A Hybrid Engine Control System based on Genetic Algorithms

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Abstract: - In this paper an optimal management of the energetic flows in a hybrid vehicle based on a Genetic Algorithm is introduced.
The aim is maximize the use of the electric engine, minimizing the use of the internal combustion one, increasing the driving pleasure and reducing consumptions, emissions and noise. From the available literature, a typical configuration series-parallel hybrid engine as has been chosen. In particular the Toyota Prius engine has been taken as a practical reference.
A Genetic Algorithm for optimal parameters identification of the control system (PID Controller) has been applied to hybrid engine. Moreover, the parameters which influence the optimal behavior of a hybrid vehicle have been selected and organized in a two levels control strategy: "High Level Optimization" and "Low Level Optimization".

Key-Words: - Control Systems, Genetic Algorithms, PID Controllers, Power Management, Hybrid Engines.

1 Introduction

Today one of the most important emergencies of the National and European urban area are the negative effects of motor traffic. The traffic is the main source of atmospheric and acoustic pollution with consequent damage for environment and for health. Pollution from automobile tailpipes increases the risk of asthma, lung cancer, leukemia and other ailments, particularly in people who live near busy roads such as interstate highways. In December 1997, representatives from 160 countries met in Kyoto, Japan, and agreed to a Protocol that calls for further reductions in greenhouse gas emissions. On Dec 15, 2006 the European Commission (EC) takes Legal Action to Enforce Kyoto Protocol. (EC) plans to send four member states final written warnings that they face court action unless they rapidly submit national allocation plans for the second trading period of the European Union Emissions Trading Scheme (EU ETS) from 2008 to 2012. The EC is also taking infringement action against seven member states for failing to provide complete reports on their progress in limiting or cutting greenhouse gas emissions. The auto industry has the technology to address these concerns. It's the **hybrid car**. There are a lot of models on the market these days, and most automobile manufacturers have announced plans to manufacture their own versions. Moreover, a hybrid vehicle incentive has been already enacted. Some provide consumer tax benefits, others parking perks. The Toyota Camry has been the top-selling vehicle in America for eight of the last nine years. This year, Toyota Camry Hybrid wins 2007 Green Car of the Year. Other cars in contention included the Honda Civic GX, Lexus LS450H, Prius, Mercedes-Benz E320 Bluetec and Saturn Vue Green Line. As with the Prius, the hybrid Camry's engine uses Toyota's version of an Atkinson-cycle engine, delaying the closing of the intake valves to create an engine with a high 12.5:1 expansion ratio paired with a conventional 9.6:1 compression ratio.

2 Paper's Overview

The aim of this work is the optimal management of the energetic flows in a hybrid vehicle, maximizing the use of the electric engine, minimizing the use of the internal combustion one, increasing the driving pleasure and reducing consumptions, emissions and noise.
Work steps have been organized as follows:

1. Analysis of the architecture of a hybrid vehicle.
2. Design and Realization of a System Model in MATLAB®/ Simulink®.
3. Design and Realization of a PID Controller for the System Model.
4. Design and Realization of a Genetic Algorithm (GA) in C language.

5. Application of the GA for optimal parameters identification of the Control System (PID Controller) applied to hybrid engine.

Toyota Prius engine has been taken as a reference hybrid engine. Starting from available literature, a suitable Simulink® Model approximating the real behavior of Toyota engine has been obtained. Parameters which influence the optimal behavior of a hybrid vehicle have been selected and organized in a two levels control strategy [1]:

Low Level Optimization

A. <u>Dynamic load repartition on both engines</u>, depending on:
   - Battery State Of Charge (SOC).
   - Power requirement from the user (accelerator position).
   - Mechanical load and road slope (torque on axis).

