Model Predictive Control for Power Management in Hybrid Fuel Cell Vehicles

Carlos Bordons, Miguel A. Ridao, Antonio Pérez, Alicia Arce and David Marcos

Abstract— **Fuel Cell Hybrid Electric Vehicles (FCHEV) are being investigated in many research and development programs motivated by the urgent need for more fuel-efficient vehicles that produce fewer harmful emissions. Hybridization can greatly benefit fuel cell technology. There are many potential advantages such as the improvement of transient power demand, the ability of regenerative braking and the opportunities for optimization of the vehicle efficiency. The coordination among the various power sources requires a high level of control in the vehicle.**

This work presents a control system that fulfils the power demanded by the electric motor making use of two power sources: a primary source (fuel cell) and a battery pack. Both power sources, independently or together, supply power to the vehicle in order to satisfy driver's demand.

The real-time control computes the power distribution between the primary energy source and its associated Energy Storage System (ESS) to optimize the global hydrogen consumption while maintaining drivability. The coordination between the various power sources requires a high level of control in the vehicle. Model Predictive Control (MPC) is used in order to minimize the overall energy use in the presence of several constraints that appear due to drivability requirements and the characteristic of the components.

The proposed control strategy has been tested on a simulated model of a SUV (Sport Utility Vehicle), showing that a good control strategy can fulfil the power requested by the driver with the minimum fuel consumption.

I. Introduction

The development of a free-emission vehicle is the objectives of Hercules Project as detailed in [4]. It is a demonstration project that implies the development and integration of technology throughout the hydrogen value chain, including renewable hydrogen production, distribution and supply of hydrogen as vehicle fuel and finally, the design, development and test of a fuel cell car prototype. Hercules Project uses photovoltaic panels to generate electrical energy, which will be used in a electrolyzer for the production of renewable hydrogen. A refueling station to supply the electrical vehicle with hydrogen will be installed. This paper is focused on the hybrid fuel cell vehicle developed in Hercules Project and specifically in the power management control system.

The goal of a hybrid vehicle power management is to control the power flow accordingly to control objectives, usually related to fuel consumption minimization, taking into account other aspects, as the final state of charge of batteries or driving comfort, while satisfying operating constraints, ensuring that variables as engine torque and speed, state of charge, etc., are within their limits. Many different approaches have been used to implement power management strategies for hybrid electric vehicles [7].

Most of the practical controllers in real vehicles are heuristic rules based [9], [11], [15], [16]. These strategies are based on the requested drive torque and on the vehicle speed. Most of these approaches try to maintain the state of charge of the batteries between an upper and a lower limit. An algorithm for a hybrid vehicle with combustion engine, trying to operate the engine in the highest efficiency range is presented in [12]. The main advantage of these controllers is that they are intuitive and easy to implement but they present a limited robustness.

Some other approaches are based on optimal or suboptimal control strategies. A method to define and calculate an equivalence factor that weighs the fuel energy with the electrical energy is presented in [13], [7]. Then, the cost function is defined taking into account the fuel energy and the fuel equivalent of the electrical energy. This strategy is called Equivalent Consumption Minimization Strategy (ECMS). The main problem in this approach is the computation of the equivalence factors, because they are different in the battery charge and discharge phases and depend on energy conversion efficiencies. Adaptive approaches, where the equivalence factors are computed during the real time operation are presented in [8] and [10]. Also, the T-ECMS [14] approach estimated continuously the control parameters on-board by using data from the static features of the route and from a telemetry system.

Recently, Model Predictive Control (MPC) [6] is appearing as a practical alternative for power management method in hybrid vehicles. Different applications can be found in [17], [5], [3]. A hybrid MPC strategy has been proposed for the Hercules project in [2] with the objective of preserving battery lifetime by imposing charging and discharging strategies.

This paper presents a multivariable MPC approach for power management in Hercules hybrid fuel cell vehicle that will minimize hydrogen consumption and will keep the state of charge of the battery around a desired level. The strategy is compared with two common approaches: a heuristic algorithm and the ECMS method.

