Dossier

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Analysis and Experimental Implementation of a Heuristic Strategy for Onboard Energy Management of a Hybrid Solar Vehicle

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Résumé — Analyse et expérimentation d'une stratégie heuristique pour la gestion d'énergie à bord d'un véhicule hybride solaire — Ce document présente l'analyse et la mise en œuvre d'expérimentation de règles bases RB (*Rule Base*) de stratégie de contrôle pour la gestion d'énergie à bord d'un véhicule hybride solaire HSV (*Hybrid Solar Vehicle*) qui est constitué d'un véhicule hybride électrique fabriqué en série et alimenté par des panneaux photovoltaïques. La stratégie RB se compose de deux tâches : l'une externe, qui détermine l'état final de charge de la batterie (SOC, *State of Charge*) qui doit être atteint à la fin du cycle de conduite pour permettre la pleine exploitation de l'énergie solaire pendant la phase de stationnement, l'autre interne, dont le but est de définir le générateur électrique optimal (ICE-EG, *Internal Combustion Engine – Electric Generator*), la trajectoire de la puissance et l'oscillation du SOC autour de la valeur finale. Cette stratégie de contrôle a été mise en œuvre en temps réel dans une unité de contrôle NI® cRIO (*National Instruments compact RIO*), permettant ainsi d'effectuer des essais expérimentaux pour la validation de la gestion d'énergie sur un prototype réel HSV développé par l'Université de Salerne.

Abstract — Analysis and Experimental Implementation of a Heuristic Strategy for Onboard Energy Management of a Hybrid Solar Vehicle — *This paper focuses on the simulation analysis and the experimental implementation of a Rule-Based (RB) control strategy for on-board energy management of a Hybrid Solar Vehicle (HSV), consisting in a series hybrid electric vehicle assisted by photovoltaic panels. The RB strategy consists of two tasks: one external, which determines the final battery State of Charge (SOC) to be reached at the end of the driving schedule to allow full exploitation of solar energy during parking phase; the other internal, whose aim is to define the optimal Electric Generator (ICE-EG) power trajectory and SOC oscillation around the final value. This control strategy has been implemented in a real time NI® cRIO control unit, thus allowing to perform experimental tests for energy management validation on a real HSV prototype developed at the University of Salerno.*

ACRONYMS

EG	Electric Generator
$E_{sun,day}$	Daily solar energy
$E_{sun,p}$	Solar energy during parking phases
HEV	Hybrid Electric Vehicle
HSV	Hybrid Solar Vehicle
ICE	Internal Combustion Engine
NI® cRIO	National Instruments compact RIO
RB	Rule-Based
SOC	State of Charge
P_{EG}	Power of the electric generator
P_{EM}	Power of the electric motor
S_f	Sun factor

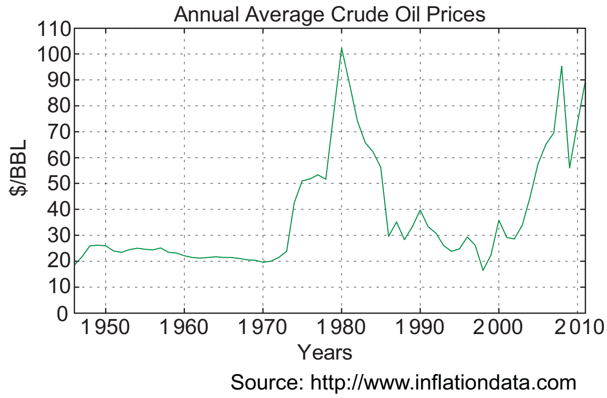

Figure 1

Trends in oil price.

INTRODUCTION

In the last years, there is an increasing awareness about the need to achieve a more sustainable mobility, allowing meeting the mobility needs of the present without compromising the ability of future generations to meet their needs [1]. The most pressing arguments towards new solutions for personal mobility are the following:

- proved reserves of oil, largely used for car propulsion, will end in about 45 years at the actual consumption rate [2]; moreover, oil price is subject to large and unpredictable fluctuations (*Fig. 1*);
- the CO_2 generated by the combustion processes occurring in conventional thermal 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, especially in China and India; as a consequence, energy consumption and CO_2 emissions related to cars and transportation are increasing.

