

Genetic Algorithms Based Optimization of Intermittent ICE Scheduling on a Hybrid Solar Vehicle

I. Arsie, G. Rizzo, M. Sorrentino

Abstract - Hybrid Solar Vehicles (HSV), derived by integration of Hybrid Electric Vehicles with Photo-Voltaic sources, may represent a valuable solution to face both energy saving and environmental issues, particularly in urban driving. This paper focuses on their management strategies, evidencing some significant differences with respect to the case of Hybrid Electric Vehicles. In order to develop a supervisory control for an 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. The results obtained by the application of Genetic Algorithms (GA) to the optimal energy management of an HSV with series structure are discussed. The optimal powering strategy accounts for fuel mileage and state of charge, also considering solar contribution during parking mode and the effects of engine thermal transients on fuel consumption and HC emissions.

Key-words: Hybrid Vehicles, Optimal Management, Photovoltaic Panels, Genetic Algorithm

I - INTRODUCTION

In the last years, increasing attention is being spent towards the applications of solar energy to electric and also to hybrid cars. But, while cars only fed by sun 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. The reasons for studying and developing a Hybrid Solar Vehicle can be summarized as follows:

- fossil fuels are doomed to depletion, and their price is subject to large and unpredictable fluctuations;
- the CO₂ generated in conventional engines contributes to the greenhouse effects, with dangerous and maybe dramatic effects on global warming and climatic changes;
- the worldwide demand for personal mobility is rapidly growing;
- Photovoltaic Panels are subject to continuous technological advances in terms of cell efficiency; their diffusion is rapidly growing, while their cost, after a continuous decrease and an inversion of the trend occurred in 2004, is being reduced again [1][2];
- solar cars do not represent a practical alternative to

conventional cars, due to limitations on maximum power, range, dimensions and costs;

- Hybrid Electric Vehicles (HEV) 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 [3].

The outline of the paper is the following: in chapter II the Hybrid Solar Vehicles are presented, while in the chapter III some issues related to their control are discussed, with particular attention to thermal effects connected to start-stop operation. In Chapter IV an optimization approach of energy management based on genetic algorithm is illustrated, while in the following chapter the results obtained are shown and discussed.

II - HYBRID SOLAR VEHICLES

In principle, Hybrid Solar Vehicles (HSV) could sum up the advantages of HEV and solar power, by the integration of Photovoltaic Panels in a Hybrid Electric Vehicle [4][5]. But it would be simplistic to consider the development of a HSV as the simple addition of photovoltaic panels to an existing Hybrid Electric Vehicle. In fact, the development of HEVs, despite it was based on well-established technologies, showed how considerable research efforts were required for both optimizing the power-train design and defining the most suitable control and energy-management strategies. Analogously, to maximize the benefits coming from the integration of photovoltaic with HEV technology, it is required performing accurate re-design and optimization of the whole vehicle-powertrain system, due to the impact of solar panels on vehicle dimension, aerodynamics, performance, weight and costs [2][6].

Another difference between HEV and HSV may concern their structure. In fact, the prevailing architectures for HEV are parallel and parallel-series, while in case of HSV the series structure seems preferable [4]. Despite some disadvantages (higher efficiency losses due to more energy conversion stages), series structure is simpler and may offer some advantages:

- It is more suitable for plug-in and V2G applications [4][7]; moreover, the generator can be used as co-generator when the vehicle is parked at home.
- Due to absence of mechanical links between generator and wheels, very effective vibration insulation can be achieved, with less constraints for vehicle layout.

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- Advanced techniques for noise reduction could be more easily applied, since the engine can work at fixed conditions.
- Engines specifically optimized for steady operation can be used.
- It is compatible with the use of in-wheel motors with built-in traction control and anti-skid.
- It will potentially act as a bridge towards the introduction of hybrid fuel cell powertrains.

A possible layout of a HSV with series structure is presented in Fig. 1. 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.

