Hybrid Vehicles and Solar Energy: a Possible Marriage?

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ABSTRACT

In last years, as a consequence of the diffusion of Hybrid Electric Vehicles and to the growing recourse to renewable sources, increasing attention is being given to the integration of these vehicles with photovoltaic panels. Hybrid Solar Vehicles might represent a valuable solution to face both energy saving and environmental issues, particularly in case of intermittent use in urban conditions, but relatively little research effort has been spent in this direction. This paper focuses the main problems related to the development of these vehicles, with specific attention on photovoltaic panels and power electronics. Some results obtained by a model for the optimal design of a hybrid solar vehicle with series structure, including effects of vehicle dimensions, weight and costs, are presented and discussed.

Key-words: Hybrid Vehicles, Solar Energy, Photovoltaic Panels

INTRODUCTION

In line with the increasing recourse to renewable sources, the last decades have seen a growing interest in the use of Photo-Voltaic technology (PV) for automotive applications. The former applications of PV technologies to Electric Vehicles (EV) were developed mainly for demonstrative and didactic aims and for prototype competitions (Wellington, 1996; Ozawa et al., 1998; Pudney and Howlett, 2002; Gomez de Silva and Svenson, 1993). Despite of a significant technological effort and some spectacular outcomes, the limitations due to low density and unpredictable availability of solar source, the weight associated to energy storage systems, the need of maximizing panel area while minimizing weight, friction and aerodynamic losses make these vehicles quite different from the current idea of car.

FIG. 1 – A Prototype of Solar Car

More recently, as a consequence of the positive impact of Hybrid Electric Vehicles (HEV) on fuel consumption and emissions and, moreover, of the surprising and somewhat unexpected success obtained by some HEVs in the automotive market, increasing attention is being given to the integration of photovoltaic panels within conventional HEV architectures (i.e. Hybrid Solar Vehicles, HSV).

In next chapters, after a short review on photovoltaic sources, their application to Hybrid and Electric vehicles are presented. Then, the potentialities and the problems related to Hybrid Solar Vehicles are discussed, and the results obtained by a model for the optimal design of a HSV are reviewed and commented. Finally, some aspects related to PV operation and power electronics in solar hybrid vehicles are discussed.

PHOTOVOLTAIC SOURCES: STATE OF THE ART

Solar cells are produced by means of the discards of the production of semiconductors of the microelectronic industry. Most solar cells use crystalline silicon because it ensures stable solar cells with good real efficiencies, ranging from 11% to 16% but far from the theoretical maximum. On the other hand, crystalline silicon is a relatively poor absorber of light and requires a considerable thickness (several hundred μm) of material. Wafers smaller than 150mm of diameter and 350 μm of thickness are sliced from a high-purity single crystal boule if a monocrystalline silicon is produced, while multicrystalline silicon is made by sawing a cast block of silicon first into bars and then wafers (www.solarbuzz.com).

The most efficient production cells use monocrystalline silicon with laser grooved, buried grid contacts for maximum light absorption and current collection. Each cell generates about 0.5V, so 36 cells are usually soldered together in series to produce a module with an output that is suitable to charge a 12V battery. The cells are hermetically sealed under toughened, high transmission glass to produce highly reliable, weather resistant modules that may be warranted for up to 25 years.

Monocrystalline and multicrystalline silicon cells based panels cover the 93% of the market. Their lower cost is about 3.20 €/Wp for both Mono-Crystalline and Multi-Crystalline Modules. Wp is the dc output power of a solar module as measured under an Industry Standardized Light Test just before its putting on the market. Standard conditions refer to 1000 W/m2 illumination intensity, 25°C ambient temperature and a spectrum that relates to sunlight that has passed through the atmosphere, that is Air Mass 1.5.

The cost of crystalline silicon wafers make up 40-50% of the cost of a finished module, so that industry is looking at cheaper materials to make solar cells. Amorphous silicon or the polycrystalline materials, such as cadmium telluride and copper indium (gallium) diselenide, are the most common materials, because they are all strong light absorbers and only need to be about 1μm thick, so materials costs are significantly reduced. Although they exhibit a low efficiency, ranging from 5% to 8%, thin films are potentially cheaper than crystalline silicon because of their lower materials costs and larger substrate size. Moreover, weather resistant and environmentally robust module can be created by lamination of thin film cells.

Amorphous silicon is the most well developed of the thin film technologies. Unfortunately, such cells suffer from significant degradation in their power output (in the range 15-35%) when exposed to the sun. In addition, some thin film materials have shown degradation of performance over time and stabilized efficiencies can be 15-35% lower than initial values. Many thin film technologies have demonstrated best cell efficiencies at research scale above 13%, and best prototype module efficiencies above 10%.

The lowest price of a thin film module is quite similar to that one of a multi-crystalline one, namely 3.12 €/Wp.

As for prices, the market has experienced a long period of falling down of the prices since January 2002 up to May 2004. Afterwards, prices began rising again and now are about the level of November 2002. Such a prices rise is due to the global demand for solar modules that continues to outstrip supply, so that the manufacturers of the silicon needed for photovoltaic production cannot provide enough raw materials to fill the needs of manufacturing plants capable of increased production. It has been foreseen that these shortages may not be relieved until 2008 (http://www.backwoodssolar.com).

In order to take the maximum power from the solar panels, thus making up for the low efficiencies and the rising costs of cells, it is important to know and foresee the main factors that might reduce the cells performances. In (Gregg, 2005) it has been put in evidence that tilt and azimuth angles, which define the orientation of the photovoltaic generator, are critical factors for crystalline cells. In fact, they are much more sensitive to the angle of the incident light, as well as soiling, temperature and shading. Even small differences among the angles of incidence of the solar radiation concerning different cells/panels that compose the panel/string may cause a mismatching effect that greatly affects the resulting photovoltaic generator overall efficiency. Such reduction may become more significant at high cell temperatures, with a de-rating of about 0.5%/°C for crystalline cells and about 0.2%/°C for amorphous silicon cells (Gregg, 2005). The wider area and a softer knee in the voltage-current characteristic of amorphous silicon cells with respect to those ones of crystalline cells make the latter less affected from partial shading and mismatching. Nevertheless, such detrimental effects need to be known and characterized in order to foresee the shape of the power-voltage characteristic the photovoltaic generator will exhibit during operation. This will lead to an optimized design of the generator and of the power circuitry that ensures its optimal employment.

