounts for fuel mileage and state of charge, also considering solar contribution during parking mode. The results show that the presence of engine thermal transients due to start-stop operation cause a non negligible reduction in fuel economy with respect to the results obtained in steady-state warmed-up case. Moreover, the distributions of ICE operation phases differ from steady-state case, indicating that such effects should be taken into account in HEV and HSV control where ICE start-stop operation can occur. Concerning HC emissions, simulation results evidence that the intermittent ICE operation usually results in higher HC though a local minimum can be detected considering the trade off between number of engine start events and catalyst light off. Future developments will include the development of a supervisor control for a HSV prototype and the study of thermal transient in catalyst and their effects on vehicle emissions.

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