# Power Management Solutions for Hybrid Electric Vehicles

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***Abstract*— This paper describes three control strategies for a hybrid electric vehicle, in order to reduce the fuel consumption, and to maintain a reasonable state of charge (SOC) of the battery at the end of the drive cycles. The main goal is to split the requested power from the driver between the internal combustion engine (ICE), and the electric motor (EM), such way to decrease the fuel consumption, and to maintain the dynamic performances. The algorithms were tested using Matlab Simulink and ADVISOR interface. All three strategies are applied to a parallel hybrid power train. The first solution is an original rule-based strategy with the electric motor as a primary power source. The second one is a distributed control strategy for a hybrid electric vehicle. The vehicle is built from control nodes, every one of them having the same priority. The control laws are based on the dc-bus signaling. Every source of power (control node) is entering or leaving the network (dc-bus) depending on the voltage thresholds. The last one is a control strategy for hybrid electric vehicles based on the dynamic programming. Using the fuel converter (FC) fuel map, and SOC of the battery pack, it was designed an algorithm that will choose at each moment the required torque and speed from the first and second source of power.**

***Keywords— Energy system management, Hybrid electric vehicle, Hybrid power integration***

## I. INTRODUCTION

A typical hybrid electric vehicle (HEV) power train has an internal combustion engine with a fuel tank and an electric motor (EM) with its associated energy storage devices such as batteries and/or ultra capacitors. The coordination and the control strategy for the energy components have significant influences on vehicle dynamic performance, fuel economy, and emissions [1]-[5]. In HEV designing configuration, the commonly constraints are: vehicle range, acceleration, maximum speed, and road grades. All these factors are directly related to driving patterns. The required specifications in HEV design are usually divided into two categories. The first depends on consumer's demand such as acceleration performance, maximum speed and fuel economy. The second category is based on ecological issues such as vehicle emissions. There are three major types of hybrid systems that are being used in the hybrid vehicles market as: series, parallel and series-parallel hybrid types. The control unit should maintain the SOC between some limits, to keep the battery in long life, and high power. The U.S. Environmental Protection Agency has historically measured vehicle fuel economy using standard driving cycles such as the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET). The drive cycle data for this study was obtained using the National Renewable Energy Laboratory's (NREL) vehicle level simulation software. ADVISOR was used to evaluate and compare the simulated performance of the hybrid electric vehicle, on different drive cycles using different strategies [6].

In the first power management solution proposed for parallel configuration, the internal combustion engine can assist the EM during times of high power demand, according to the control strategy, if first is sized with less power than the second one. Energy storage system (ESS) and the electric motor are capable of providing all of the vehicle's power demands. A vehicle can meet its performance requirements with minimum power rating if the power train operates mostly in constant power. In its normal operation mode, the EM can provide constant rated torque up to its base or rated speed. The operation beyond the rated speed, up to the maximum speed, is limited to this constant-power region. The range of this constant-power operation depends on the particular motor type and its control strategy.

Another solution describes a hybrid power system controlled from three control nodes like fuel converter, energy storage system, and super capacitors. To maximize the use of rechargeable sources the control algorithms must be in a distributed fashion. This control maintains the reliability inherent in the structure of the system by using the dc-bus itself as the communication link. DC-bus signaling is an extension of the concept of using charge/discharge thresholds to schedule individual sources to join or leave the bus. The goal of scheduling the sources is achieved, using the source interface converters dependent on the bus voltage [7]. These voltage changes are used by sources and interface converters to determine their operation point.

The third control strategy based on dynamic programming with the aim of reducing fuel consumption and exhaust emissions. The efficiency of an engine varies with speed and power output. The intention is to run the vehicle at the maximum possible efficiency. If there is an extra energy, it is

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wise to save it in batteries, and if it is needed more power to the wheels, to be granted by the EM and ESS. Specific Fuel Consumption (SFC) is the rate of fuel consumed divided by the power produced. Efficiency is inversely proportional to the SFC. The IC engine is switched off if power demanded is less than a certain efficiency limit.

## II. A Rule- Based Strategy for Energy Management in HEV

Several approaches and methods have been reported to optimize HEV component sizes and control strategy parameters, with the aim of simultaneously reducing FC and exhaust emissions [4], [8]. In most of the recent studies, the conflicted optimization targets such as FC and exhaust emissions are aggregated into a multi objective function [9], [10].

A parallel hybrid power train is used in this paper, where two mechanical powers are added together in a mechanical coupler. The control strategy of a parallel HEV is responsible for distributing the driver's required torque between the IC engine and electric motor. The IC engine is the primary power plant, and the batteries and the electric motor drive constitute the energy bumper. Both IC engine and EM may deliver power to the vehicle wheels. In addition, the EM may also be used as a generator to charge the battery by either regenerative braking or absorbing the excess power from the engine when its output is greater than the output required to drive the wheels. In order to reduce the fuel consumption, less torque was required from the ICE in the control strategy, and more torque required from EM. In ADVISOR the cumulative fuel use (CFU) is calculated as:

$$CFU=1/r*61.02/231*x*1/s \tag{1}$$

where $r$ is the fuel density (749), and $x$ is the fuel use (FU), measured in gal/s. 1/s means that the function is integrated.