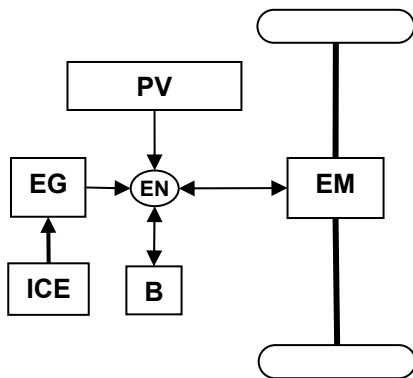


Fig. 1 - Scheme of a series hybrid solar vehicle

In spite of these encouraging perspectives, the use of solar energy on cars has been considered with a 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 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 [8]. 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 [2][6][9]. In the following section, we make an overview of HSV related literature.

Despite their potential interest, hybrid solar cars have received relatively little attention in literature [4], particularly if compared with the great effort spent in last years toward other solutions, as hydrogen cars, whose perspectives are affected by critical issues regard to hydrogen production, distribution and storage. Some prototypes have been developed in last decade in Japan [10][11], at Western Washington University [12], at the Queensland University [13] and, more recently, by the French company Venturi. A prototype of Solar Prius has

also been recently developed by Solar Electric Vehicles, equipped with a PV panel of 16% nominal efficiency [14]. It has been estimated that the PV Prius can have a range based on solar power alone between 5 and 8 miles per day, and that it can consume between 17% and 29% less gasoline than the standard Prius. Some educational projects in that area have also been developed [2], and a multi-lingual website [15] has been developed by the authors within a project financed by EU. A comprehensive model for the optimal design of a hybrid solar vehicle with series structure, considering performance, weight and costs, has been formulated by the authors and presented in previous papers [2][6][9]. It is shown that, if the car is used in intermittent way and at limited average power, a significant percent, about 20-40%, of the required energy can be provided by the sun. The results of an optimal design analysis, also considering weight and costs, have shown that economic feasibility could be achieved in a medium term scenario, with mild assumptions in terms of fuel price increase, PV efficiency improvement and PV cost reduction. A prototype of HSV with series structure has also been developed [2][16], within a project funded by EU [15].

An overview on the ongoing research on 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 is available by previous papers of the authors [2].

A method for fuel consumption minimization based on Model Predictive Control has been recently proposed [17]. The aspects related to the engine generator management in case of intermittent use have been focused in other papers, both for HEV vehicles [18] and for HSV vehicles [19][20], and will be further analyzed in the next paragraphs.

III - CONTROL ISSUES FOR HYBRID SOLAR VEHICLES

Although HSV have many similarities with HEV, for which numerous studies on energy management and control have been presented in last decade [3][21][22], there are also some significant differences between these kind of vehicles. In particular, 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 a HSV.

As it is known, in most HEV a charge sustaining strategy is adopted: at the end of a driving path, the battery state of charge should remain unchanged. With a HSV, 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 [19].

Moreover, the series configuration suggests to operate the engine in an intermittent way at constant operating conditions, i.e. corresponding to the minimum fuel

consumption. 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. In case of ICE 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 HEVs, where a steady-state approach is usually used to evaluate fuel consumption and emissions.

In order to provide a suitable benchmark for control strategies 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. In fact, 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 on energy management should be considered, also in order to develop suitable solutions for vehicle thermal management. A method based on the application of Genetic Algorithms (GA) is presented in the following.

IV - OPTIMIZATION OF ELECTRIC GENERATOR SCHEDULING BY MEANS OF GENETIC ALGORITHM

In case of intermittent ICE scheduling, the optimal EG power trajectory can be found by solving the following constrained optimization problem:

$$\min_X \int \dot{m}_{f,HSV}(X) dt \quad (1)$$

subject to the constraints

$$\Delta SOC_{day} = SOC_f - SOC_0 + \Delta SOC_p = 0 \quad (2)$$

$$SOC > SOC_{min} \quad (3)$$

$$SOC < SOC_{max} \quad (4)$$

where $\dot{m}_{f,HSV}$ is the HSV fuel consumption [kg/s], SOC_f and SOC_0 are the initial and final state of charge in the driving phase, respectively, and ΔSOC_p is the SOC increase due to PV recharging during vehicle parking. It is worth mentioning here that driving and parking hours are set to 1 and 9, respectively.