High Level Optimization

B. <u>Emissions and consumption minimization</u>, depending on:
   - Battery State Of Charge (SOC).
   - Engines Efficiency (through **Low Level Control).**

3 Series-Parallel Hybrid Vehicle

There are many ways to create an electric-internal combustion hybrid. The variety of electric-ICE designs can be differentiated by the structure of the powertrain, the degree of hybridization and the mode of operation. The main categories are *series hybrids* and *parallel hybrids*, with *combined hybrids* having common characteristics of series and parallel designs.

Hybrids other than electric-internal combustion exist, for example hydraulic and pneumatic hybrids, where compressed fluids and compressed air, respectively, are used for energy storage with regenerative braking.

Combined hybrid systems have features of both series and parallel hybrids. They incorporate power-split devices allowing for power paths from the engine to the wheels that can be either mechanical or electrical. The main principle behind this system is the decoupling of the power supplied by the engine (or other primary source) from the power demanded by the driver.

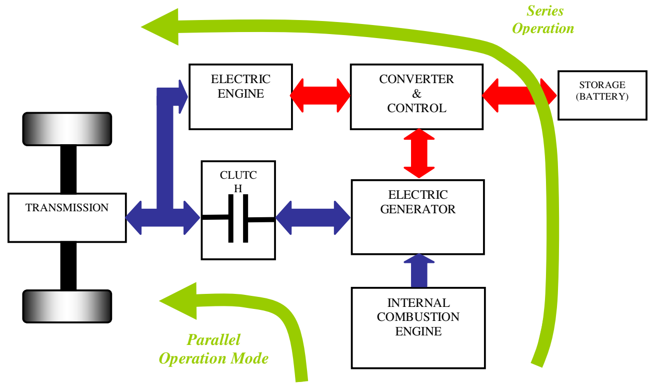


Figure 1: Structure of a combined hybrid electric vehicle

This system ensures a high autonomy and low consumption in highway, while in city working condition low consumptions and emissions are ensured by the extensive use of the "electric-only" mode.

In a combined hybrid, a smaller, more flexible, and highly efficient engine can be used. It is often adopted a light variation of the conventional Otto cycle, such as Miller cycle or Atkinson cycle. This contributes significantly to the highest overall efficiency of the vehicle.

Examples of interesting improvements of this structure implemented on Toyota Prius are the following:

- Addition of a fixed gear second planetary gear set as used in the Lexus RX400h and Toyota Highlander Hybrid. This allows in a motor with less torque but higher power (and higher maximum angular speed), higher power density.
- Addition of a ravigneux-type planetary gear (planetary gear with 4 shafts instead of 3) and two clutches as in the Lexus GS450h. By switching the clutches, the gear ratio "electric engine/wheels" changes, either for higher torque or higher speed (up to 250 km/h / 155 mph) providing a better transmission efficiency.

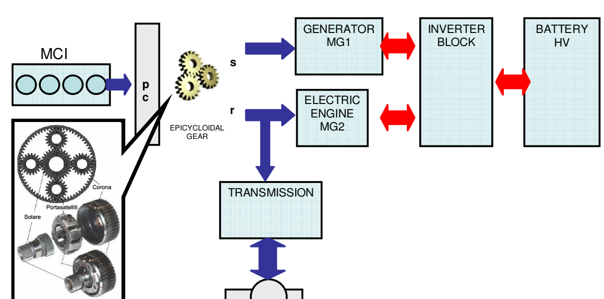


Figure 2: Series-Parallel Hybrid Vehicle (Toyota Prius).

Figure 2 shows mechanical configuration of Toyota Prius hybrid vehicle with following symbol legend:

- MG1: Electric Generator;
- MG2: Electric Engine;
- CVT:(Continuously Variable Transmission) a type of automatic transmission that can emulate a continuous range of gear ratios;
- MCI: Thermic Engine.

MG1 and MG2 can work whether as engine or as generator. Blue and red arrows show Mechanical Energy Flow and Electrical Energy Flow respectively.

The following figure shows the diagram of several vehicle operation conditions: stopped or still, departure, starting of MCI, normal going, braking, vehicle recharging deceleration with MCI off.