PHOTOVOLTAIC IN AUTOMOTIVE APPLICATIONS

Such remarks are of great importance for any photovoltaic panels installation, but they become fundamental in automotive applications, since the available area is quite small and the need for maximum power extraction is taken to its extreme. For example, the need of connecting cells of different types (technology as well as electrical and manufacturing characteristics) within the same array usually leads to mismatching conditions. This may be the case of using standard photovoltaic cells and transparent ones, in place of glasses, connected in series.

Regardless from such limitation, the use of solar panels for automotive applications is increasing, beyond the car racing prototypes. For example, actually the use of solar energy for extending the life of standard batteries has both producers of solar modules and buyers of the car industry. ICP Solar (www.icpsolar.com) produces a charger specifically designed to prevent dead batteries from vehicle factory to dealer lot. Volkswagen is becoming the first customer worldwide to embrace such a solution that guarantees the saving of substantial costs per car manufactured. A large number of producers (see for example www.siliconsolar.com) is now proposing small solar panels that allow to start a car after a long period of non-use and/or allowing to prolong car battery life and to keep the level of the car battery constant.

Whenever the area of the panel is negligible, its management is quite usual. On the contrary, peculiar problems arise if the photovoltaic generator has a significant extent, because the problem of partial shading and maximum power extraction must be analyzed and afforded by means of efficient and reliable techniques, in order to ensure a valuable amount of energy. Results obtained by means of prototypes seem to be encouraging.

THE ADVANTAGES. The adoption of HEV or EV assisted by PV cells, besides the reduction of the environmental pollution and the use of the free and abundant solar energy, offers a number of additional advantages. In fact a modern HEV is equipped with a number of devices fed by batteries: clocks, security systems, cigarette lighters, automatic diagnostic systems, lights, power windows, radio, windshield wipers, vent fans, ignition systems, entertainment systems, etc. Some of these devices (e.g clocks, security systems, diagnostic systems etc.) drain the battery even when the engine is off and no passengers are inside the car. In addition it should be considered that, due to its self-discharge, a fully charged battery can fully discharge, even in absence of loads, after a period of inactivity of 2-3 months. On the basis of the above considerations it is easy to realize that, after a period of inactivity of many days, the battery of a HEV or of course that one of an EV can be no more able to allow the starting of the engine. A PV source installed on a HEV or on an EV, depending on its total surface and on the irradiance level, is not only able to directly feed some of the devices listed above, but can provide the excess energy to the battery preserving its charge level and extending its life. Moreover, it is possible to use PV cells to power ventilators in order to vent internal air of the car, parked under the sun, to the outside to the aim of adding comfort for the driver, reducing the air conditioning load, shortening the cooling times at the starting and protecting the car's internal materials. A 35 W ventilator system, powered by PV cells, is able to allow a 30% reduction of the size of the conditioner. Furthermore, adding PV cells to a HEV allows to reduce the generator and internal combustion engine sizes leading to a reduction of the operation costs. Finally, a full integration of a GPS planar antenna and a solar cell module in only one device, suitable for vehicular applications and allowing to avoid the shading effects of conventional antennas on PV modules, has been patented.

SOLAR HYBRID VEHICLES

The attention to solar hybrid vehicles dates to the 90’s, when some pioneering prototypical applications appeared. An innovative vehicle (Viking 23) has been developed at Western Washington University (Seal, 1995; Seal and Campbell, 1995), adopting advanced solutions for materials, aerodynamic drag reduction and PV power maximization with peak power tracking. Another study on a solar hybrid vehicle has been presented by Japanese researchers (Saitoh et al., 1992), with PV panels located on the roof and on the windows of the car: fuel consumption savings up to 90% could be achieved in some conditions. A further prototype of solar hybrid car powered with a gasoline engine and an electric engine has been proposed and tested by Sasaki et al. (1997). In this case, a relevant amount of the solar energy was provided by PV panels located at the parking place, while only a small fraction was supplied by PV panels on the car. The hybridization lead to a significant weight increase (350 kg), due to the adoption of lead batteries. A very advanced prototype (Ultra Commuter) has been recently developed at the Queensland University, adopting a hybrid series structure (Simpson et al., 2002). The Canadian engineer Steve Lapp applied 270 W PV panels over a Toyota Prius, achieving a 10% savings in fuel consumption with respect to the original hybrid vehicle (www.lapprenewables.com).

The interest toward this solution has been growing in recent years due to the increasing attention to fuel shortage and environmental issues, to the industrial and commercial success of hybrid vehicles and to the diffusion of PV sources. According to some recent studies (Neil C., 2006), PV panels added to hybrid cars could be even more cost effective than PV panels added to buildings. The incremental cost of solar PV panels on hybrid cars and displacing gasoline could have a payback period much shorter than the payback for solar PV panels on buildings and displacing electricity. These results, however, seem not supported by a detailed technical analysis and are affected by somewhat optimistic assumptions. A wide overview over the Vehicle Integrated Photo Voltaic (VIPV) is reported by Letendre et al. (2003). The opportunities offered by the integration of electric vehicles with grid and stationary systems are remarked (Vehicles connected To Grid, V2G; Plug-in Hybrid Electric Vehicle, PHEV). A radio controlled system already available in California could allow to charge and draw power from parked EV. Moreover, the author remarks that the battery pack of parked EV or HEV can enhance the capabilities of stationary photovoltaic installations.

SOLAR ENERGY: A RICH DOWRY? In principle, hybrid solar vehicles may potentially combine the benefits of HEV and solar cars by the integration of photovoltaic panels with a basic hybrid vehicle. But in every marriage one can legitimately evaluate how rich is the dowry brought by the bride. The average power that can be captured by panels mounted on the vehicle roof is lower than 1kW, therefore almost negligible as compared to the maximum power of most of the actual cars. Nevertheless, considering that many drivers (i.e. about 40 % according to some statistics for road transport reported by UK government, see references) use their cars for less than 1 hour, mostly in urban areas and with just one occupant (i.e. the driver), such power contribution becomes more significant.