II. Hercules vehicle description

A scheme of Hercules vehicle is shown in fig 1. Two energy systems, the fuel cell and lithium-ion batteries, feed an electrical motor through DC/DC converters to connect the

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Fig. 1. Scheme of the hybrid vehicle

The main subsystems of the Hercules vehicle and its characteristics are:

- **Polymeric Electrolyte Membrane fuel cell**: Nuvera with a maximum peak power of 56 kW.
- **Lithium-ion Batteries:** Four modules in series of 13 Li-ion 3.7 V Kokam SLPB cells in series.
- **Permanent Magnet Synchronous Motor (PMSM):** The nominal motor power is 66 kW and the maximum torque is 460 Nm.
- **Hydrogen tank:** The vehicle autonomy requirement is 100 km which is equivalent to 2.4 kg of hydrogen. Three tanks at a pressure of 350 bar.

A model of the system has been used to simulate the vehicle performance under control. This model comprises 2 sub-models, called vehicle model and energy generation system model.

The objective of the vehicle submodel is to obtain the power demanded by the electric motor to achieve a certain pre-specified driving cycle. This submodel is not required for the control design but is necessary to calculate the motor power demand which the power management control must satisfy to achieve the desired driving cycle. Its inputs are the speed, acceleration and road slope profiles and its output is the motor power demand. The speed profile depends on the driving pattern, for instance urban or highway patterns. The quasi-static models presented in [7] have been used to obtain the vehicle energy losses, motor torques and motor angular speeds from driving cycle data. The following model of the motor calculates its power demand profiles from the motor torque and motor angular speed data contemplating different power losses, considering that the motor power demand can be negative in the generator mode (regenerative braking) or positive in the motor mode.

III. CONTROL STRATEGY

The objective of the control strategy is to compute the power that must be supplied by each power source (fuel cell and battery) to fulfil the mechanical power demanded by the driver while the operational constraints are fulfilled. The control actions are computed in real time solving a multivariable Model Predictive Control (MPC) problem that will minimize fuel consumption and will keep the state of charge of the battery at the desired level.

MPC is a well-known control strategy [6] which has already been applied to hybrid vehicles, as presented in the introduction. In this case, the plant to be controlled is depicted in figure 2 which has the following variables:

- Manipulated variables:
  - u_1: Power demanded to the fuel cell P_{FC}
  - u_2: Power demanded to the battery P_B (which will be negative if the battery is being charged)
  - u_3: Braking power that cannot be stored in the battery and must be dissipated, P_D.
- Controlled variables:
  - y_1: Mechanical power developed by the electric motor P_M
  - y_2: State of charge of the battery (SOC).

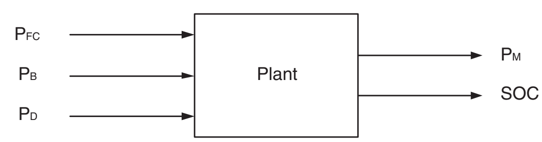

Fig. 2. System inputs/outputs

The model that is used by the controller is a very simple one. The evolution of the battery state of charge is modeled as an integration using the following equation:

$$\text{SOC}(t+1) = \text{SOC}(t) - 2.8797 \times 10^{-8} P_B(t)$$

and the electric motor is modeled as a first order system.

As stated before, the control actions must be computed taking into account the operational constraints of the fuel cell and the battery. The fuel cell has a maximum power of 56 kW with a slew-rate of 7 kW per second. Notice that this last constraint is included for operating reasons, since this prevents the degradation of the fuel cell, therefore increasing its lifetime. The current of the battery also has limits: it must be kept under 30 A during charge and under 200 A during discharge. The state of charge must also be kept into the operating range, which is set between 0.2 and 0.8.