$$FU=y*(0.1*pow((m-n)/(m-20), 0.65)+1) \tag{2}$$

where y is the hot fuel use (HFU), m is the engine coolant thermostat set temperature (96 Celsius), and n is the coolant temperature. HFU is obtained from a 2-D lookup table with the inputs arguments: *fc_map_spd* (speed map), and *fc_map_trq* (torque map). The torque available (T) from the ICE is calculated as below:

$$T=max(min[(Tr+Ei), maxt], Tcl)-Ei \tag{3}$$

where $Tr$ is the required torque, $Ei$ is the engine inertia, maxt is the maximum torque required, and $Tcl$, is the torque when the throttle is closed. In the torque coupler block built in Advisor, the needed power from the driver is divided between the requested power from the ICE and the requested power from the motor. The inputs in the torque coupler bloc are: torque and speed required, torque and speed available from the ICE, and torque and speed available from the EM. The outputs are torque and speed available at torque coupler, torque and speed required from ICE, and the required torque and speed from EM. Torque available at torque coupler (Ta) is the sum of the torque available from the ICE and EM, minus the losses.

$$Ta=Ti+Te*tc\_mc-L \tag{4}$$

where $Ti$ is the torque available from ICE, $Te$ is the available torque from EM , $tc\_mc$ is the constant ratio of speed at motor torque input to speed at engine torque input, and $L$ is the parameter according to the losses due to the friction force. Speed available at the torque coupler (Sa) is the minimum speed available of the ICE and EM:

$$Sa=min(Sf, Se/tc\_mc) \tag{5}$$

where $Sf$ is the speed available from the ice, $Se$ is the speed available from the EM.

The parameters used are: fuel converter with maximum power of 41 Kw, 25 modules of lead batteries with maximum power 25 Kw, and nominal voltage of 308 Volts, and a 75 Kw electric motor. Because the maximum power of the electric motor is almost double than the ICE, in the control strategy proposed, the electric machine is used as the primary source of power, and the mechanical machine is used to recharge batteries and to sustain the request of torque and speed as much as possible. If the required torque and speed is less than maximum torque and speed available from the EM, and the necessary power from the batteries is less than actual power, and SOC is greater than 0.64, or the requested torque is negative, then only the electric machine is used. In these conditions, the internal combustion engine is shut down. As long as the controller is using only the EM, the system is a zero emission vehicle.

The control strategy that it was used is illustrated in the Fig. 2. If SOC is below the low limit, and the required power is greater than the power available, then both ICE and EM are running together to overcome the need of torque and speed. A logic scheme of the control strategy is presented in Fig. 2.

The engine's ON/OFF condition is dependent on the SOC of Battery, power requested and vehicle speed [1]. Trq&Spd is the torque and speed required, Preq is the power required, Pa, is the available power, Tchg is the torque necessary to recharge the batteries, TaICE is the available torque from ICE, Trq&Spd a EM, is the available torque and speed from EM.

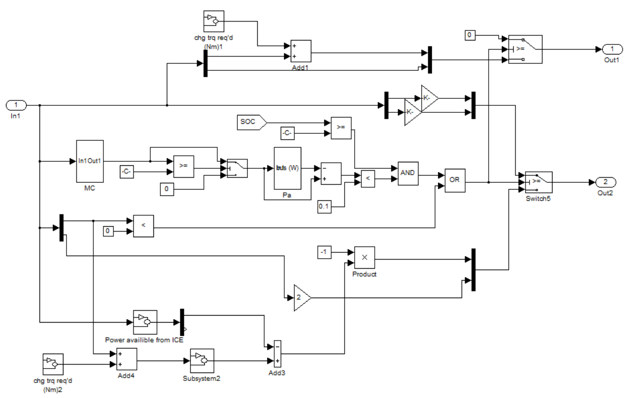


Fig. 1. Control Strategy in Torque Coupler

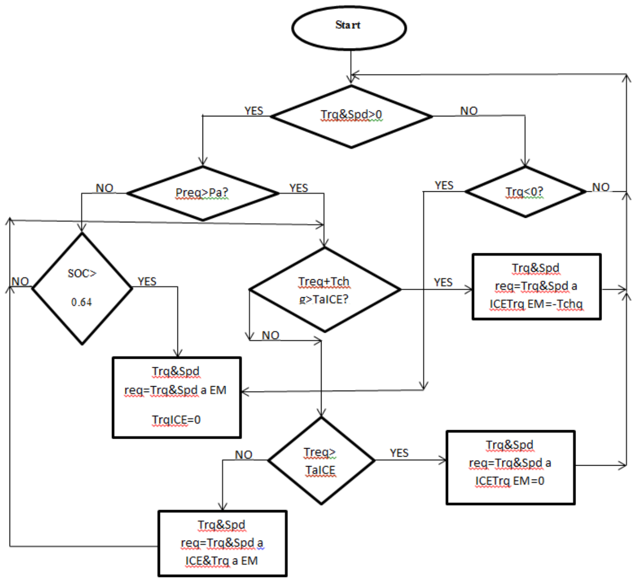


Fig. 2. Control strategy logic scheme

When the required torque is below 0, meaning that the vehicle is moving and the driver is no longer pressing the acceleration pedal, the ESS is charging. 0.64 is the lower limit of SOC, for keeping a long life of the batteries. When the current SOC is higher than its low limit $L_{SOC}$ and if the required speed is less than a certain value, the engine will turn off. This specific speed is called the electric launch speed $V_e$. If the required torque is less than a cutoff torque $F_{off} \times T_{max}$, the engine will also turn off. When the battery SOC is lower than its low limit, an additional torque $T_{chg}$ is required from the engine to charge the batteries like in the Fig. 3.