One of the most realistic short term solutions to the reduction of gaseous pollution in urban drive, as well as the energy saving requirements, is represented by Hybrid Electric Vehicles (HEV) [3-5]. These vehicles that have evolved to industrial maturity allow achieving significant benefits in terms of fuel economy but still using fossil fuels. On the other hand, in recent years increasing attention is being spent towards the applications of solar energy to electric and also to hybrid cars [6]. But, while pure solar vehicles 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 (HSV) can be therefore summarized as follows:

- solar energy is renewable, free and largely diffused, and photovoltaic panels are subject to continuous technological advances in terms of cell efficiency [7]; their diffusion is rapidly growing, while their cost exhibits in last years a marked decreasing trend [8];
- solar cars, in spite of some spectacular outcomes in competitions as World Solar Challenge [9], do not represent a practical alternative to conventional cars, due to limitations on maximum power, range, dimensions and costs;
- there is the possibility of fruitfully combining HEV and solar power related energetic benefits [6, 9].

A considerable research has been carried out in last decades about the energy management and control of hybrid vehicles [3, 10]. Most of the papers focus on parallel hybrid vehicles, while some techniques can be applied both to parallel and series hybrid. Regard to series hybrid, different Rule-Based (RB) methods were studied. Both switching logic control for battery recharge [11] and Fuzzy-Logic methods [12] were proposed. Load-leveling approach, consisting on a method of forcing the engine to operate near the peak efficiency region, has been also studied [13]. More complex approaches, based on optimal control and on application of Pontyragin maximum principle, were also proposed for series hybrid vehicles [13-16].

In next chapters, the RB control strategy applied on the HSV prototype, developed at the University of Salerno [17], is presented. The convenience of this strategy has been first analyzed by simulation analysis, through a model developed in MATLAB®. Then, the strategy was implemented in the real-time programmable controller CompactRIO (cRIO) by means of the National

Instrument® (NI) LabVIEW® graphical programming language. Some preliminary experimental tests are presented at the end of the paper to highlight the suitability of NI cRIO to perform on-board energy management of series HSV by means of the RB strategy developed in [17].

It is worth remarking here that the experimental assessment of real-time implementability and cost-effectiveness of supervisory control policies for series hybrid vehicle architectures is a significant contribution to the field, as demonstrated by the not so extended literature on series HEV experimental testing [18-22].

1 RULE-BASED CONTROL STRATEGY APPLIED TO AN HSV PROTOTYPE

The RB strategy for a HSV with series structure consists of two tasks, external and internal, respectively [21]:

- the external task determines the final battery State of Charge (SOC_f) to be reached at the end of the driving schedule. SOC_f allows full exploitation of solar energy during parking phase (*i.e.* $E_{sun,p}$);
- the internal task estimates: i) the average power of the Electric Generator P_{EG}, delivered by ICE-EG and ii) SOC deviation ($dSOC$) from SOC_f, as a function of the average power required for traction. The map (Eq. 3) determines the limits of variation of SOC around its final value SOC_f. It is timely to remark that $dSOC$ does not represent the instantaneous SOC variation but the limit values where the engine/generator group is set on or off (a sort of thermostatic control with variable range).

The overall RB control architecture consists of three look-up tables:

$$SOC_f = f(E_{sun,p}) \tag{1}$$

$$P_{EG} = f(\bar{P}_{EM}) \tag{2}$$

$$dSOC = f(\bar{P}_{EM}) \tag{3}$$

The look-up tables (2) and (3) are determined off-line *via* optimization analysis, as a function of the average vehicle power demand P_{EM}. The best values are determined using a detailed vehicle dynamical model, considering also the effects of thermal transients (due to start-stop operation) on fuel consumption and of the energy required for starting the engine [21-24]. For each condition, a constant vehicle power demand was simulated, and the best combination of P_{EG} and $dSOC$ were determined *via* mathematical optimization. The actual values of P_{EG} and $dSOC$ were then obtained on-board *via* interpolation techniques from the optimal values.

The final value of SOC in Equation (1) is obtained as a function of the expected incoming solar energy in next parking phase [25, 26]. In fact, working with SOC values of 0.6-0.7 allows to minimize battery losses and fuel consumption during driving but also reduces the energy that could be captured for free in next parking phase. On the other hand, the use of an unnecessary low value of SOC_f increases battery losses during vehicle operation. The estimation of the incoming solar energy, also by using real-time weather forecast [25], allows to select the most appropriate SOC_f value.

Previous studies have shown that the optimal power P_{EG} delivered by ICE-EG is strongly dependant on required power (2), and therefore can differ substantially from the conditions of engine minimum fuel consumption [21]. This implementable RB strategy has been validated against a benchmark strategy obtained off-line *via* Dynamic Programming [24] and *via* Genetic Algorithms [23], showing that very limited decay of fuel economy was obtained, even with the use of *a posteriori* estimate of traction power. The benefits obtainable by using on-board weather forecast for the estimation of final SOC (*Eq. 1*) have also been assessed [23-25, 26].