Therefore, the control problem can be formulated as the minimization of a cost function along a certain future horizon, while fulfilling operational constraints. That is:

$$\min\ J = \sum_{i=1}^{i=N_2} \rho_1 [P_M(t+i) - w_1(t+i)]^2$$
$$+\rho_2[\text{SOC}(t+i) - w_2(t+i)]^2$$
$$+ \sum_{i=1}^{i=N_u} \lambda_1 P_{FC}(t+i)^2 + \lambda_2 P_B(t+i)^2 + \lambda_3 P_D(t+i)^2$$
$$+\lambda_4 \triangle P_{FC}(t+i)^2 + \lambda_5 \triangle P_B(t+i)^2$$
$$\text{subject to :}$$
$$4000 \leq P_{FC}(t) \leq 56000$$
$$-4171 \leq P_B(t) \leq 27808$$
$$-7000 \leq \triangle P_{FC}(t) \leq 7000$$
$$0.2 \leq \text{SOC}(t) \leq 0.8$$

Notice that the increments of the manipulated variables are also included in the cost function in order to avoid sudden changes of the power demanded to the power sources, which could reduce their lifetimes. w_1 and w_2 are the setpoint for demanded power and SOC respectively. The setpoint for the demanded power is not known, so it is considered constant along the prediction horizon. Notice that the performance could be improved if this value was known in advance; this is not the case in general but the extended use of GPS (Global Positioning System) and GIS (Geographical Information System) will lead in a near future to the knowledge of the power that will be demanded to the vehicle once the trip is fixed.

A lower limit in the power demanded to the fuel cell has been set to 4 kW in order to avoid operating regimes with very low performance. However, if the controller detects that the fuel cell is supplying low power for a certain time and the battery is full, it switches off the fuel cell in order to avoid wasting energy on the auxiliary equipment and to preserve the fuel cell lifetime. Once the fuel cell has been switched off, the control strategy avoids a new start-up until a fixed time (600 seconds) has elapsed, in order to avoid frequent start-ups and close-downs which could damage the fuel cell.

The weighting factors ρ_i and λ_i have been chosen using heuristic criteria. Note that the ratio between λ_1 and λ_2, which represents the relative cost between the energy supplied by the fuel cell and the energy supplied by the battery could be obtained from a deeper study of the system, as done in the ECMS method already presented in the introduction.

The values for the weighting factors that have been used are shown in table I (notice that the variables have different ranges: the SOC is between 0 and 1 and the powers are in the range of 10^4). The prediction horizon has been chosen as $N_2 = 100$, the control horizon $N_u = 10$ and the sampling time is 50 ms.

IV. Simulation results

In this section some results obtained when using the proposed MPC strategy are presented. Although the controller uses a very simple model of the system, the simulation is run on the complete model presented in section 2 and shown in figure **??**. The simulations show the behaviour of the control system in different situations.

TABLE I
COST FUNCTION WEIGHTS

ρ_1	10^3
ρ_2	4×10^7
λ_1	5
λ_2	0.2
λ_3	70
λ_4	500
λ_5	1

The objective of the first experiment is to track the New European Driving Cycle (NEDC), see figure 3. The driving cycle sets the evolution of the vehicle speed, which must be translated to mechanical power using the quasi-static model previously described (see figure **??**).