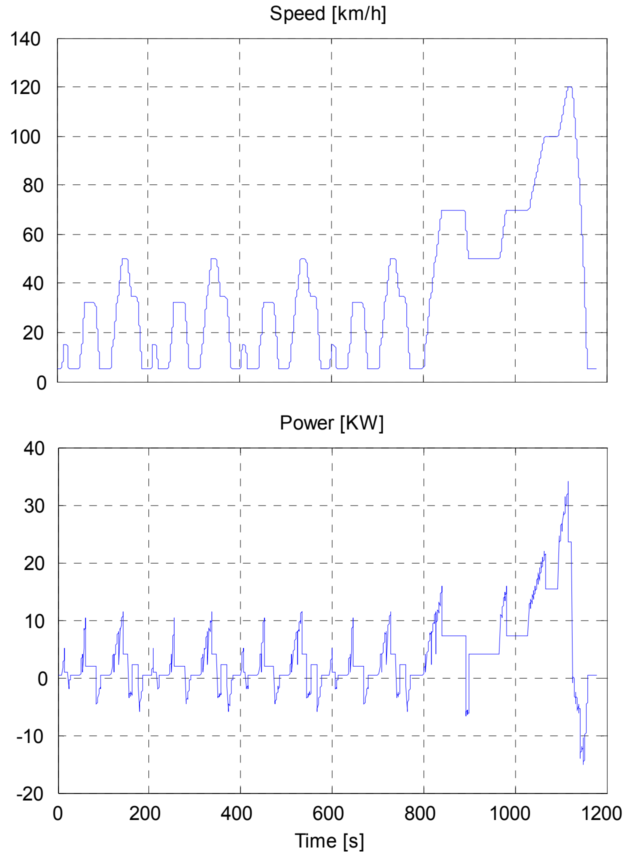

FIG. 2 – Power demand on ECE cycle

An example is shown in previous figures. Power demand of a small car (mass = 1000 kg, length = 3.5 m) is determined integrating the longitudinal vehicle model over a typical mission profile including a urban drive (up to 50 Km/h, time=0-800 s) and an extra-urban drive (up to 120 Km/h, time=800-1200 s). Although the maximum required power is about 40 KW (at maximum speed), the power values during other phases, particularly in urban drive, are quite limited, and the average power is substantially lower than the maximum value (**FIG. 2**).

Therefore, a proper design of the vehicle-powertrain system may allow meeting a significant share of the total energy required with the energy captured by the panels, during both driving and parking phases (Arsie et al., 2005). The following figure shows the average solar contribution as function of number of driving hours and average traction power, for a series hybrid vehicle vehicle with 6 mq of PV panels in horizontal position (Location: San Antonio, TX):

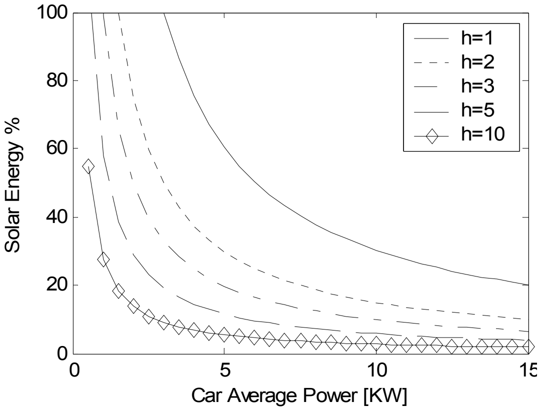

FIG. 3 - Solar energy contribution vs. power at different daily driving hours

It may be observed that, in case of "continuous" use (h=10), the solar energy can completely satisfy the required energy only at very low power (about 1 KW), of course not compatible with "normal" use of a car. On the other hand, 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. For instance, a car operating for 2 hours a day at 5 KW or for 1 hour at 10 KW can save about 30% of fuel, with respect to the hybrid vehicle without PV panels: the improvement with respect to the conventional vehicle is of course much greater, since HEVs allow fuel saving up to 40% with respect to conventional car with gasoline engine (Arsie et al, 2004).

Since the production feasibility of solar hybrid vehicles relies on the development and mutual integration of nearly mature technologies, their introduction might significantly contribute to the achievement, in the near future, of the targets established by the Kyoto protocol in terms of fuel savings and emissions. Therefore, in the short/medium term solar hybrid vehicles represent a more suitable alternative than to fuel cell vehicles, which strongly suffer from the critical issues related to the production and distribution of hydrogen.

The development of hybrid electric vehicles, despite it was based on well-established technologies, showed how considerable research efforts were required for both optimizing the powertrain 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.

Moreover, the selection of the optimal powertrain lay-out cannot be simply borrowed from hybrid electric vehicles. As is known, three different structures are possible for HEVs, parallel, series, and parallel/series. With parallel design, both engine and motor concur in powering the wheels. This structure requires a significant mechanical complexity and sophisticated control strategies to optimize the recourse to the two parallel drive systems. The models produced by Honda (Civic and Insight) belong to this category. With series design, only the motor is used to drive the wheels, while an electric generator powered by an internal combustion engine is used to charge the motor or to recharge batteries. In this case, the system is simpler but may attain lower efficiency due to cascade energy losses between the components. A more complex approach, that can be defined as parallel-series structure, is adopted in Toyota Prius HEV.

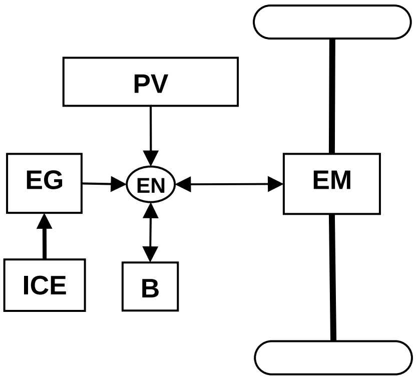

FIG. 4 - Scheme of a series hybrid solar vehicle

For solar hybrid vehicles, the adoption of series configuration (FIG. 4) is prevailing, due both to its simpler structure and to the possibility of integration with grid (Letendre et al., 2003). Moreover, the adoption of electric motors integrated into the wheels (Simpson et al., 2002) would allow to reduce mechanical losses and to apply advanced traction control strategies.