The RB control strategy has been applied to a HSV prototype, developed at University of Salerno [9], whose main technical specifications are given in Table 1.

A yearly average value of 4.31 kWh/m^2 for the daily solar energy $\bar{E}_{sun,day}$ irradiating on an horizontal surface was assumed.

Fuel economy was evaluated considering three different scenarios, as shown in Table 2.

Each scenario was analyzed on a 860 s long driving cycle (*Fig. 2*). The impact of solar energy contribution also was investigated by varying the sun factor S_f in the range (0÷1.5), where $S_f = 1$ corresponds to the average daily energy that impacts on an horizontal surface at the University of Salerno region (4.31 kWh/m^2).

TABLE 1
HSV prototype specifications

HSV specifications	
Nominal ICE-EG power (kW)	6
Fuel	Gasoline
EM peak power (kW)	15
Number of Lead-acid battery modules	16
Battery capacity (kWh)	17
PV horizontal surface (m^2)	1.44
PV efficiency	0.10
Weight (kg)	1 900

TABLE 2
Simulated control policy scenarios

Scenario	Characteristics
1	RB strategy: P_{EG} and $dSOC$ are obtained by Equations (2) and (3)
2	Parametric analysis with $dSOC$ obtained by Equation (3) and P_{EG} variable in the range (0.25÷0.75) times the nominal EG power (*i.e.* 6 kW, as shown in *Tab. 1*)
3	Parametric analysis with $dSOC$ variable in the range (0.01÷0.02) and P_{EG} obtained by Equation (2)

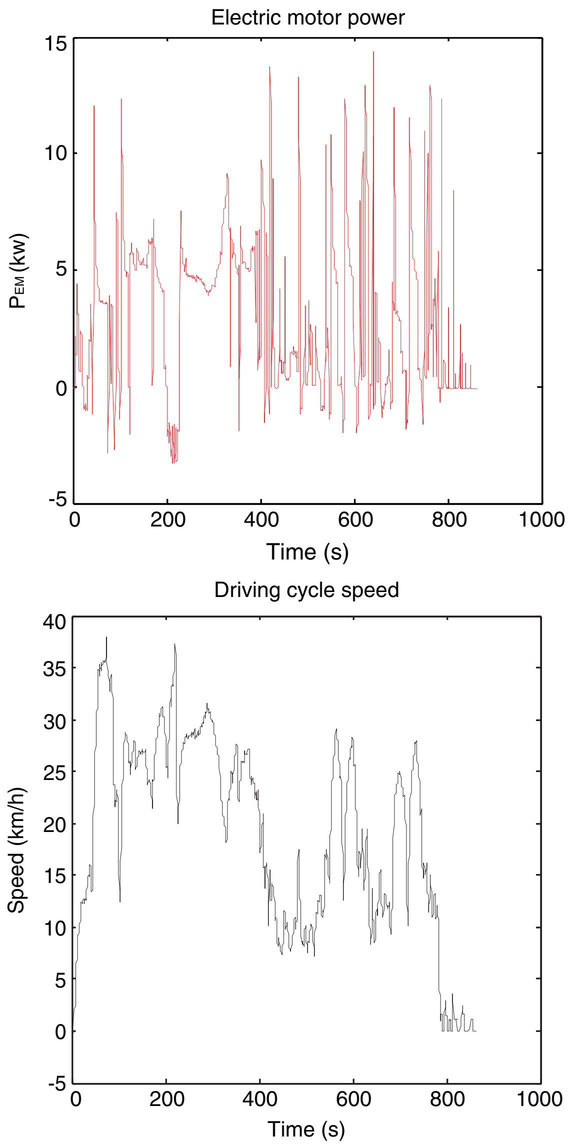

Figure 2

Electric motor power and speed of the considered driving cycle.

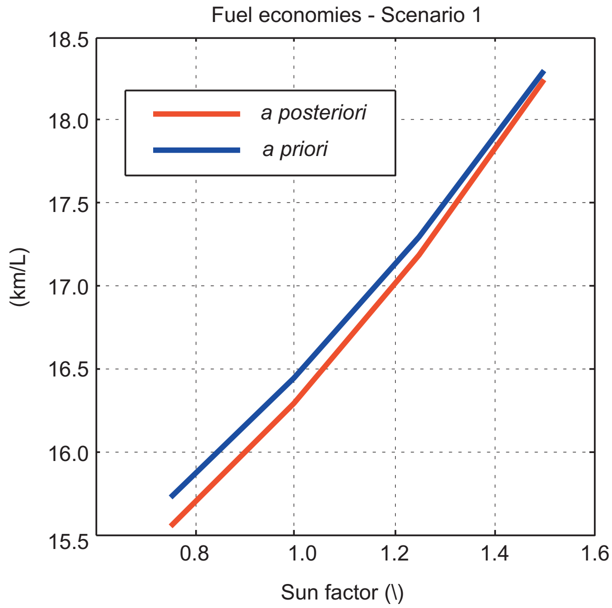

Figure 3

Fuel economy with RB strategy (scenario 1).