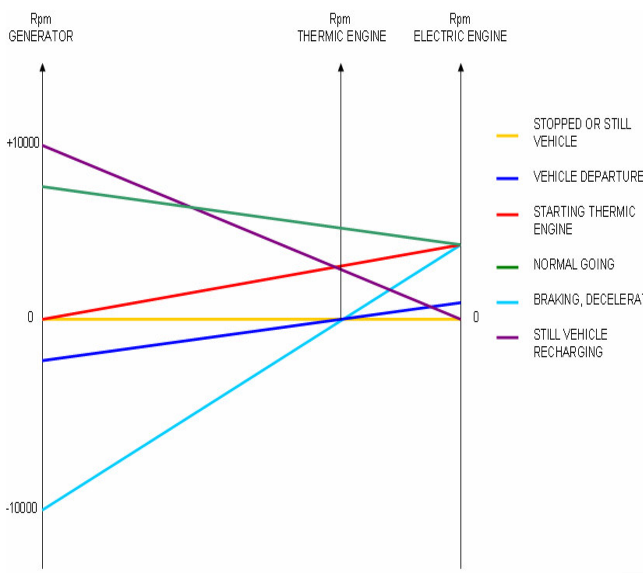


Figure 3: Vehicle Operation Conditions.

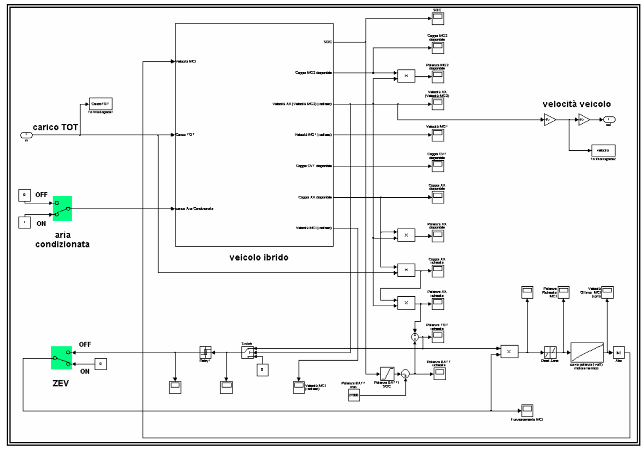
4 Toyota Prius Simulink® Model

Hybrid Vehicle modeling expects a multilevel structure to be optimized also for other vehicles. It performs the gear only by electric engine, hybrid gear by both engines (electric and thermic), battery charging HV and regenerative braking by MG2.

External level modeling

The architecture of this first level includes all possible driving conditions. Hybrid system is contained into a single block, realizing input and output control, showing the vehicle speed.

Main gateway is set by the user with the total load, which depends on the accelerator treadle by changing its angular position. The following figure shows the model of the total system.



The second gateway is constituted by the manual command of air-condition, performed with a manual switch.

The third gateway concerns the optimal velocity of thermic engine. This fact will be detailed explained in next section.

All variables are monitored by the corresponding scope blocks, located at the output of the system, showing the states evolution during all simulation time.

Internal level modeling

The second model level includes all main parts of hybrid system with their mechanical and electric connections.

In the following figure left and right sections show respectively mechanical and electric parts, while bottom-right section indicates the recharging energy system, for the recovery of dynamic energy during the deceleration.

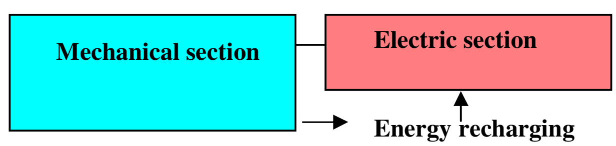


Figure 4: Mechanical and electric sections

In the mechanical section showed in figure 5, the MCI block gets as input the number of rpm for supplying the power of system, the amount of power to be provided to the axle of transmission and of power to be provided in order to maintain the battery within a chosen range of charge.