A MODEL FOR OPTIMAL DESIGN OF HSV

According to the above considerations, Hybrid Solar Vehicles may represent a valuable solution to face both energy saving and environmental issues, but relatively little research effort has been spent in this direction. Although several prototypes and some theoretical work demonstrate the general feasibility of this idea, a detailed presentation of results and performance is not generally available on the open literature, and a systematic effort to the design and control of a solar hybrid vehicle seems still missing. Such work seems particularly necessary since the technological scenario is rapidly changing, and new components and solutions are becoming available or will be available in the next future. Moreover, cost and prices are also subject to rapid variations, thus requiring the development of a general model considering both technical and economic aspects related to the design and operation of a HSV. A specific difficulty in developing a HSV model is due to the many mutual interactions between energy flows, propulsion system component sizing, vehicle dimension, performance, weight and costs, whose connections are much more critical than in conventional and also in hybrid cars.

Preliminary studies on energy flows in an HSV have been recently developed by Arsie et al. (2005 I, II, 2006). The model describes energy flows between horizontal and/or vertical solar panels, internal combustion engine, electric generator, electric motor and batteries, considering vehicle longitudinal dynamics and the effect of control strategies. Vehicle weight is predicted, starting from a database of commercial vehicles, considering the effects of power-train sizing, vehicle dimensions and possible use of aluminum. The effects of vehicle dimensions on aerodynamic losses and maximum panel area also can be accounted for. The model predicts the additional costs with respect to conventional vehicles, and the pay-back. The comparison of HSV and conventional vehicle over a driving cycle is obtained by integrating a dynamic vehicle simulator, previously developed by the authors (Arsie et al., 2000), with sub-models of the electric components (i.e. Battery, electric motor and generator) derived from ADVISOR (Burch et al., 1999).

Regarding powertrain optimal control, some significant differences occur between HSVs and HEVs. In the former case, battery charge sustaining can be guaranteed within a daily time window, whereas HEVs are usually required to restore the initial state of charge within the single driving path. Such feature allows mostly operating the internal combustion engine at maximum efficiency, corresponding in our case to an optimal power $P_{opt} \approx 0.5\ P_{max}$. If the energy required to restore battery charge corresponds to an average power lower than P_{opt} (case B), an intermittent operation can be adopted throughout the driving time h_d (cases A1-A2). In case that more energy is required, the internal combustion engine is operated at constant power between P_{opt} and P_{max} (case C). The different operating modes can be described by the variable ϕ, ranging from 0 to $\phi_{max} = P_{max} / P_{opt}$, as described in the table below.

A1	$\phi < 1$	$P_{ICE} = 0$	$0 < t < \phi h_d$
A2	$\phi < 1$	$P_{ICE} = P_{opt}$	$\phi h_d < t < h_d$
B	$\phi = 1$	$P_{ICE} = P_{opt}$	$0 < t < h_d$
C	$1 < \phi < \phi_{max}$	$P_{ICE} = \phi P_{opt}$	$0 < t < h_d$

Tab. 1 - Engine control strategies for HSV.

Fig. 5 and **Fig. 6** show the model outputs for a selected HSV configuration, simulated over an ECE-EUDC driving cycle and controlled according to the strategies defined in **Tab. 1**.

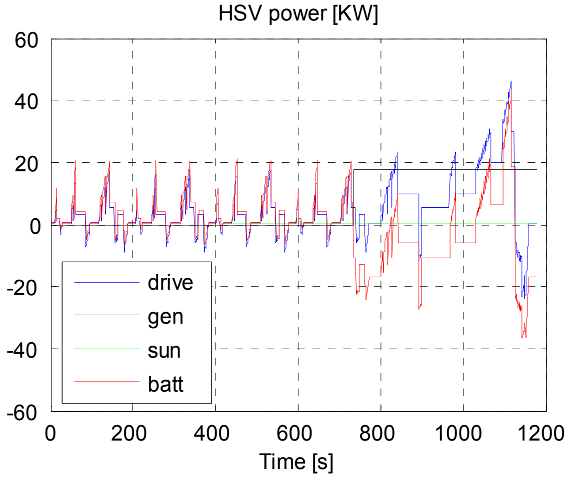

Fig. 5 – Power contributions for the ECE-EUDC cycle ($A_{PV,H}$ = 3 m^2, P_{EG} = 35.5 kW, l = 4.2 m, w = 1.75 m, h =1.5 m).

Since, for the selected case, the optimal ϕ is lower than 1, the thermal engine can be operated at constant load and speed corresponding to its highest efficiency in an intermittent way, as shown in **Fig. 5** (black line). According to the imposed control strategy, the engine operates during the latter part of the driving cycle, when the power requested to drive the vehicle reaches its highest values (blue line); this way the engine power is supplied to the driveline without being stored into the batteries, thus minimizing charge/discharge losses in the peak power time window (1050 – 1150 s). On the other hand, in the former part of the transient, the drive power is exclusively supplied by the batteries (red line). This trend is inverted around 700 s, when the engine is switched on and, due the low-power demand, is mainly devoted to recharge batteries until 800 s. Afterwards, the engine concurs with batteries to power the vehicle. **Fig. 6** shows a comparison of engine speeds in case of hybrid and conventional vehicle, evidencing that in the latter case (solid line), the ICE works in most cases at partial loads, with higher values of specific fuel consumption.