$$T_{chg}=cs\_chg\text{-}trq/(50*(1-SOC)*(cs\_hi\_soc-cs\_lo\_soc)) \quad (6)$$

where *cs_chg_trq is 15.2, cs_hi_soc* is 0.7, and *cs_lo_soc* is 0.65.

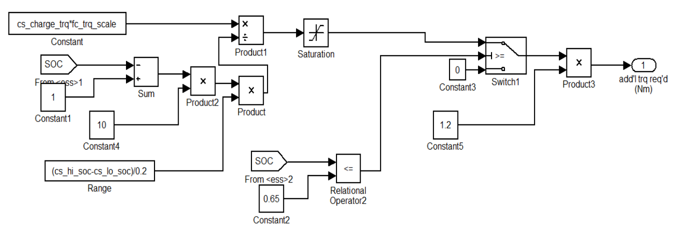


Fig. 3. Charge torque required

## III. Control Strategy using DC Bus Signaling

### A. Distributed Structure and Strategy

The power sources in a hybrid electric vehicle can be controlled in a centralized, decentralized or distributed manner. A distributed structure can be shown in Fig. 4. In Fig. 4, W+G are the wheels and the generator, E.S. 1 is the energy storage 1 (batteries), E.S. 2 is the energy storage 2 (supercapacitors), S.I. is the source interface, St.I. is the storage interface, L.I. is the load interface.

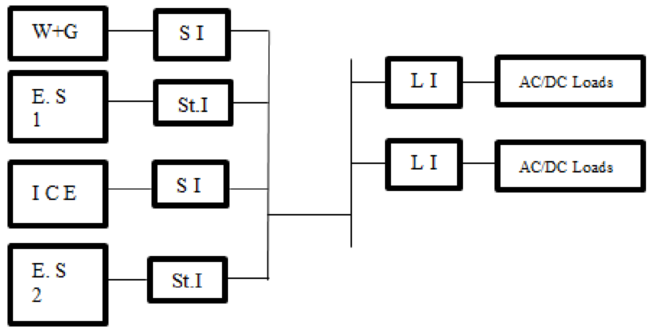


Fig. 4. Distributed structure in HEV

The strategy of distributed control has the advantage over the centralized one that the system using this kind of control can still function even if a node fails, and is not dependent on an external communication link. Since the communication between the source controllers is on the DC-bus (not on the external link), the sources are controlled only using terminal quantities. The control based on the voltage droops of the DC-bus has been proposed also to ensure high-priority loads in dc systems, and continuous supply of power even in overload conditions [11], [12]. The main difference between the proposed priority loads and distributed bus signaling (DBS) is that in DBS the DC-bus is used for scheduling the sources, not the loads. In the distributed strategy the source and storage interface converters are working independently, based on the voltage level of the bus. Each one has its own threshold for charging or discharging. Even if the automobile in discussion is not full electric, (it has a combustion engine as one of the sources), the control may be applied easily because the available torque and speed from this source can be converted into electric power. This way, all the components may be considered as electric nodes. First it was analyzed the behavior of voltage droops. It was used the conventional centralized control, in order to establish the thresholds for charging, discharging and stand-by of the sources. By default the batteries are on when the vehicle is starting. They are the primary source of energy. When the system is running the voltage on the bus will decrease because of the discharging of the batteries, and then the super capcitors will give power. The voltage range for discharging the second source of power (capacitors) is between 370 and 300 Volts. If the voltage droops under 300 Volts the internal combustion engine will interfere and supply the lack of energy.

### B. Implementation of Control Strategy in ADVISOR

The control strategy was built using Matlab Simulink blocs and ADVISOR. A parallel configuration was chosen in order to modify the controller, and the energy storage. It was added a pack of supercapacitors, which is useful in the moments when is needed a peek power for short time. The capacitors model with the controller that allows the connection to the dc-bus for charging or discharging are shown in Fig. 5.

Charging equation is given by:

$$\frac{dV_c(t)}{dt} = -\frac{1}{R \cdot C} V_c(t) + \frac{1}{R \cdot C} u(t) \qquad (7)$$

where $u(t)$ is the step size (source voltage).