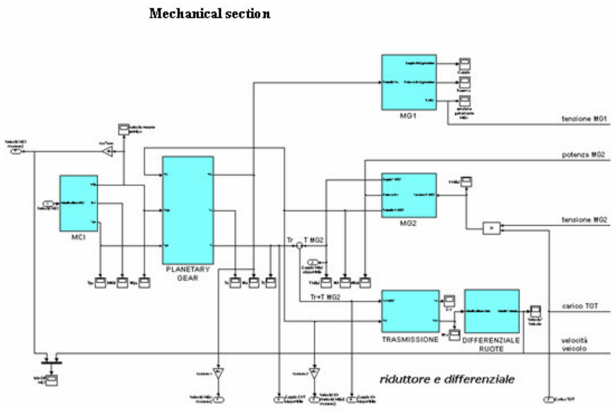


Figure 5: Mechanical section

In the electric section, the main blocks are battery HV and inverter. Parameters that connect the two sections are:

- the voltage coming from the MG1 generator;
- the voltage supplied to the electric engine MG2 in deceleration;
- the power supplied by it;
- the total load and the velocity of vehicle.

Bottom-right section performs the energy recharging.
This recovering of dynamic energy happens during braking (or deceleration) only if:

- vehicle velocity is not zero;
- total load imposed by user is null, that is when acceleration treadle is released;
- voltage supplied by MG1 is zero.

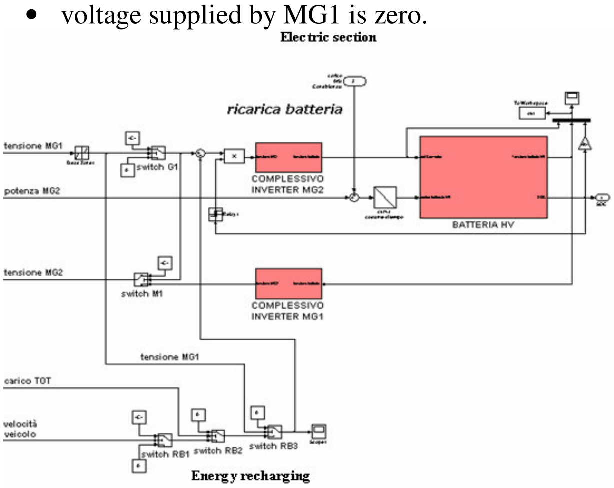


Figure 6: Electric section and recharging energy blocks

5 Optimization

The aim of this work is the optimal management of the energetic flows in a hybrid vehicle, maximizing the use of the electric engine, minimizing the use of the internal combustion one, increasing the driving pleasure and reducing consumptions, emissions and noise.
Parameters which influence the optimal behavior of a hybrid vehicle have been selected and organized in a two levels control strategy: **High Level Optimization** and **Low Level Optimization:**

High-level Optimization
(Emissions& Consumptions)

- Minimization of polluting Emissions
- Minimization of specific Consumption
- Saving of batteries State of Charge (SOC)

Low-level Optimization
(Performances):

- Find out of PID optimal parameters
- Limitation of Control Variables
- Saving of batteries State of Charge (SOC)

High-Level Optimization
Starting from system required power (power on axis + power to obtain a suitable SOC), it is computed the optimal speed of the combustion engine for the minimization of: *Nitrogen-Oxide emissions* (NOx), *Carbon-Oxide emissions* (CO), *Unburned Hydrocarbons emissions* (HC) and *Specific fuel consumption*.
From technical data in literature of Toyota Prius fuel engine, are obtained the diagrams of: *Polluting Emissions weighted average* and *Fuel Consumption*. They can be combined into the **Emissions-Consumption weighted average diagram**, showed in figure 7.