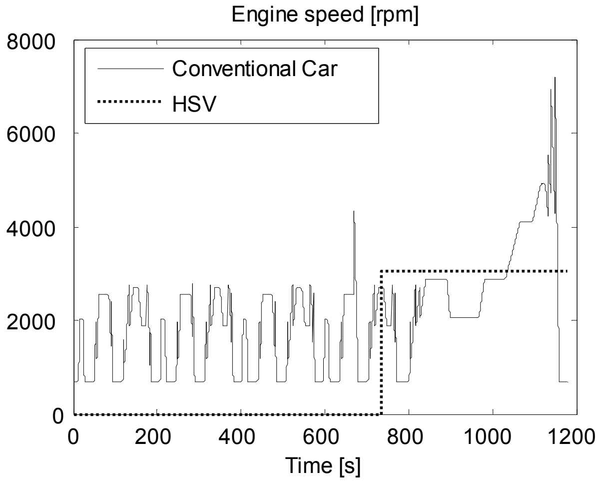

Fig. 6 – Comparison between CC and HSV rpm over the ECE-EUDC cycle**.**

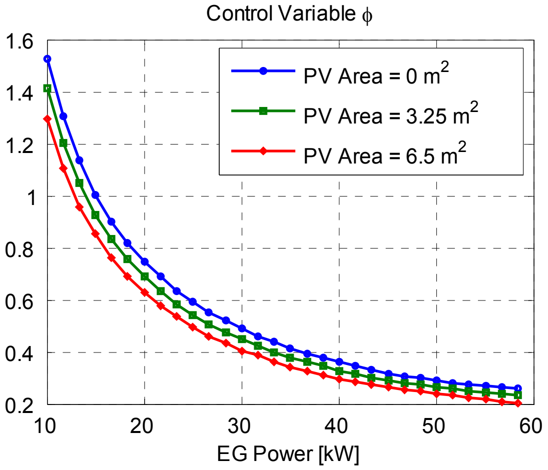

Fig. 7 – Control variable ϕ vs. electric generator power for different panels area.

The effects of the Electric Generator power and PV area over control variable and fuel savings are described in **Fig. 7** and **Fig. 8**. The comparison with the Conventional Car is performed imposing the same Power to Weight ratio. At lower EG power, control variable is greater than unit, resulting in non optimal engine operation and lower fuel savings. Fuel saving up to 15% can be obtained by the hybrid vehicle without panels, and a further 15% can be saved by adding 6.5 mq of solar panels (**Fig. 8**). These results, of course, depend on driving cycle and solar radiation.

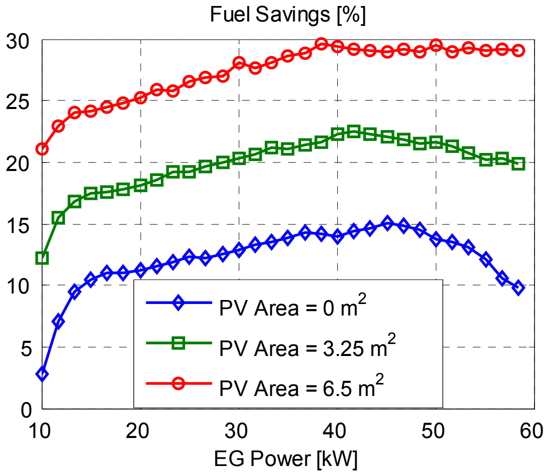

Fig. 8 – Fuel savings vs. electric generator power for different panels area.

The cost (Tab. 2) and mass (Tab. 3) breakdowns for both the HSV configuration previously simulated (see **Fig. 5**) and reference conventional car (CC) are also shown. It can be observed that HSV exhibits a significant increase in costs, mainly due to solar panels and batteries. The increment of weight due to the additional components can be partly reduced by adopting a smaller engine and a lighter chassis, with aluminium instead of steel (the additional costs have been also considered by the model).

Component	**CC**	**HSV**
ICE	1800	852
EM		1571
EG		426
PV		2600
Batteries		1008
Total cost (Chassis not included)	1800	6457

Tab. 2 - Cost (Eur) breakdown for reference conventional car and selected HSV configuration.

Component	**CC**	**HSV**
Chassis	1100	936
ICE	150	71
EM		93
EG		29
PV		36
Batteries		385
Total mass	1250	1550

Tab. 3 - Mass (kg) breakdown for reference conventional car and HSV.

The results presented in **Tab. 4**, finally, show that, while, at the actual values of fuel and panel costs and PV efficiency, the pay-back is still too high (10.63 years, #2), acceptable values (2.25 years, #4) can be reached with large but not unrealistic variations in fuel (3.54 €/kg) and panel (200 €/m^2) costs, and with reasonable (0.16) values of panel efficiency (Arsie et al., 2006). The adoption of suitable incentives could reduce the cost of PV systems and stimulate the diffusion of such vehicles, and this could lead to further cost reduction due to increased production and to scale economy.

#	c_f [€/kg]	c_{PV} [€/m^2]	η_P [/]	$A_{PV,H}$ [m^2]	P_{EG} [kW]	PB [yrs]	SF [%]
1	1.77	800	0.13	0	9.14	6.74	0
2	1.77	800	0.13	2	9.14	10.63	13.12
3	1.77	200	0.13	3.63	10	6.14	20.27
4	3.54	200	0.16	5.85	7.64	2.25	31.09

Tab. 4 - Optimization results for different fuel cost and PV technology scenarios (see nomenclature).

MPPT IN AUTOMOTIVE APPLICATIONS

In automotive applications, PV generators often work with fast time-varying solar irradiation levels due to the movement. Moreover, especially if the solar cells are not placed only on the roof of the car, different subsections of the PV generator may receive different sun irradiance levels, not only during gear, but also whenever the vehicle is parked and trees, lattices or structures in the neighbourhood shade a part of the PV generator. Such working conditions make hard the extraction of the maximum power from the PV generator at each time instant. In fact, even under uniform working conditions, typical of many stationary roof mounted PV generator, it is mandatory to match the PV source with the load/battery/grid in order to draw the maximum power at the current solar irradiance level. To this regard, a switching dc-dc converter controlled by means of a Maximum Power Point Tracking (MPPT) strategy is suitable (Hohm, 2000) to ensure the source-load matching by properly changing the operating voltage at the PV array terminals in function of the actual weather conditions and distribution of the sun irradiance over the PV generator. Any efficient MPPT technique must be able to detect the time-varying voltage value corresponding to the maximum power that can be delivered by the PV source. In literature, many MPPT strategies have been proposed, the greatest part of them being derived by the basic Perturb and Observe (P&O) and Incremental Conductance (IC) approaches. Both P&O and IC strategies, if properly designed, correctly work in presence of a uniform irradiance of the PV array, since they are able, although by means of different processes, to detect the unique peak of the power vs. voltage characteristic of the PV array (FIG. 9). For example, in (Egiziano, ATEF 2006) and (Femia, 2005) a technique aimed at optimizing the operating parameters of P&O strategy is introduced. It ensures a reliable MPPT even in presence of a quickly varying irradiation level. Steady-state performances of

P&O strategy have been also improved (Egiziano, ATEF 2006) by means of an approach based on the run time interpolation of the operating points on the voltage-power PV characteristic.