In scenario 1 (RB strategy fully active, *Tab. 2*) fuel economy was simulated assuming both *a priori* and *a posteriori* knowledge of average power to be supplied by the series powertrain to the electric motor EM to meet driving cycle demands.

A priori strategy consists in estimating future power values with suitable methodologies (*i.e.* recurrent neural networks [20, 27]) while in case of an *a posteriori* strategy past values of power are used to estimate the current reference power. In this case, perfect *a priori* knowledge of power values has been assumed as benchmark for *a priori* strategy. As expected (*Fig. 3*), fuel economy values with *a posteriori* strategy are slightly lower than the ones obtained with *a priori* strategy. This result is in accordance with the conclusions of previous studies [21, 23], showing that the proposed RB strategy exhibits limited sensitivity to the method of power estimation, and that acceptable results can be achieved also with a simple *a posteriori* strategy.

In Figures 4 and 5 fuel economy was computed considering scenario 2 and scenario 3 assumptions, respectively (*Tab. 2*).

The results in Figures 4 and 5 show that fuel economy is rather sensitive to generator power P_{EG}, while the sensitivity to $dSOC$ is much lower. In this case (*i.e.* with this driving cycle) the best fuel economy is obtained with P_{EG}/P_{EGnom} = 0.75 and $dSOC$ = 0.016. Moreover,

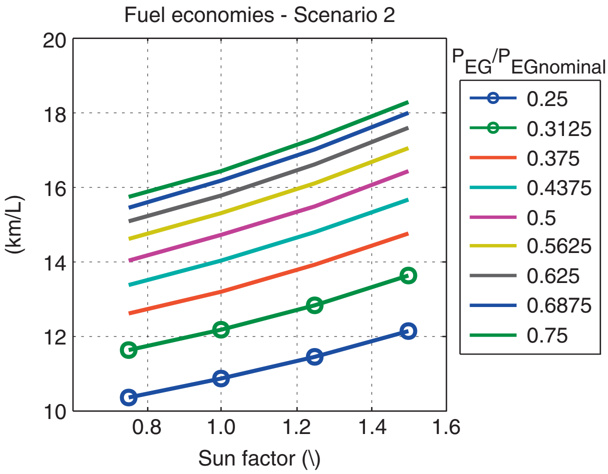

Figure 4

Fuel economy for scenario 2.

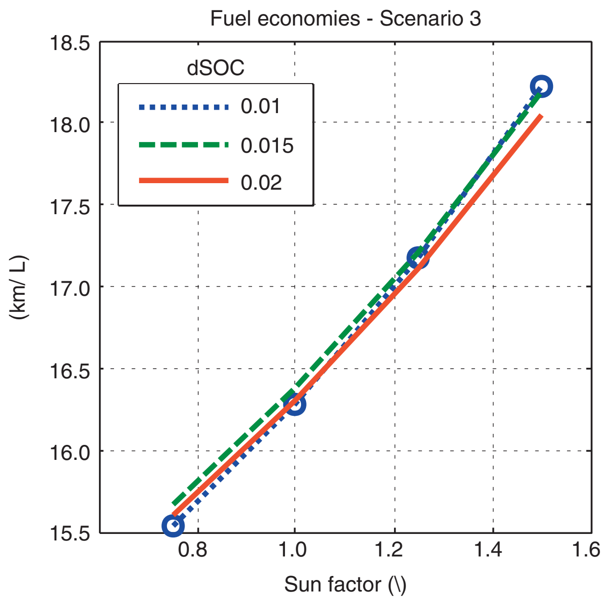

Figure 5

Fuel economy for scenario 3.

while fuel economy of course increases with sun factor, the best combination of P_{EG} and $dSOC$ is rather independent of it.