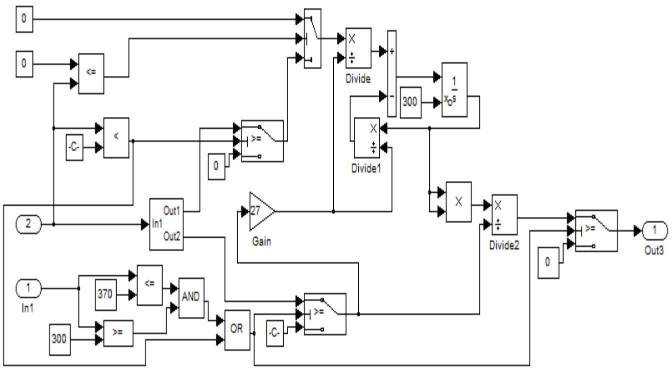


Fig. 5. Supercapacitors model together with the controller

The initial voltage of the supercapacitors is 300 V. First input is the dc-bus voltage, and the second one is the power required from energy storage. For simulating charging, the supercapacitors model was connected to the bus voltage, and for discharging 0 V as input. When this source of power is charging or discharging it was used as resistance the load, and when is disconnected from the bus, a great resistance it was used for very slow discharge. The renewable sources are charging when the requested power is negative, but not in the same time. The charging threshold for supercapacitors is -8000 W. When the power is between 0 and -8000, the batteries are charging. A control scheme of the supercapacitors is shown in Fig. 6.

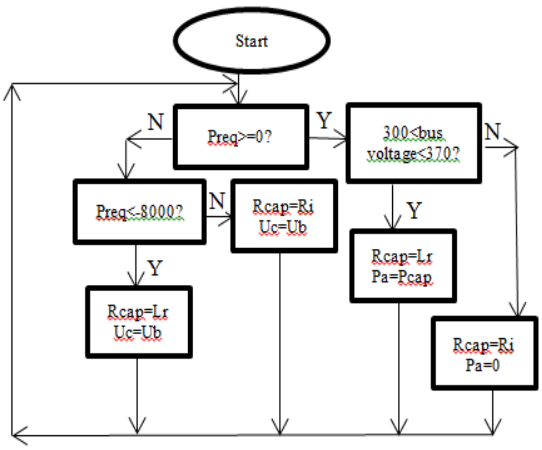


Fig. 6. Control scheme for supercapacitors

In Fig. 6, Preq is the required power, Pa is the available power from the capacitors pack, Rcap, is the load resistance of the model, that can be Lr (load resistance from the circuit), or Ri (infinite resistance, here is 156789-slow charge or discharge). Uc is the capacitors voltage, and Ub is the bus voltage. The capacitors are discharging on the load circuit if the bus voltage is between 370V and 300V, and power required is greater than 0. If the bus voltage is not in this range and power required is greater than 0, the capacitors are discharging on the internal resistance, and they are not releasing power. The same happens when the required power is between 0 and -8000 W. Charging cycle is when the voltage is also between the limits above but the required power is below -8000W. The voltage thresholds are for joining or leaving the network, and the power thresholds are for charging or discharging.

The second source of power is a pack of batteries that can give 300 V on the circuit. In the original model of ADVISOR the current across the batteries is $I_{bty}$ if $I_{bty} \geq I_{abs}$, and $I_{abs}$ otherwise:

$$I_{bty} = \frac{\left(V_{oc} \cdot \left(V_{oc}^{2} - 4R_{int} \cdot P_{bty}\right)^{5}\right)}{2R_{int}} \tag{8}$$

$$I_{abs} = \frac{V_{oc} - V_{\max}}{R_{\text{int}}} \tag{9}$$

where $V_{oc}$ is the pack open circuit voltage, and $P_{bty}$ is the limited output power. Voltage of the pack batteries is given by:

$$U = V_{oc} - I_{bty} \cdot R_{\text{int}} \tag{10}$$

where $V_{oc}$ is the energy storage open circuit obtained from a 2-D lookup table that has on x axis the temperature of the batteries pack, and on the y axis the SOC. State of charge of the batteries pack, is permanently monitored and it is calculated as below:

$$SOC = \frac{\max\_Ah\_capacity - Ah\_used}{\max\_Ah\_capacity} \tag{11}$$

where $\max\_Ah\_capacity$ is the maximum capacity of the ESS, in hour amps, and $Ah\_used$ is the used capacity.

The model from ADVISOR suffered several adjustments because of their controller shown in Fig.7. First input is the available power from the supercapacitors, and the second one is the total required power from the bus. Input one minus input two is the required power from the batteries pack. Every time the vehicle is running, it is preset to use electrical energy from the batteries. So this source of power is always on. The available power will decrease with the bus voltage, and when the minimum threshold is achieved, the supercapacitors will give power to the bus. Charging cycles are when the required power is between 0 and -8000 W. The available electrical power is the sum of the batteries power and supercapacitors power.

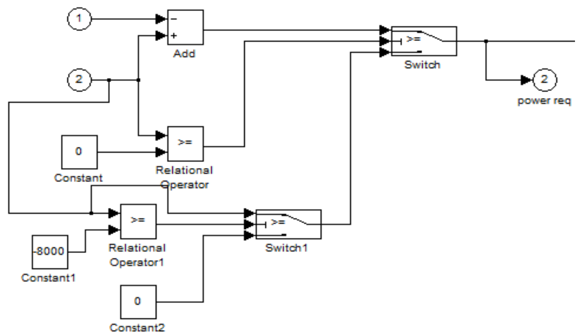


Fig. 7. Controller of the batteries

The available power of the ESS is:

$$P_a = U \cdot I_{bty} \tag{12}$$

The third source of power is not renewable and it is ICE. The torque available T from the ICE is calculated as:

$$T = \max\left[\min\left(\left(Tr + Ei\right), \max t\right), Tcl\right] \qquad (13)$$

where *Tr* is the required torque, *Ei* is the engine inertia, max t is the maximum torque required, and *Tcl*, is the torque when the throttle is closed. The original model was not modified but added the controller scheme shown in Fig. 8.