The decision variables X include number of EG-on events N_{EG} , along with corresponding starting time $t_{0,EG,i}$, duration $\Delta t_{EG,i}$ and EG power level $P_{EG,i}$, where i is the i -th EG-on event.

The first constraint (i.e. Eq. 2) allows to restore the initial state of charge within the end of the day, also considering parking phases.

The other constraints (i.e. Eqs. 3 and 4) were defined accounting for internal resistance dependence on battery

state of charge. For lead-acid batteries in the SOC range [0.55 0.9] both charging and discharging resistances are fairly constant while being close to their minimum values [16]. Therefore in this analysis SOC_{min} and SOC_{max} were set to 0.55 and 0.9, respectively.

The problem stated by Eqs. (1) through (4) involves both integer (e.g. N_{EG}) and real variables, thus falling in the field of Mixed Integer Programming (MIP) problems. Among the several techniques that can be adopted to solve such problems, genetic algorithms (GA) is one of the most efficient [23] and has thus been selected for optimizing EG scheduling on a hybrid solar vehicle. The GA search was performed in Matlab environment by means of the GAtbx tool developed by Chipperfield et al. [24][25]. GA optimization consists of an iterative procedure that can be schematized as follows:

Phase 1: an initial population of N_{ind} individuals (or solutions) representing the search domain (i.e. the decision variables domain) is generated randomly. If a binary representation is adopted to define the individual genotype, the number of bits n_{bit} requested for the j -th decision variable has to be computed as function of precision π and definition range, as follows:

$$n_{bit} = \log_2 \left(\frac{X_{j,max} - X_{j,min}}{\pi} + 1 \right) \quad (5)$$

An example of genotype representation for the S_k individual can be the following:

$$S_k = \left[\overbrace{011\dots1}^{X_1}, \overbrace{11\dots0}^{X_2}, \dots, \overbrace{10\dots1}^{X_M} \right] \quad (6)$$

where M is the number of decision variables.

Phase 2: The objective function F is evaluated for each individual. Then, assuming that a minimization task is being accomplished, all the individuals are ranked in ascending order on the basis of their F_k value. This way the so-called “fitness” is assigned to the k -th individual, whose value will range from a maximum to a minimum depending on its rank position.

Phase 3: Fitness-based selection of best individuals. According to the evolutionary theory, the best individuals have the highest probability to join the next population. The “Roulette Wheel” and “Stochastic Universal Sampling” [24] are among the most widely adopted techniques to perform a random selection of the strongest individuals as function of their fitness. Particularly, the higher its fitness is, the more likely that individual will be selected. In this work, the latter method was applied.

Phase 4: Generation of new individuals. Phase 3 usually yields a new set of individuals containing a higher number of “strong” (i.e. with high fitness) solutions, whereas some of the weakest ones disappear. This intermediate set undergoes a renewal process consisting of two different steps: crossover and mutation. The

former step basically makes a certain number of individual pairs, selected randomly, to exchange part of their genotype with each other. The resulting genotypes will of course behave differently in the next population, thus yielding a couple of new individuals. After crossover, mutation takes place, once again based on random selection of some individuals. Particularly, one of their genotype bits is switched from 0 (1) to 1 (0), thus resulting in a new individual. Upon completion of Phase 4, the off-springs from the current population are created, resulting in a new generation of N_{ind} solutions to be tested in Phase 2 according to the iterative procedure.

It is worth mentioning that an elitist approach is usually followed in Phase 4, in that some of the strongest individuals from the current population are ensured to be present in the next one. This way, even though a lower number of off-springs is introduced, the best solutions from the current population are preserved [24].