To check the convenience in adopting the RB strategy, the fuel consumption obtained in scenario 1 and the most convenient cases in scenario 2 and 3 have been compared (*Fig*. *6*). It emerges that even though RB does not achieve the highest fuel economy, its values always

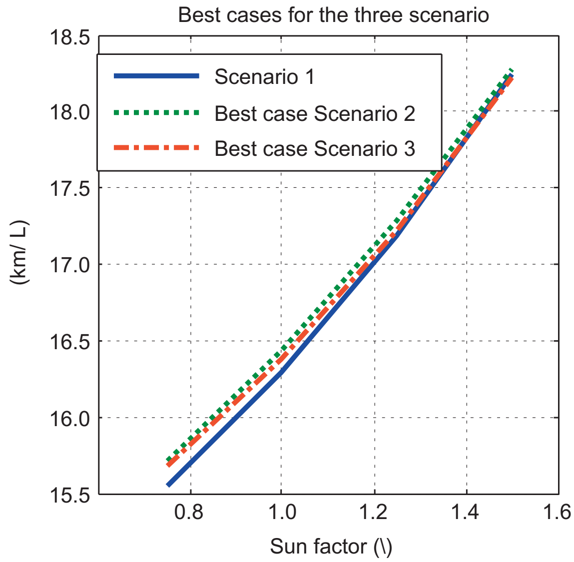

Figure 6

Fuel economies in the three different scenarios.

fall very close to the best ones computed in scenario 2 and scenario 3.

Therefore, it emerges that strategy of scenario 1, which is implementable on-board, has given almost the same results of the best cases of scenarios 2 and 3, which have been determined off-line after a comparison of simulation results with other cases and therefore are not implementable on-board (in other words, their best results would depend on driving cycle). The fact that scenario 1 is not necessarily the best is consistent with the fact that the proposed strategy is not optimal but heuristic. This result is therefore not a 'proof' of optimality but rather a further confirmation of suitability of the proposed strategy. In fact, a more rigorous approach has been followed in previous papers, where the Rule-Based strategy has been compared with the results of Dynamic Programming, used as a benchmark. The results demonstrated that heuristic intermittent management of the ICE-EG group on series HEV architectures ensures achieving performance significantly close to the optimal ones, resulting in fuel economy as high as 95% of the optimal values computed *via* Dynamic Programming [24].

2 IMPLEMENTATION OF RULE-BASED CONTROL STRATEGY IN LABVIEW

After proving its suitability for real-time energy management of HSV, the RB strategy was then implemented

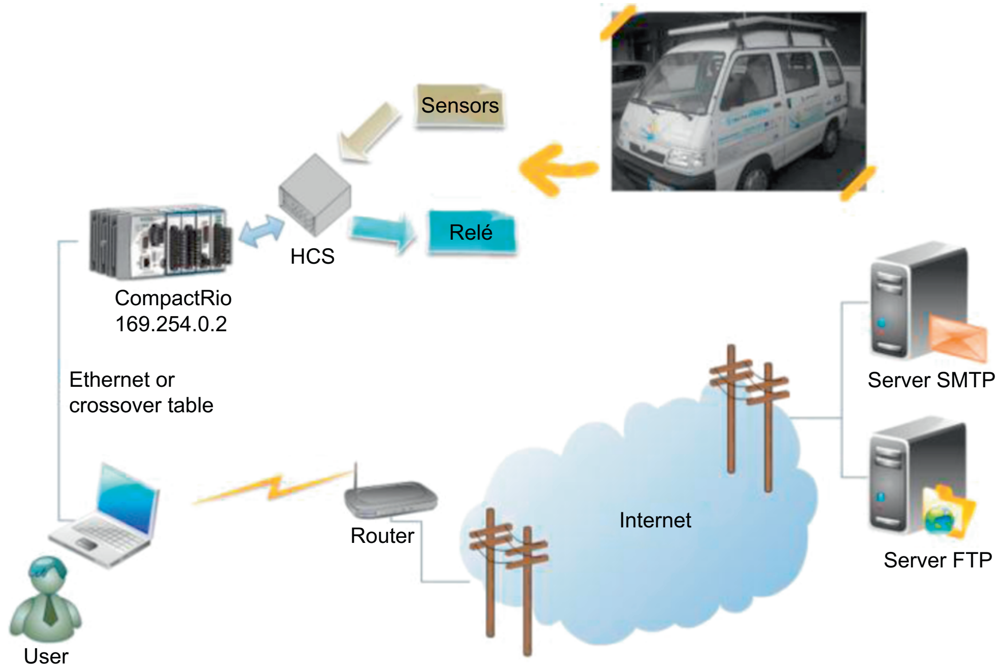

Figure 7

Flow of information for the Real Time application of RB strategy on HSV.