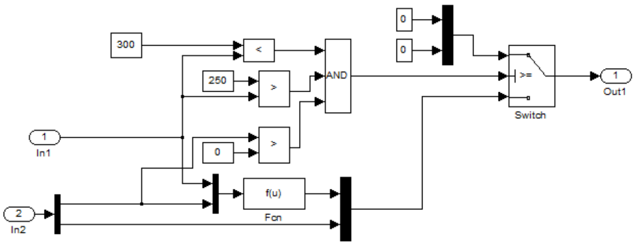


Fig. 8. ICE controller

The ICE is on only if the bus voltage droops under 300 V, and the required torque in the gearbox is greater than 0. When this source is on the required torque from it is calculated as it follows:

$$Treqe = \frac{Treq * (320 - Bv)}{50} \qquad (14)$$

where Treqe is the torque required from the engine, Treq is the torque required at the output of the gearbox, and Bv, is the bus voltage. The more voltage is dropping more torque is required from the ICE, to overfill the leak of power. The available power at the gearbox is the sum of available power from the electric motor, and the available power from the ICE.

## IV. CONTROL STRATEGY BASED ON DYNAMIC PROGRAMMING

When solving a problem by dynamic programming, the most important question is what are the subproblems. As long as they are chosen properly, it is an easy matter to write down the algorithm to solve iteratively one subproblem after the other, in order of increasing size. Unlikely the divide and conquer method, which consider all the subproblems to be independent, dynamic programming is applied when the subproblems are not independent. Dynamic programming saves each result in a table, avoiding duplicate solving of the same problem. This method is applied whenever it is wanted a quick result for an optimization problem. In fact, applying this technique is granting an optimal solution of the problem but may be not the only one.

The amount of time it takes to run a dynamic programming algorithm is easy to discern from the dag of subproblems: in many cases it is just the total number of edges in the dag. All we are really doing is visiting the nodes in linearized order, examining each node's in edges, and, most often, doing a constant amount of work per edge. By the end, each edge of the dag has been examined once. Suppose we know the largest independent sets for all subtrees below a certain node u; in other words, suppose we know I(w) for all descendants w of u.

To compute I(u) let split the computation into two cases: any independent set either includes u or it doesn't.

$$I(u) = \max\left\{1 + \sum_{grandchildren\_w\_of\_u} I(w), \sum_{children\_w\_of\_u} I(w)\right\} \qquad (15)$$

If the independent set includes u, then we get one point for it, but we aren't allowed to include the children of u; therefore we move on to the grandchildren. This is the first case in the formula. On the other hand, if we don't include u, then we don't get a point for it, but we can move on to its children.

The coordination between the powertrain and control strategy has significant impacts on the operating performance of HEVs. A methodology based on dynamic programming is presented achieve parameter optimization for both the powertrain and the control strategy, with the aim of reducing fuel consumption and exhaust emissions. The efficiency of an engine varies with speed and power output. Hence as a user we may want to run the vehicle at the maximum possible efficiency. As a solution to this, it is wanted to operate the engine where the efficiency is maximum. If there is an extra energy it is wise to save it in batteries, and if it is needed more power to the wheels, to be granted by the electric motor and energy storage system (ESS). The internal combustion engine, it is modeled as a 2D lookup table. The one that was chosen for the experiments (FC_SI41-emis), has a power of 41 Kw, and a peak efficiency of 0.34. The fuel consumption map it is shown in Fig. 9.

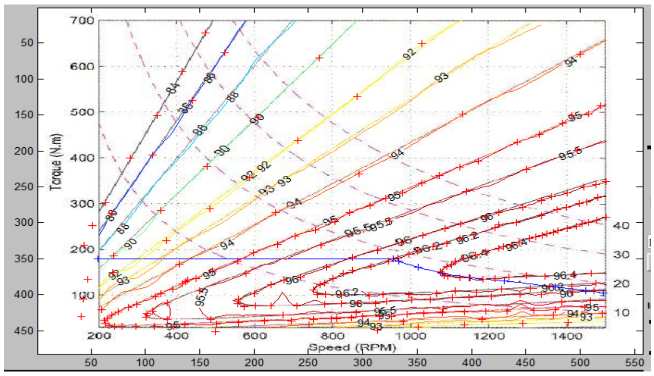


Fig. 9. ICE fuel map

All control schemes try to optimize fuel economy by exploiting the SFC v/s power variation. The IC engine is switched off if power demanded is less than a certain efficient limit. This limit can be decided statically or dynamically. Prior HEV control strategies have used a static approach to control the vehicle operation and they have typically focused on improving fuel economy rather than emissions. The approach presented here considers dynamic vehicle operating conditions that affect both fuel economy and emissions. For testing all the configurations it is used ADVISOR. This environment has a model for each component of a vehicle: wheel, drive shaft, gearbox, torque coupler, controller, internal combustion engine (ICE), electric motor, etc. All the components are connected through the torque and speed required link, and torque and speed available link. Block diagram of the system is shown in Fig. 10.