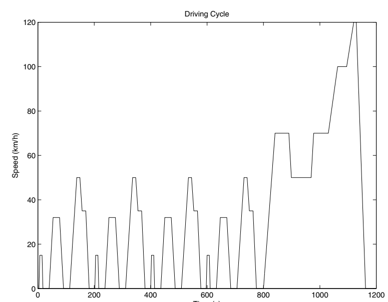

Fig. 3. New European Driving Cycle

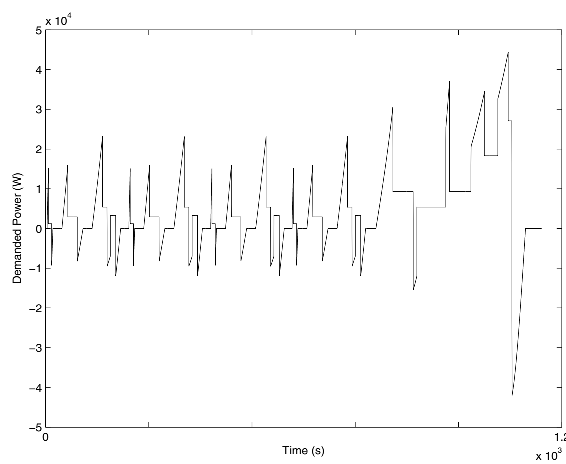

Fig. 4. Demanded Power

The simulation starts with a SOC of 0.4 and 2.4 kg of H_2 in the tank and lasts 20 minutes. The power that must be supplied in order to track the demanded power corresponding to the driving cycle, that is, reference ω_1 in the cost function is shown in figure 4. Figure 5 shows the distribution of demanded power between the battery and the fuel cell in order to fulfill the demand. The first part of the cycle corresponds to a urban cycle, where batteries are being charged thanks to the excess power supplied by the fuel cell and to regenerative braking. The controller is softly moving the SOC to the desired value of 0.5, see figure 6.

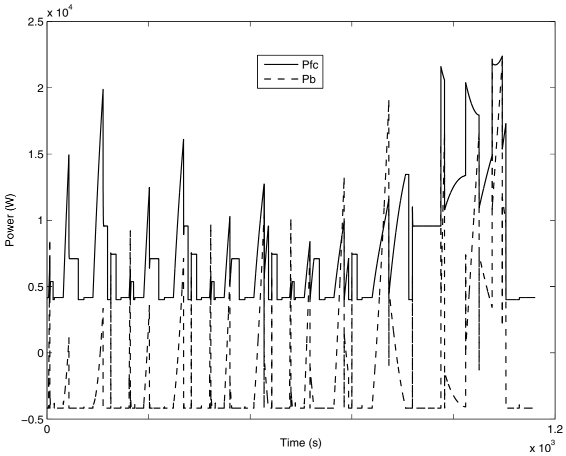

Fig. 5. Power distribution

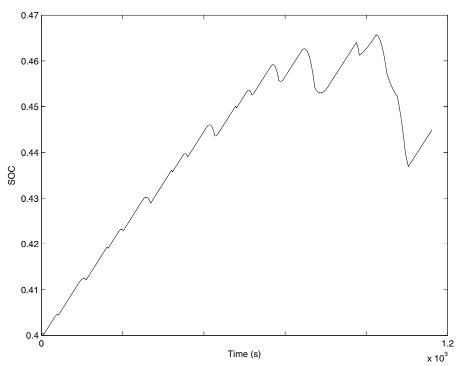

Fig. 6. Battery State of Charge

Around $t = 800$ seconds (extra-urban part of the cycle) the battery supplies more power due to two reasons: the fuel cell cannot supply more than 7 kW per second and, since the battery is close to its setpoint value, the controller decides to use part of the stored energy in order to reduce hydrogen consumption. Notice that the constraints are fulfilled (slew-rate of the fuel cell lower than 7 kW per second and battery current between -30 and 200 A). Besides, since the increments in the power delivered by the fuel cell are penalized, its evolution is smooth, preventing internal damages. The peaks in the demanded power are supplied mainly by the battery. Several experiments can be done changing the initial value of the SOC. If this value is high, the controller decides to use the energy stored in the battery until it is not enough to supply the demand.

The next experiment shows the response to a highway driving cycle (figure 7). This driving cycle presents some high accelerations, which make the fuel cell unfeasible to deliver all the requested power due to the slew-rate constraint. The battery injects all the power it is allowed to deliver (200 A), see figure 8.