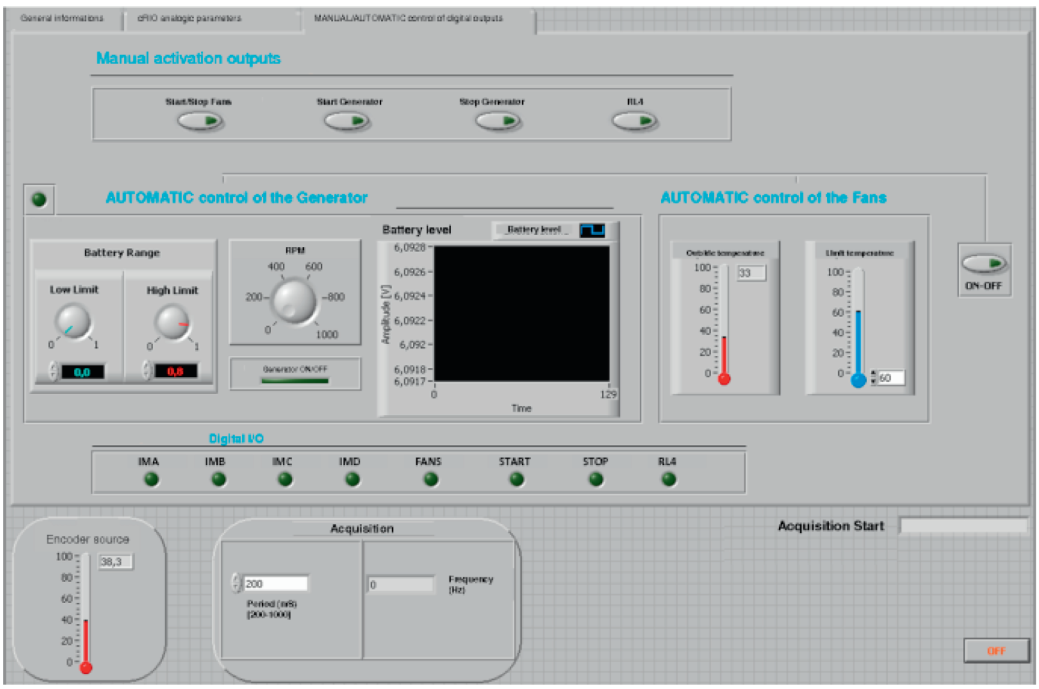

Figure 8

The cRIO interface.

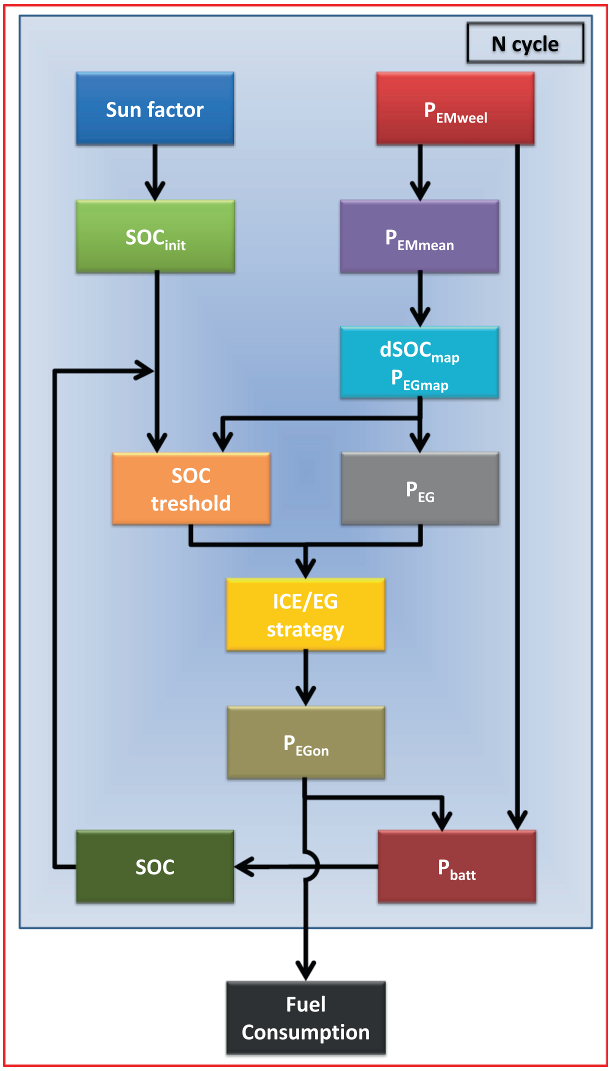

Figure 9

The scheme of the RB strategy implemented into the NI-cRIO platform.

onboard into a National Instrument compact Rio (NI® cRIO) platform, connected to a number of analog and digital I/O ports.