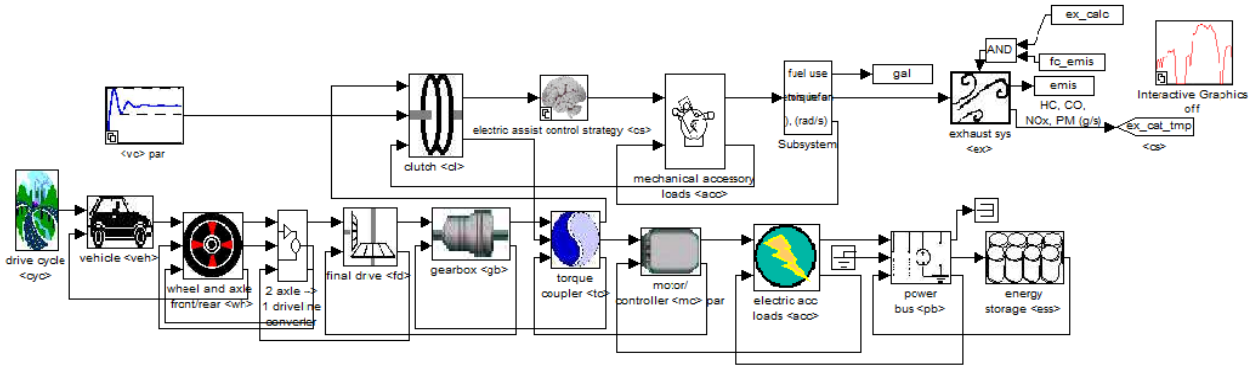


Fig. 10. Bloc diagram of the system

TABLE I
FC FUEL MAP (GAL/S)

| | speed | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 104.5000 | 0.1255 | 0.2510 | 0.3206 | 0.3531 | 0.3462 | 0.3915 | 0.4285 | 0.5072 | 0.5905 | 0.6564 | 0.7222 | 0.7880 |
| 2 | 149.2000 | 0.1912 | 0.2819 | 0.3752 | 0.4367 | 0.4638 | 0.5078 | 0.5834 | 0.6366 | 0.6821 | 1.0060 | 1.1068 | 1.2077 |
| 3 | 220.9000 | 0.1934 | 0.3867 | 0.5102 | 0.5843 | 0.6104 | 0.6995 | 0.7774 | 0.8444 | 1.0099 | 1.2614 | 1.5413 | 1.6817 |
| 4 | 292.5000 | 0.3863 | 0.6275 | 0.8292 | 0.9563 | 0.8277 | 0.9365 | 1.0256 | 1.0952 | 1.2827 | 1.4808 | 1.6481 | 2.1025 |
| 5 | 364.1000 | 0.4078 | 0.8155 | 1.0205 | 1.0822 | 1.0088 | 1.1473 | 1.2637 | 1.3589 | 1.5744 | 1.8000 | 2.2258 | 2.6559 |
| 6 | 435.7000 | 0.5497 | 0.8638 | 0.9422 | 1.1584 | 1.3180 | 1.4982 | 1.6493 | 1.7764 | 2.1469 | 2.5511 | 2.9876 | 3.2599 |
| 7 | 507.4000 | 0.6044 | 1.2088 | 1.5023 | 1.5760 | 1.4435 | 1.7419 | 2.0430 | 2.3238 | 2.7039 | 3.1038 | 3.4456 | 3.7597 |
| 8 | 552.2000 | 0.7285 | 1.0441 | 1.3411 | 1.6384 | 1.8498 | 2.1043 | 2.3877 | 2.6521 | 3.0765 | 3.5214 | 3.8185 | 4.1665 |
| 9 | 596.9000 | 0.8468 | 1.4382 | 1.7626 | 1.8391 | 2.2030 | 2.5473 | 2.8552 | 3.1292 | 3.2244 | 3.8244 | 4.2080 | 4.5915 |
| | | 6.8000 | 13.6000 | 20.4000 | 27.2000 | 33.8000 | 40.6000 | 47.4000 | 54.2000 | 61.0000 | 67.8000 | 74.6000 | 81.4000 |
| | | Torque | | | | | | | | | | | |

The internal combustion engine, it is modeled as a 2D lookup table. It has two vectors (torque and speed) as inputs, and as output the fuel consumption map shown in Table 1.

When the driver press the acceleration paddle due to the drive cycle requirements, a certain torque and speed is required. These parameters are transformed in each bloc (adding loses by friction, additional torque for auxiliary loads, etc.). With fuel consumption map of the engine, the goal is to ask from engine only the torque and speed correspondent to low fuel consumption region, even if the driver requirements are different. The difference from the required torque to wheel, and requested torque from the engine is asked from the EM. The controller who splits these parameters has to be sure that there is enough power in the batteries to support the requested power from the electric motor.