In (Egiziano, ISCAS 2006) such improvements of the P&O strategy have been also applied to a single stage inverter for grid-connected PV applications.

MISMATCHING - Unfortunately, in automotive applications, besides the problems related to the MPPT under time-varying, but uniform, irradiation conditions, it must be accounted for that the PV field does not receive a uniform irradiation and/or not all its parts (panels as well as single cells) work at the same temperature, so that mismatches among different subsections of the array may arise. Such a situation has been evidenced in literature and the detrimental effect due to a panel of a PV array working under an irradiation level or at a temperature, which is significantly different from that characterising the other panels.

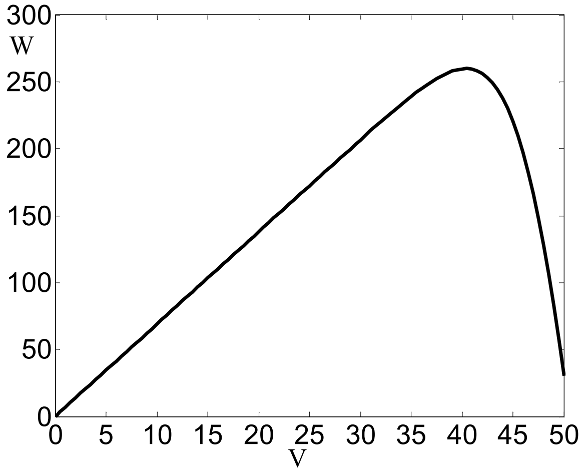

FIG. 9 - Power vs. voltage characteristic of a PV field under uniform working conditions.

Mismatching conditions are more likely to occur in automotive applications than in stationary ones. For example, parts of the array may be shaded by other parts of the vehicle when the sun is at low angle and, moreover, unpredictable shading takes place when the vehicle passes under the shadows of buildings, trees, advertising panels. Even in automotive applications characterized by a relatively small duty cycle in the use of the vehicle, mismatching may play a strong role on battery charging during the long parking time. In such cases the shadows produced by objects surroundings the car can give rise to a marked waste of available solar energy.

To relieve the power drop caused by a mismatch, a bypass diode is used in anti-parallel with each PV basic unit, e.g. a panel. A blocking diode is placed in series with each totem of PV basic units connected in series. This precaution increases the plant cost, but avoids that a basic PV unit or a series of them absorbs the current produced by others.

Whenever a mismatch occurs, both P&O and IC based MPPT techniques have a high probability to fail the MPPT goal. Indeed, the power vs. voltage characteristic of a PV field under a uniform solar irradiation exhibits a unique maximum point that is easily tracked by standard MPPT techniques. Unfortunately, mismatches deeply affect the shape of the PV characteristic, which may exhibit more than one peak, with one absolute maximum point and one or more relative points of maximum power. In this case, standard MPPT techniques are likely deceived and consequently track a point where dP/dv=0, but that is not the maximum power point (see FIG. 10).

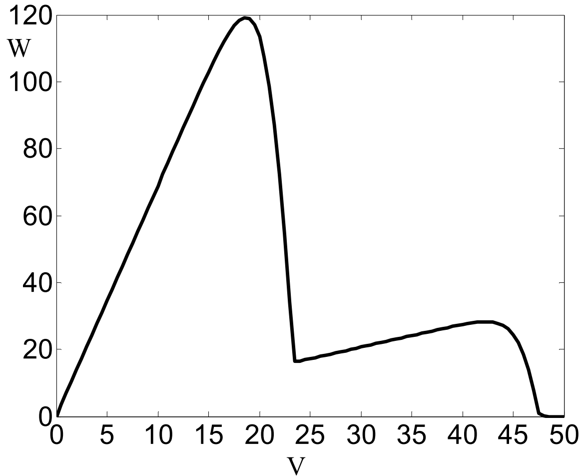

FIG. 10 - Power vs. voltage characteristic of a mismatched PV field.

In order to design a MPPT strategy able to perform a “global” tracking of the true PV array voltage associated to the maximum power, without being trapped in local maxima, it is of fundamental importance the realization of an accurate numerical model of the PV field. It must be able to simulate the PV basic units mismatching in a reliable and fast manner, also accounting for the behaviour of real bypass and blocking diodes. In (Jain, 2006) a numerical model of PV fields that allows simulating both uniform and mismatched operating conditions is introduced. It allows the simulation of a PV generator whose subsections, e.g. cells, groups of cells, panels or group of panels, work under different solar irradiation values and/or different temperature. Furthermore, different nominal characteristics, rated power, production technology, shape and area can be accounted for any subsections of the photovoltaic generator.

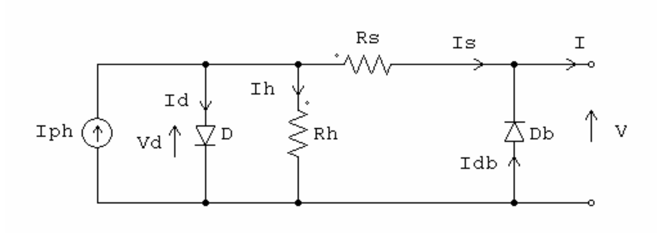

FIG. 11 - Circuit model of a PV unit including the bypass diode Db.

The model proposed is reliable and results into a non linear system of equations that requires a moderate computational burdensome, both in terms of memory use and processor speed.

Starting from the circuit model of a PV unit (Liu, 2002) depicted in **FIG. 11** and by means of the use of the Lambert W-function, a non linear explicit model of the PV generator has been obtained. The non linear model has been obtained by manipulating the system's equations within a symbolic software environment as Matlab, so that an explicit expression of the equations and of the Jacobian matrix has been obtained. For any PV array voltage, the model is solved by means of the classical Newton-Raphson method in order to obtain the voltage distribution on the different PV array subsections and the current produced by the whole PV generator.

The model has been implemented in a circuit-oriented software simulator as PSIM and exhibits good performance both in terms of memory requirements and computation time.