The main idea is the Real Time application of RB strategy on the HSV: the flow of information is shown in Figure 7.

The interface between the cRIO platform and the PC to control manual and digital I/O are represented in Figure 8.

Main analog inputs include current, voltage, temperature, speed, angular speed, solar irradiation, torque and pedal position measurements. The digital outputs are mainly applied to electrical switches aimed at effectively performing the control actions addressed by the RB strategy, as shown on the scheme plotted in Figure 9.

The main inputs for the on-board RB strategy are:

- S_f: sun factor, depending on which the value of SOC_f is determined, see Equation (1). S_f can be computed on-board as function of sun irradiation measured by a pyranometer or estimated by comparing the actual solar power with its maximum value based on latitude and time;
- P_{EM}: electric motor power (kW), affecting Equations (2) and (3).

An *a posteriori* strategy is applied online to update every t_h seconds the average power requested by the EM to power the wheels ($\overline{P}_{EM}$). Then, according to $\overline{P}_{EM}$, the upper and lower SOC thresholds, depending on which ICE intermittency is managed, are evaluated:

$$SOC_{\min,\bar{t}} = SOC_{\bar{t}} - dSOC \tag{4}$$

$$SOC_{\max,\bar{t}} = SOC_{\bar{t}} - dSOC \tag{5}$$

In order to estimate on-board the current value of battery SOC, the battery model utilized in Matlab® was transferred into LabVIEW environment.

3 EXPERIMENTAL RESULTS

The on-board implementation of the RB strategy was tested by running the HSV prototype along the driving route shown in Figure 10 -speed plot. During the test, a time horizon t_h = 41.7 s was imposed to suitably update average EM power. Figure 10 also shows the following measurements: a) SOC and its thresholds; b) speed of the HSV; c) power of Electric Generator; d) traction power, computed starting from the torque measured with a torquemeter; e) electric motor power; and f) mean power of electric motor.

In order to discuss the real operation of RB strategy, the values of SOC, speed, generator power and traction power are analyzed by referring to each section numbered in the figure:

1. in this sections, HSV's speed and power traction are zero, so there is no variation of SOC;
2. there is a strong SOC decrease due to a rapid acceleration from 0 to 10 km/h;
3. the value of SOC decreases until the value of SOC_{min} (point 3), as imposed by the RB strategy;
4. despite the ICE is on there are two little battery discharges due to two strong accelerations;
5. there is a linear increase of SOC, as a consequence of the almost constant value of traction power;