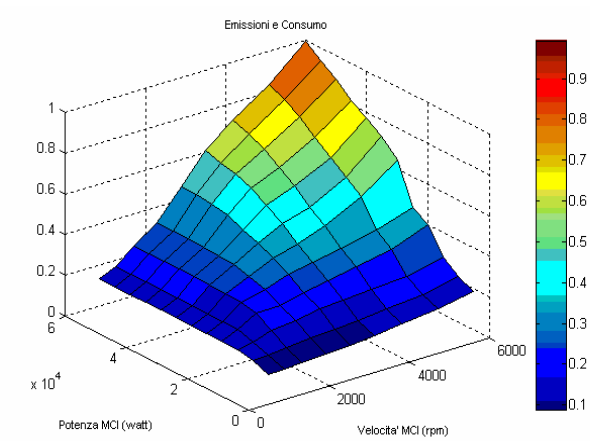


Figure 7: Emissions-Consumption weighted average

By inspection of level curves of this graphic, reported in figure 8, it follows that it is possible to approximate the optimal working point in the neighborhood of the curve of maximum power.
High-Level Optimization could be performed graphically or via classical gradient techniques without losing accuracy in final results.

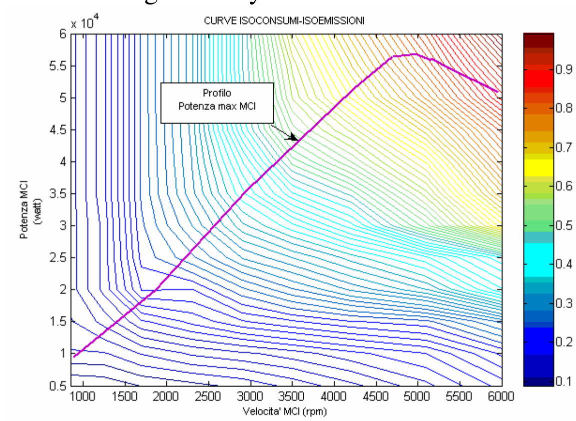


Figure 8: Emissions-Consumption level curves

High Level Optimization is performed using classical techniques in order to find a set of low emissions working points which constitutes "the search space" of the low level control.

Low Level Optimization
This optimization operates within the ranges imposed by high level. The dynamic control is performed via a Genetic Algorithm-based Tuning of PID Parameters such that: *System* produces an output that is a good approximation of the desired behaviour (target), *Control variable* is limited in amplitude during the transient and *SOC* is maintained close to its average value. The following figure shows the *Control System.*

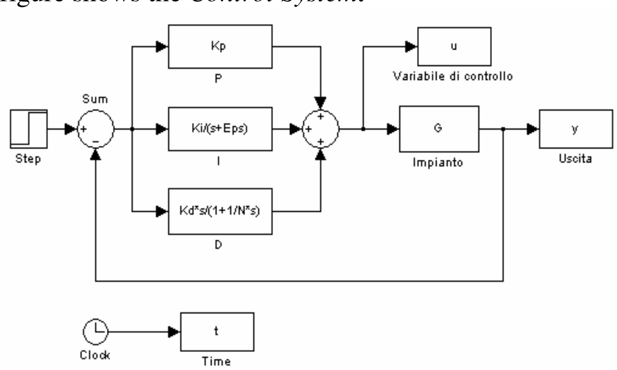


Figure 9: Control System

The PID model used presents the following transfer function:

$$R_{PID}(s) = k_P + \frac{k_I}{s+\varepsilon} + \frac{k_D s}{1+\frac{1}{N}s}$$

Where PID Parameters are: $\mathbf{K_p}$, $\mathbf{K_i}$, $\mathbf{K_d}$, **Eps**, **N.** Control variable u is the Electric Engine input voltage. Step input is a rapid variation of the load. Output y should follow this trend as fast as possible.
In brief, in Low Level Optimization, this feed-back control allows the output (the vehicle speed) to follow very fast the reference value (imposed by the driver), keeping the control variable bounded during the transient.