It has been firstly used to put in evidence the limits of the basic P&O approach in tracking the absolute maximum of the power-voltage characteristic of the PV array in mismatched conditions. It has been assumed that the PV characteristic roughly changes from that one depicted in FIG. 9 to that one of FIG. 10.

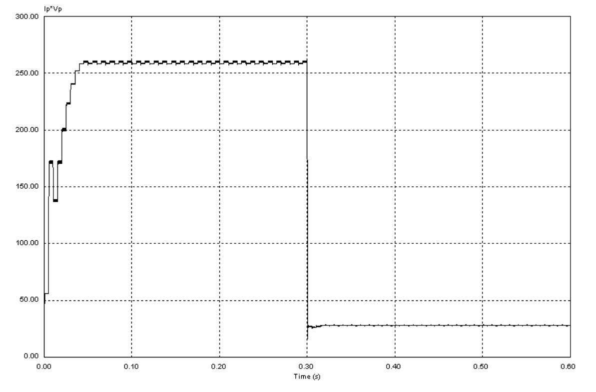

FIG. 12 - PV field output power.

The sudden power drop occurs at t=0.03 s (see FIG. 12). The P&O controller tracks the lower maximum because the voltage at which it occurs (see FIG. 13) is close to the voltage (about 40V) corresponding to the unique maximum of the characteristic depicted in FIG. 9. Starting from that voltage level, the P&O strategy is not able to go beyond the vertex occurring at about 25 V and tracking the absolute maximum. FIG. 13 also puts in evidence the three-points behaviour at both steady states: this characterizes the hill climbing of the two maximum power points tracked at the two different conditions.

The model will be of great help in developing an improved MPPT algorithm that is robust with respect to this kind of conditions, since it allows to test the MPPT performance with respect to different shapes of the power-voltage characteristic of the PV generator.

By means of the analysis of the section of the power-voltage and power-current characteristic in the voltage/current range wherein the PV generator is working when it is driven by the switching converter that performs the MPPT, the P&O strategy will be able to identify if the PV field is working under uniform or mismatched conditions.

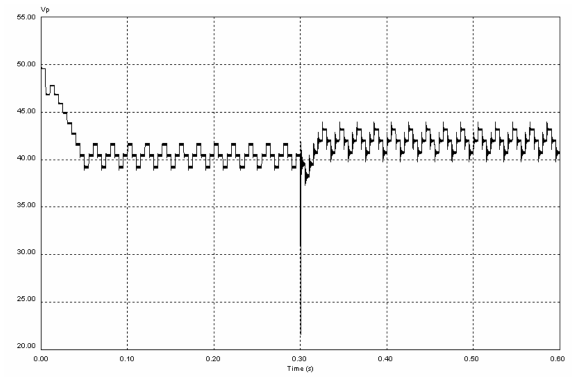

FIG. 13 - PV field voltage.

POWER ELECTRONICS IN SOLAR HYBRID CARS

In the proposed hybrid solar car, electrical energy is used to connect all power systems and to drive the vehicle. As a consequence, power electronics plays a strategic role enabling better utilization of both conventional and renewable energy sources.

Targets / Solutions	*High efficiency*	*High lifetime*	*High reliability*	*Low cost*
Soft Switching	●			
No electrolitic capacitors		●		
Low voltage & current stress	●	●	●	
Reduced no. of components			●	●

Tab. 5 – Electrical power systems requirements and solutions.

Such goal can be reached realizing high efficiency converter topologies and particular control algorithms as the MPPT technique (Kassakian, 2000; Blaabjerg et al., 2005; Emadi et al., 2004). Main targets and practical solutions of a good electronic conversion system are shown in **Tab. 5**. Unfortunately, some solutions are in contrast among them, then a suitable compromise must be found.

New solutions for electronic conversion stage should be considered involving in the investigation of innovative converter topologies, different system configurations and technology issues (Cacciato et al., 2004 I, 2004 II; Gerber et al., 2005).

In order to solve the problems of solar generators such as PV modules mismatching and partial shadowing, it is considered the possibility of properly split the modules installed on the vehicle using multi-converters configurations.

To this aim three different configurations have been analyzed that allow the best exploitation of the different energy sources present on board, also considering the effects on the cost and size of the conversion system. The standard configuration shown in **FIG. 14** consists in the connection of all modules in series or in parallel and the use of a single dc/dc converter to charge the batteries and another ac/dc converter to connect the electric power generator to the batteries.

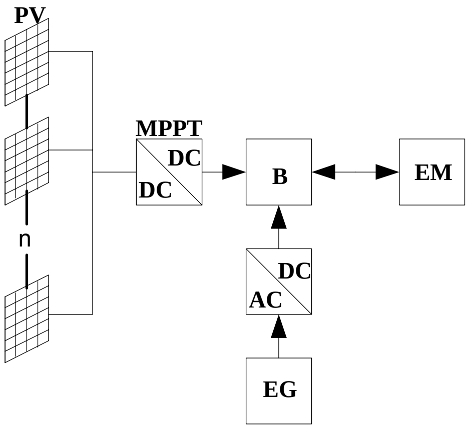

FIG. 14 - Standard configuration of the conversion system for hybrid solar vehicles

A second possibility, shown in **FIG. 15**, consists in using several dc/dc converters, one for each module, in order to dramatically reduce the mismatching and partial shadowing problems. It involves the use of higher number of converters of reduced power, each equipped with its own controller and MPPT algorithm, all connected to a single dc bus. In comparison with standard configuration such a solution ensures the optimal exploitation of the modules and perfect matching between the solar source and batteries.

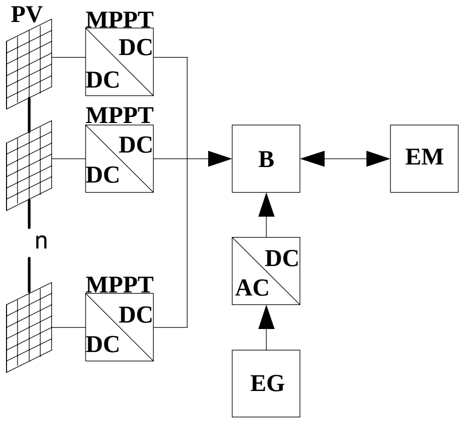

FIG. 15 - DC/DC multi-converters configuration of the conversion system for hybrid solar vehicles

In **FIG. 16** is shown the third solution that instead of the controlled ac/dc rectifier uses a single dc/dc multi-input converter to connect the solar and diesel generators to the batteries. In this configuration, a non-controlled rectifier is required between the diesel generator and the multi-input converter. The advantage of this configuration is that the power flow to the batteries can be suitably controlled.