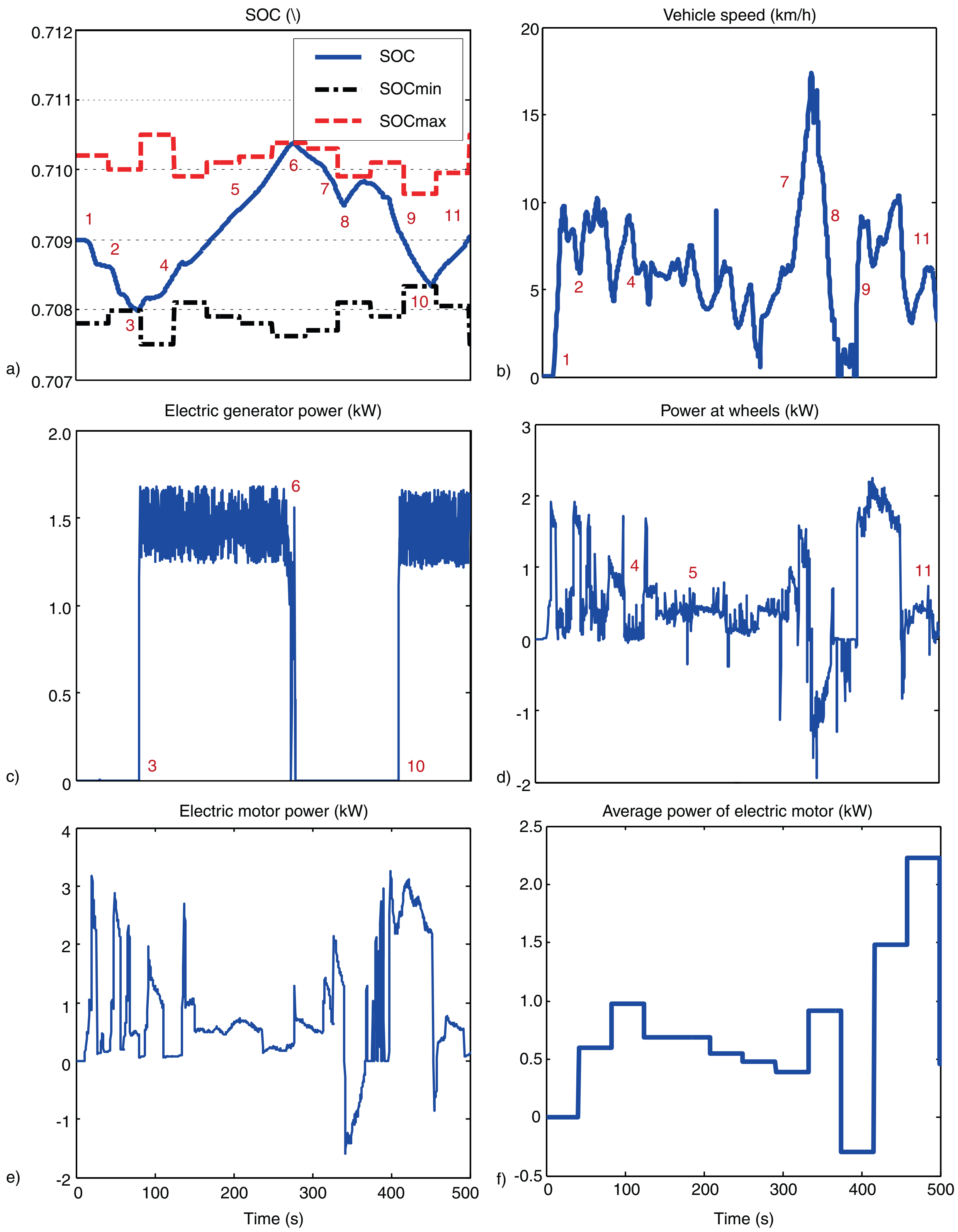

Figure 10

Plots of main acquired variables during the on-board test of RB strategy. a) SOC and its thresholds; b) speed of the Hybrid Solar Vehicle; c) power of Electric Generator; d) traction power, computed starting from the torque measured with a torquemeter; e) electric motor power; and f) mean power of electric motor.

6. the value of SOC grows till the SOC_{max} (point 6) value imposed by the RB strategy;
7. there is a rapid SOC decrease due to the high acceleration;
8. the ICE is off but there is a brief recharge. This happens because there is a strong braking (regenerative braking) as it is possible to see in the speed plot;
9. the value of SOC decreases again with a strong gradient due to high acceleration;
10. the value of SOC decreases until another value of SOC_{min} (point 10) that is imposed by the RB strategy;
11. the speed till the end of the cycle is low and almost constant, so the battery gets smoothly charged back to the initial value, thus guaranteeing overall charge sustaining operation.

Obviously the trends of SOC's thresholds depend on (Figure 10) measurement.

It is worth mentioning that at the current stage it is not possible to fully apply the rule expressed by Equation (2) on-board, due to the features of the battery charger, through which ICE-EG and battery are interfaced, that limits the maximum charging power to about 1.5 kW. This in turn also avoided running the vehicle at speed higher than 18 km/h, on one hand, and, on the other, did not allow to test the prototype under charge depletion operation to fully evaluate solar contribution. Therefore, the final fuel economy achieved in the real-world cycle shown in Figure 10 was as high as 12.5 km/l. Such value is 23% lower than what can be achieved by the rule based strategy, as shown in Figure 6 in correspondence of normal PV contribution (*i.e.* at sun factor equal to 1). This is of course due to:

- at 1.5 kW the ICE-EG group works at 18% efficiency [17, 23];
- charge depletion was not imposed thus excluding the PV contribution during the parking phase;
- Equation (2) was not active.

Nevertheless, the experimental test presented and discussed in the current section has been certainly useful to test the reliability of the developed control algorithm and to overcome the many difficulties encountered when passing from theory to practice in automotive control applications.

CONCLUSIONS

The paper presents the application of a previously developed Rule-Based control strategy on a prototype of series Hybrid Solar Vehicle developed at the University of Salerno. The strategy, validated in previous papers against results obtained *via* Dynamic Programming and Genetic Algorithms, has been analyzed *via* simulation analysis, by comparing fuel economy obtained with the application of RB strategy with the results of two extensive parametric analyses.

The RB strategy has been then implemented on the prototype through the development of a LabVIEW algorithm, which was then embedded onto a NI cRIO platform. Preliminary experimental tests have been performed to test the reliability of the control strategy and of the vehicle control system.

Future work will focus, on one hand, on extending the numerical analyses to other driving cycles and/or HSV architecture and, on the other hand, on further testing the correspondence of real fuel consumption measured on the vehicle and the ones obtained by a simulator developed in LabVIEW.

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