The idea is to calculate at each moment of time, a certain tolerance for torque, and a certain tolerance for speed, depending on the SOC. These tolerances are increasing if the SOC is increasing and otherwise. A high value of the torque tolerance is letting the controller to choose the lowest fuel consumption, meaning a certain torque and speed correspondent to this choice. Having enough energy inside the batteries pack the vehicle may run even all electric (no fuel use). If the SOC is decreasing the controller must choose higher and higher torque, meaning in most cases more fuel to use. The same is happening with the speed tolerance. In the proposed algorithm first is calculated the torque tolerance (trq_tol), and then the speed parameter (spd_tol), like below:

$$\begin{aligned} &trq\_tol = (SOC-0.5)*366 \\ &spd\_tol = (SOC-0.5)*17.925 \end{aligned} \tag{16}$$

The algorithm will chose the minimum torque from the fc_fuel_map, so the difference between required torque from the driver, and one of the listed values of torque from the matrix should not be more than the calculated tolerance:

$$trq\_req\text{-}fc\_fuel\_map[i,9] < trq\_tol \tag{17}$$

The same is happening with the speed:

$$spd\_req\text{-}fc\_fuel\_map[0,j] < trq\_tol \tag{18}$$

Usually the starting SOC is 0.7, and the minimum threshold for depleting is 0.5. Tuning parameters were chosen so the tolerance should increase or decrease such way that the algorithm may choose between maximum and minimum values of the fc_fuel map matrix.

The algorithm is listed below:

```
Int i, j;
float trq_req, trq_tol, spd_req, sod_tol;
i=9;
j=12;
fc_fuel_map=M[i,j];
i=1;
j=1;
flag=bool;
flag=0;
trq_tol = (SOC-0.5)*366;
```

```
spd_tol= (SOC-0.5)*17.925;

'Choose TRQ'
until flag{
       If (trq_req -M[i,9]> trq_tol
 then
       i++
 else
      flag=1
      TRQ=M[i,9]
      }

'Choose RPM'
until flag{
      If (spd_req-M[1,j]>spd_tol then
      j++
else
      flag=1
      Rpm=M[0,j]
      }

'Consuption verification
if M[i,j]>M[i+1,j] then{
       i++
       TRQ=M[i,9]
       }
if M[i,j]>M[i,j+1] then{
        j++
        Rpm=M[0,j]
        }
```

In the control strategy this algorithm is enabled if the torque required is positive (if negative then charging batteries) and torque tolerance is below 65. If it is higher then the vehicle may run all electric (no required torque nedeed).

## V. Experimental Results

For the rule-based strategy some fixed parameters are used in the parallel HEV [9]:

- rolling resistance coefficient: 0.009;
- aerodynamic drag coefficient: 0.335;
- vehicle front area: 2.0 m2;
- wheel radius: 0.282 m;
- cargo mass: 136 kg;
- gear ratio: 2.48, 3.77, 5.01, 5.57, and 13.45;
- efficiency of the gearbox: 95%;
- gearbox: five-speed manual gearbox;
- gear ratio: 2.48, 3.77, 5.01, 5.57, and 13.45;
- efficiency of the gearbox: 95%;

As the ICE, a Geo Metro 1.0 L SI engine with a maximum power output of 41 kW and a peak efficiency of 0.34 is used. In addition, as the electric motor, a Westinghouse ac induction motor with a maximum power output of 75 kW and a peak efficiency of 0.92 is used. In this paper, according to the charge and discharge resistance curve of the lead-acid battery the SOC target value $T_{SOC}$ is set to 0.65. Driving cycles are defined as test cycles that are used to standardize the evaluation of vehicle fuel economy and emissions.

Driving cycles are speed–time sequences that represent the traffic conditions and driving behavior in a specific area. In this paper, three cycles of NYCC, WVUINTER, and UDDS were used to evaluate the FC and exhaust emissions. During NYCC drive cycle, the vehicle stopped 18 times, had the maximum speed 44.58Km/h, and an average speed of 11,4km/h. The results were as follows: fuel consumption is 4,4 L/100Km and a remaining SOC of 0.6495 at the end of the drive cycle.

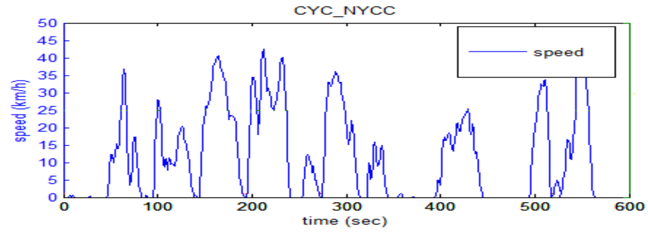


Fig. 11. Drive cycle NYCC

Using the standard control strategy under the same conditions, it was obtained a fuel consumption of 11.7L/100Km and a remaining SOC of 0.66. The difference in fuel consumption between the two control strategies is substantial.

Next test was made using the WVUINTER drive cycle.