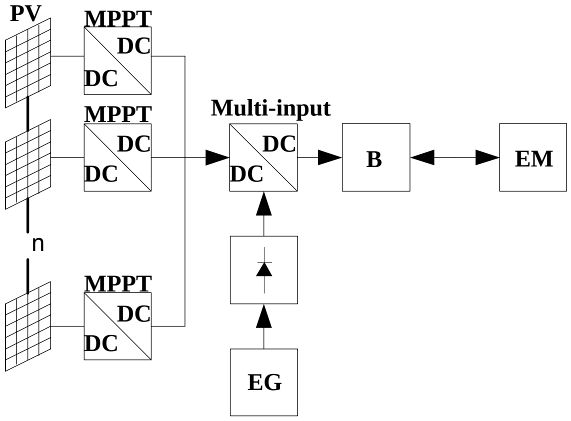

FIG. 16– Dc/dc multi-converters and multi-input dc/dc converter configuration of the conversion system for hybrid solar vehicles

In the second and third configurations, the dc/dc converters connected to PV modules could be integrated in a single chip and allocated on the PV module inside the box where the electrical connectors are normally placed (Motto, 1997).

In order to obtain a great reduction of the power devices losses, then the possibility to increase the converter switching frequencies, soft-switching topologies can be adopted. They allow to reduce the size of the passive components and, consequently, the converter weight and volume while decrease the overall Electro Magnetic Interference (EMI) that is a critical key point in automotive applications. The converters can be designed by adopting the most recent technologies such as planar magnetic structures and SMD components, in order to allow the converters to be located inside the photovoltaic modules. Finally, it should be observed that the converters MPPT control algorithms can be implemented by using low cost microprocessors as those reported in FIG. 17, where the P&O algorithm has been implemented successfully.

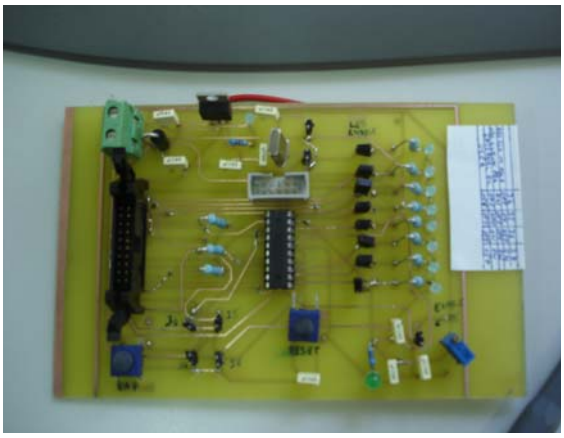

FIG. 17 – ST7 microcontroller board.

THE PROTOTYPE

In order to apply and validate the models and the solutions presented in this paper, a prototype of solar hybrid vehicle with series structures is being developed at the University of Salerno, within the EU supported Leonardo Program I05/B/P/PP-154181 "Energy Conversion Systems and Their Environmental Impact". The project aims to contribute to the diffusion of knowledge around sustainable mobility issues by the active involvement of young people in a didactic project with high symbolic impact. A web site in many European languages has also been implemented (www.dimec.unisa.it/leonardo).

Vehicle	Piaggio Micro-Vett Porter
Length	3,560 m
Width	1,395 m
Height	1,870 m
Motor	BRUSA MV 200 – 84 V
Max speed	52 Km/h
Batteries	14 Modules Pb-Lead
Mass	226 Kg
Capacity	130 Ah

Tab. 6 – Electric Vehicle Technical Data.

The prototype is being developed starting from an Electric Vehicle (FIG. 18), whose main features are summarized in the above table.

FIG. 18 – The Micro-Vett Porter Electric Vehicle

CONCLUSIONS

Hybrid Solar Vehicles, derived by integration of Hybrid Electric Vehicles with Photo-Voltaic sources, may represent a valuable solution to face both energy saving and environmental issues, but relatively little research effort has been spent in this direction. Despite their development is based on well-established technologies, accurate re-design and optimization of the whole vehicle-powertrain system is required to maximize the benefits coming from the integration of photovoltaic with HEV technology. Particular attention has to be paid in maximizing the net power from solar panels, taking into account the effects of mismatching and non uniform irradiation and temperature. Due to vehicle movement and shading effects, these problems are much more severe than in PV stationary applications. Also, the need to minimize weight and Electro Magnetic Interference while optimizing efficiency and costs requires advanced and innovative solutions for power electronics, with recourse to soft-switching topologies, planar magnetic structures and SMD components.

It has been shown that significant savings in fuel consumption and emissions can be obtained with an intermittent use of the vehicle at limited average power, compatible with typical use in urban conditions during working days. This result has been obtained with commercial PV panels and with realistic data and assumptions on the achievable net solar energy for propulsion. 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.

The results obtained by optimization analysis over driving cycles have shown that the hybrid solar vehicles, although still far from economic feasibility, could reach acceptable payback values if large but not unrealistic variations in costs, prices and panel efficiency will occur: considering recent trends in renewable energy field and actual geo-political scenarios, it is reasonable to expect further reductions in costs for PV panels, batteries and advanced electric motors and generators, while relevant increases in fuel cost could not be excluded. Moreover, the recent and somewhat surprising commercial success of some electrical hybrid cars indicates that there are grounds for hope that a significant number of users is already willing to spend some more money to contribute to save the planet from pollution, climate changes and resource depletion.

ACKNOWLEDGMENTS

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NOMENCLATURE

c_f [€/kg]	Fuel cost
c_{PV} [€/m^2]	PV Panel cost
PB [yrs]	Pay-Back
SF [%]	Solar fraction
η_P [/]	Panel efficiency

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BIPV	Building Integrated Photo Voltaic
EG	Electric Generator
EM	Electric Motor
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photo-Voltaic
V2G	Vehicle to Grid
VIPV	Vehicle Integrated Photo Voltaic