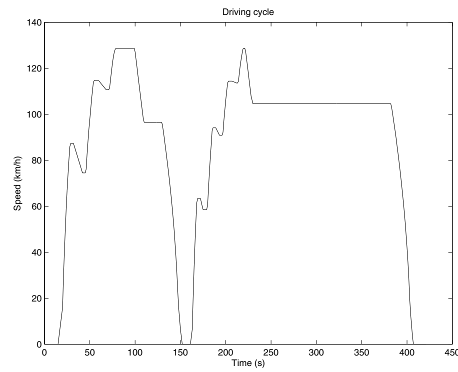

Fig. 7. Highway driving cycle

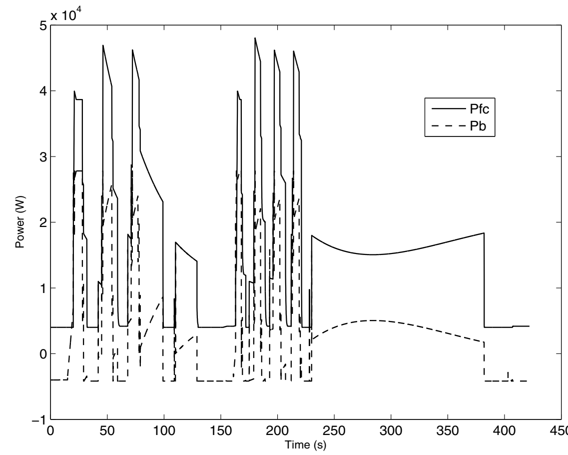

Fig. 8. Power management

A third experiment was done in order to stress on the system performance in urban mode with the battery initially highly charged, SOC $= 0.8$, and using the NEDC of figure 3 again. It can be seen in figure 9 that the fuel cell is switched off initially and all the demanded power is supplied by the batteries. Although the restart time is 600 s, the fuel cell is not restarted at that instant since the SOC is still high and the battery is able to supply all the demanded power. Only at $t = 960$, when the SOC is around 0.7, the fuel cell supply is needed and consequently it is switched on.

Notice that, in case that the driver needed extra power before the restart time had elapsed (for instance if going out of the city and therefore changing from urban mode to highway mode), the controller will relax that constraint and will switch the fuel cell on if necessary.

V. Comparison with other strategies

In this section, the proposed MPC strategy is compared with respect to other strategies used in hybrid vehicles: a heuristic controller based on experience and the ECMS

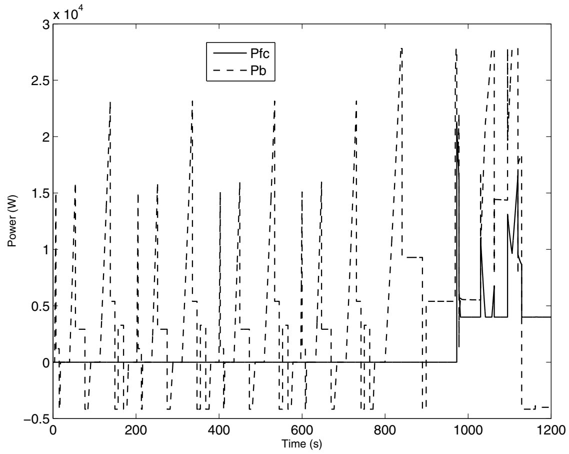

Fig. 9. Battery initially charged

method already mentioned in the introduction. The performance is compared in terms of fuel consumption, taking into account the final state of charge too. Also the computation times are considered.

The heuristic control strategy objective [1] is to track motor power demand and to keep the battery state of charge into a range near 0.5. This controller distinguishes three vehicle modes which are referred to as traction, braking and coasting modes. Moreover, seventeen states are taken totally into consideration; twelve for traction mode, three for braking mode and two for coasting mode. This controller does not take into account some operational constraints as the maximum power and slew-rate of the fuel cell and the maximum currents in the battery, so its results are not fully applicable.