Phase 2 through Phase 4 are repeated as many times as the desired number of new generations is reached. The above description highlights the need for the decision maker to select several operating parameters (N_{ind} , crossover and mutation probabilities, number of generations) depending on problem complexity and computational time requirements. Further details about GA optimization techniques can be found in the abundant literature on the topic, which the reader is addressed to [23–26].

For the current application, the following operating parameters were assumed for the GA search procedure, as addressed by a suited trial-and-error analysis:

Table 1 – GA operating parameters.

Population size	70
Number of generations	100
Crossover probability	0.8
Mutation probability	0.003

A binary representation of the decision variables was selected, as reported in Table 2.

Table 2 – Binary representation of the optimization problem.

Decision variable	Definition range	Precision	Number of bits
N_{EG}	[1 8]	1	3
t_{EG} (min)	[0 78/ N_{EG}]	$0.073/ N_{EG}$	10
Δt_{EG} (min)	[0 78/ N_{EG}]	$0.073/ N_{EG}$	10
P_{EG} (kW)	[0 43]	0.040	10

V - OPTIMIZATION RESULTS

The GA optimization was applied to minimize the fuel consumption for a driving cycle composed of 4 ECE-EUDC cycles, as the one shown on Fig. 2.

HSV fuel consumption was simulated by means of the backward longitudinal vehicle model presented in [16]. In

the analysis the effect of thermal transients on ICE performance and HC emissions were also taken into account following the approach proposed in [19][20]. Table 3 lists the specifications of the reference HSV.

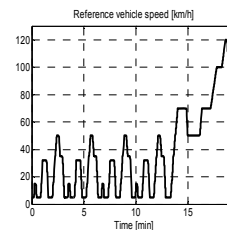


Fig. 2 – ECE-EUDC driving module

Table 3 – HSV specifications.

ICE power [kW]	46
Fuel	Gasoline
PEG [kW]	43
PEM [kW]	90
Number of battery modules [/]	27
PV horizontal surface $A_{PV,H}$ [m ²]	1.44
Coefficient of drag (C_d)	0.4
Rolling coefficient (C_r)	0.02
Frontal area [m ²]	2.6
Weight [kg]	1465

Table 4 summarizes the results of the current optimization task and also compares new outputs with previous ones obtained by derivative-based minimization (DBM) algorithm [20]. Such comparison indicates that the GA search method (i.e. column “GA” in Table 4) suggests a lower number of ICE-on events, which in turn results in a slightly higher fuel consumption and significantly lower HC emissions, as compared with classical method (i.e. column “DBM” in Table 4). The reduction in HC emissions not only depends on the lower number of EG-on events, but also on the higher GA average engine temperature (see Table 4 and Fig. 3), which of course determines a higher conversion effectiveness of the catalyst.

Table 4 – Optimization analysis.

Optimization outputs	DBM	GA 1
N_{EG}	4	3
Fuel consumption [kg]	2.41	2.48
HC emissions 1 (g)	1.13	0.85
Average engine temperature [°C]	65	68
Max SOC [/]	0.79	0.88
Min SOC [/]	0.65	0.58
HC emissions 2 (g/km)	0.025	0.018

It is worth remarking that both HC emission levels reported in Table 4 are well below the EURO 5 gasoline

emission standard (i.e. 0.1 g/km, [27]), thus confirming the benefits related to ICE intermittent use. Fig. 4 shows the required power at wheels, optimal EG and battery trajectories and SOC variation. Particularly, the last graph in figure 4 indicates that the GA search method was able to bound SOC variation within the desired limits (i.e. 0.55 and 0.9).

Finally, a further optimization analysis was run considering an increase in PV horizontal area from 1.44 to 3 m². Such configuration upgrade results in a fuel consumption reduction down to 2.28 kg. Considering that a conventional vehicle, with same power to weight ratio as the HSV described by Table 3, requires up to 2.82 kg of gasoline, the high potential offered by appropriately managed HSVs is demonstrated.