6 Genetic Algorithms

To optimize PID Parameter has been chosen Genetic Algorithms (GA). They implement optimization procedures, based on simulation of the natural law of the evolution of the species by natural selection, in order to obtain the fittest individual in the evolutionary sense. According to this theory, considering a population that evolves in a particular environment, only the fittest individual may be able to reproduce handing down its chromosomes. Therefore, the less fitted will be doomed to extinction, due to environmental constraints. Adopting this analogy, the optimal solution to a given problem corresponds to the "fittest" individuals. A simple and general genetic algorithm has the flow chart depicted in figure 10. The variables involved in the optimization must be codified in particular structures, similar to that of a chromosome. By adopting a classical approach, parameters can be translated into binary strings of a fixed length that will be manipulated by appropriate operators to reach the global minimum. However, different codification can be used. The function that assigns a fitness value to each string is strictly correlated with the optimization problem considered: a high fitness value is assigned to those strings that evolve toward an optimal condition. The strings will be chosen for reproduction probabilistically, according to their fitness, and the genetic operators are applied to selected strings with a fixed probability.
As remarked in most of literature [1] [2] [3], Genetic Algorithms provide excellent results because they avoid the problem of local minima during optimization steps. However their use could be in some cases computationally heavy, limiting this powerful tool in online application and in hardware realization.

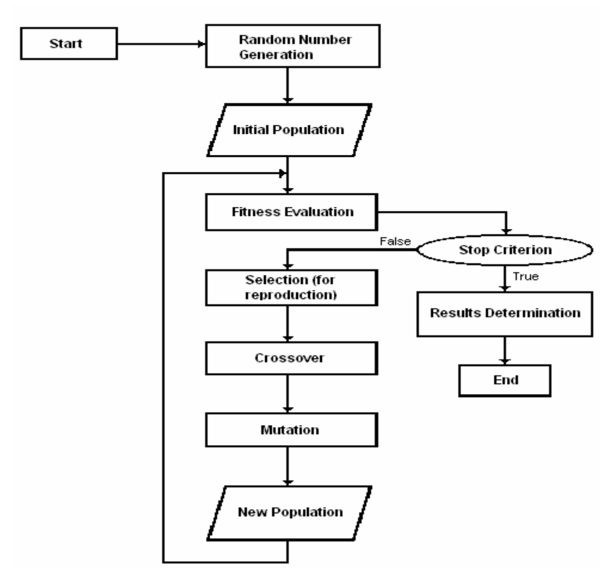


Figure 10: The flow chart of a simple Genetic Algorithm.

7 Simulation results

To provide a user-friendly application, for optimizing the algorithm, it has been used a GUI (Graphical User Interface). It's a graphic MATLAB® interface allow an efficient, complete and exhaustive view about the evolution of GA.

GUI is showed in the following figure 11. On the left side it is plotted the output with respect to the target, while on the right side it is plotted the control variable. Target is chosen in order to represent the dynamic response of a good performance motor vehicle. After only thirty generation, the output is able to follow the target very well. Optimal parameter obtained by GA for PID regulator, has been applied to the control system seen in the third paragraph. In particular has been simulated a mixed driving path, which give several travel condition with braking, stopping and restarting for about five minutes.

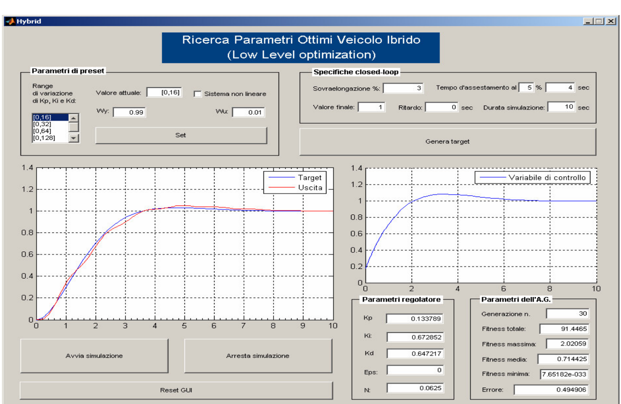


Figure 11: 30th generation

In the following figures, the simulation shows the test driving path in hybrid mode without and with air conditioned respectively. It has been analyzed the speed profile of vehicle and the idle-off running of internal combustion engine.