The performance of the three experiments described in the previous section is analyzed in terms of fuel consumption for each control strategy. Notice that, although the initial condition is the same for the three controllers, the final SOC is different for each one (see table II). Notice that this final value is an indicative of the remaining energy at the end of the test, so it is closely related to the total fuel consumption in the experiment.

TABLE II
FINAL STATE OF CHARGE

	ECMS	MPC	Heuristic
Test 1	0.4689	0.3855	0.5083
Test 2	0.4798	0.4562	0.5045
Test 3	0.6312	0.6423	0.6491

The fuel consumption in terms of kg of hydrogen is presented in table III. The result obtained by the MPC is similar (and better in 2 of the 3 cases) to that of the ECMS. The heuristic strategy is the worst since it has not been designed to minimize fuel consumption.

In order to make a better comparison, both fuel consumption and final SOC are combined in the computation of the equivalent fuel consumption, which is the sum of the fuel that is actually consumed during the experiment and the remaining energy in the battery (translated to kg of hydrogen). This remaining energy can be positive (in the case that the final SOC is higher than the initial one) or negative. The fuel required to generate this energy is computed considering that the energy contained in a kg of hydrogen is 120 MJ (lower heating value) and that the fuel cell efficiency is 50 %.

TABLE III
HYDROGEN CONSUMPTION (KG)

	ECMS	MPC	Heuristic
Test 1	0.245	0.178	0.261
Test 2	0.183	0.169	0.215
Test 3	0.0272	0.0357	0.0417

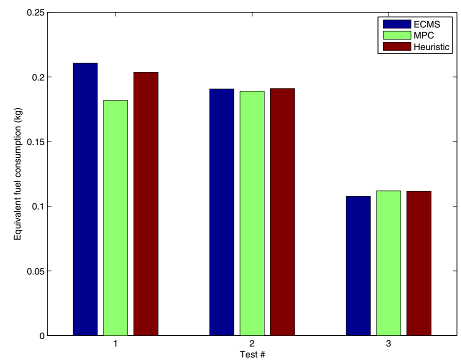

Fig. 10. Equivalent fuel consumption

From figure 10 it can be seen that the equivalent fuel consumption of the MPC is the lowest one in 2 out of the 3 cases (in the other case ECMS is the best one) following the trend of the fuel consumption (table III), since the contribution of the energy stored in the battery is small. This comparison just shows that the performance of MPC on the Hercules vehicle can be similar to that obtained with ECMS, the results depend on the experiment and also on the tuning parameters.

All the simulations are run using Simulink on a desktop PC so the absolute times are not representative of the computation time needed by a real-time controller, but its relative values are of great interest. Table IV shows the average computation times of the controllers, measured from the previous experiments and expressed in milliseconds.

TABLE IV
COMPUTATION TIMES (MS)

ECMS	MPC	Heuristic
19.67	2.79	0.84

As expected, the heuristic control law is the fastest one since it it does not involve any optimization. The ECMS algorithm involves the solution of a LP program, that has been addressed using the *linprog* Matlab function and seems to have a longer computational burden. The MPC uses the *quadprog* function and its computation time could be reduced if an explicit solution were used. It is clear that the computation times of the three algorithms can be reduced if other software packages are used, but anyway in all cases the times are smaller than the sampling time (50 ms), which would allow the real time implementation of all the strategies.

VI. Conclusions

This paper has shown an MPC strategy that has been tested on a simulated model of a fuel cell hybrid vehicle, showing that it can fulfil the power requested by the driver while minimizing fuel consumption and satisfying operational constraints. The controller uses a very simple model of the plant and provides results similar to other methods such as ECMS, specifically designed for vehicles.

There are still many open topics with respect to this control strategy. The choice of the optimum SOC setpoint and the weighting factors in the cost function are crucial, since they define the problem to be minimized. The methodology can be improved with future knowledge of the driving cycle, as the inclusion of GPS and GIS measurements of a scheduled route or information about the driving style (urban or highway modes), opening a field of new chances at a reasonable cost.

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