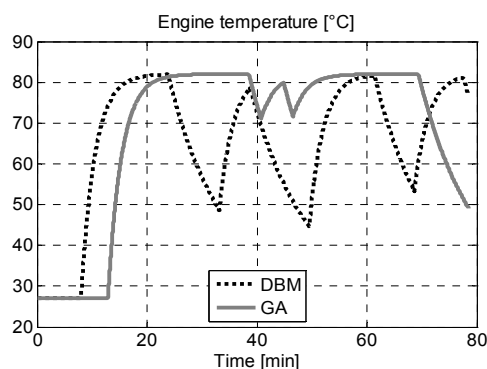


Fig. 3 – Comparison between temperature trajectories simulated in DBM and GA optimization task

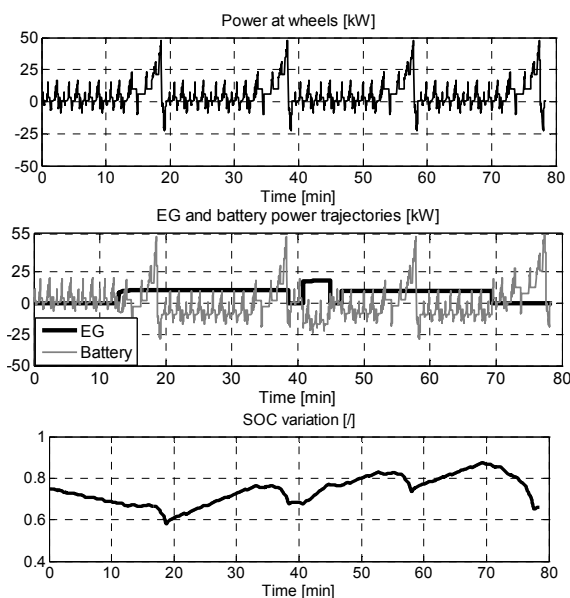


Fig. 4 – Time trajectories yielded by the GA optimization

VI - CONCLUSIONS

The electric generator management plays a key role toward the achievement of the benefits in a Hybrid Solar Vehicle. Previous studies had shown that significant

savings in fuel consumption and emissions can be obtained with an intermittent use of the vehicle, and that thermal transient effects on fuel consumption and emissions, due to start-stop occurrence, cannot be neglected. In the paper, the optimization of the EG scheduling has been presented, based on the GA search method. The results suggest a lower number of EG-on events, which in turn results in a slightly higher fuel consumption and significantly lower HC emissions (from 0.025 to 0.018 g/km), as compared with classical minimization method. The reduction in HC emissions not only depends on number of EG-on events, but also on the higher GA average engine temperature, which of course determines a higher conversion effectiveness of the catalyst. It is worth remarking that both HC emission levels are well below the EURO 5 gasoline emission standard, thus confirming the benefits related to ICE intermittent use. The results were obtained with commercial PV panels and with realistic data and assumptions on the achievable net solar energy for propulsion. Scenario analyses performed by increasing PV horizontal area from 1.44 to 3 m² evidence a further reduction of fuel consumption from 2.48 down to 2.28 kg for the assumed driving cycle.

The future adoption of last generation photovoltaic panels, with nominal efficiencies approaching 35%, may result in an almost complete solar autonomy of this kind of vehicle for such uses. By adopting up to date technology for electric motor and generator, batteries and chassis, power to weight ratio comparable with the ones of commercial cars can be achieved, thus assuring acceptable vehicle performance.

On going activity is in course to extend the study of management strategies to other cases and to develop suitable control strategies to be implemented and validated on the prototype of Hybrid Solar Vehicle, under development at the University of Salerno.

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NOMENCLATURE

DEFINITIONS, ACRONYMS, ABBREVIATIONS

B	Battery
BIPV	Building Integrated Photo Voltaic
EG	Electric Generator
EM	Electric Motor
EN	Electrical Node
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
HSV	Hybrid Solar Vehicle
ICE	Internal Combustion Engine
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photo-Voltaic
V2G	Vehicle to Grid