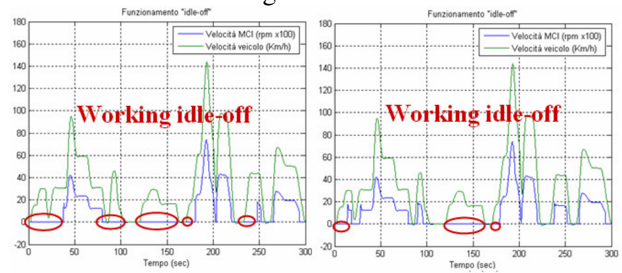


Figure 12: Hybrid mode with and without air conditioned.

Now it can be compared the result obtained with the control system and that one obtained without the control system. An important remark can be done regarding the speed of vehicle: when the control system is active, no oscillations are observed during accelerations.

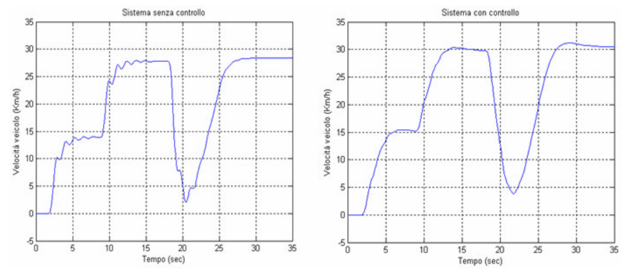


Figure 13: a) Speed without control: irregular accelerations; b) Speed with control: regular accelerations, no oscillations.

Also SOC (State Of Charge) takes advantage from control, especially in "only electric" mode because battery recharging can occur only for regenerative braking. Following figure shows the differences of SOC for a system without and with the control system respectively.

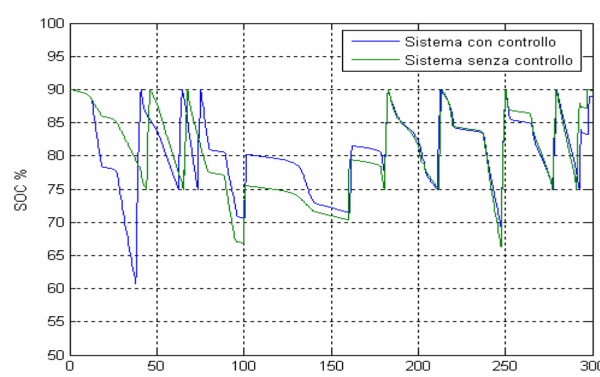


Figure 14: SOC evolution without the control system (green line) and when the control system acts (blue line).

8 Conclusions

The proposed control on the hybrid vehicle is typified by a great working regularity during acceleration and sudden variations of operation conditions. It is also able to improve driving pleasure, comfort and life of transmission mechanism. Average SOC results to be greater in high load conditions than in “electric only” mode. In the performed tests, the genetic algorithm was able to optimize, with excellent results, the objective (fitness) function, perfectly avoiding local maxima. Obtained results put in evidence the efficacy of the genetic optimization, the speed and the relative low computational cost of GA if adopted as the “refinement” part of a multilevel optimization.

9 Future developments

From some recent results of hardware implementation of Genetic Algorithm, it should be possible an on-line evaluation of the optimal parameters as soon as the working conditions change, being these computation times ten or more times lower than those involved in the vehicle dynamics. The vehicle autonomy in “electric only” mode could be increased with use of solar panels on the vehicle surface. The internal combustion engine (ICE) could be kept in temperature, also when it is not used, with some electric resistances, so avoiding its “cold-work” use, providing also a lowering of harmful emissions. A further improvement could be the possibility to switch in some working conditions (i.e. motorway travel at a constant speed), from “series-parallel” to “parallel” configuration, inserting an electromagnetic clutch between ICE and generator allowing them to work independently.

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