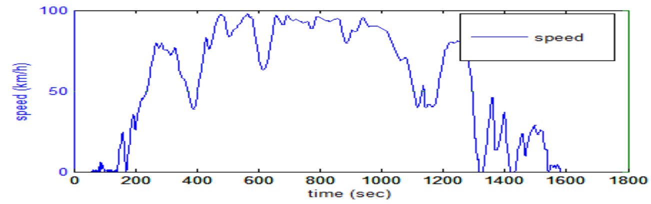


Fig. 12. Drive cycle WVUINTER

During this test (25 Km), the vehicle stopped 9 times, had a maximum speed of 97,74 Km/h, and a fuel consumption of 5.3L/100Km, and a remaining SOC of 0.6470. Under the same conditions, using the standard control strategy it was obtained a fuel consumption of 5,2L/100Km and a remaining SOC of 0.6159.

For the next test, it was considered the UDDS cycle (12 Km of urban traffic), where the vehicle had an average speed of 31Km/h, and a maximum speed of 91Km/h. The fuel consumption was 5.7 L/100Km, and the remaining SOC 0.64%. The obtained results using the standard strategy were as follows: fuel consumption 5.8 L/100Km, and a remaining SOC of 0.63.

The distributed control strategy was analysed in ADVISOR, for an urban cycle UDDS, like in Fig. 13.

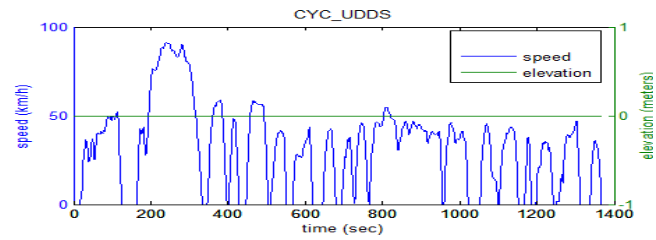


Fig. 13. CYC_UDDS drive cycle

It was chosen to test a parallel architecture with 41kw ICE, 25 modules of lead batteries (rated voltage: Vnom=308 volts), and a 75Kw electric motor. Because of the power difference between the two propulsion sources, it is obviously that the greater one (75 Kw electric motor) will be used mostly. After an UDDS cycle, meaning 12km of urban traffic in 1369 sec, (average speed 31,5km/h), and initial SOC of 0.7, it was obtained a fuel consumption of 5.8l/100Km, and a final SOC of 0.65 like in Fig.14.

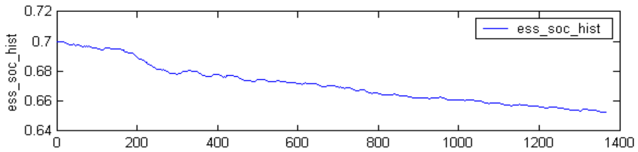


Fig. 14. Ess SOC history t(s)

For the second case it was used the distributed DBS control strategy and made a few adjustments, meaning that it was added 112 supercapacitors, each one rated with 2.7 V, weighting 0.5 Kg, and having a capacitance of 3000 F. The maximum current supported by each supercapacitor is 230 A. If they are connected in series they give a 300 V, and 26,78 F. This means an extra cargo mass of 50 Kg that was taken in account in the simulations. The results were satisfactory. The fuel consumption was 4.2L/100Km, and the remaining SOC was 0.58 like in Fig. 15.

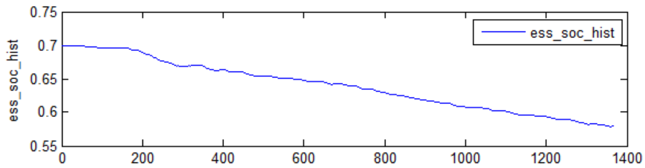


Fig. 15. Ess SOC history t(s)

In order to observe the performances of the vehicle in highway traffic, it was also made a test under a the CYC_WVUINTER drive cycle conditions. Most of the time, the speed is above 50 Km/h. The vehicle ran 25 Km, in 1640 s, with an average speed of 54 km/h. The results at the end of the test were satisfactory, because it was obtained the following results: fuel consumption of 3.9 L/100 Km, remaining SOC of 0.495.

The same test was made using the default strategy for parallel configuration (PTC_PAR), and the results were as follows: fuel consumption 5.2L/100Km, remaining SOC 0.6. In both cases the vehicle finished the test in good conditions, without any warnings.

The dynamic programming control strategy was also tested on an urban cycle CYC_UDDS with a lot of stops and starts and with few moments exceeding speed above 50km/h. We have chosen to test the same architecture as for the distributed control strategy. After an UDDS cycle, meaning 12km of urban traffic in 1369 sec, (average speed 31,5km/h), and initial SOC of 0.7, it was obtained the following results: fuel consumption of 3.9 L/100 Km, remaining SOC of 0.495. The same test was made using the default strategy for parallel configuration (PTC_PAR), and the results were as follows: fuel consumption 5.2L/100Km, remaining SOC 0.6.

## VI. CONCLUSIONS

In this paper it was presented a rule based control strategy for parallel HEV, where the EM was used most in the control strategy, with the restriction of maintaining a reasonable state of charge in the batteries. The tests showed the biggest consumption difference of fuel was obtained in the NYCC drive cycle. In this drive cycle, the vehicle had a lot of stops and goes, and it matches perfectly with the real urban traffic in the hardest conditions. The fuel consumption was more than satisfactory, and the remaining SOC also.

DBS strategy is possible by controlling each source and storage interface to act as a voltage source with a constant power limit. The dc-bus has the role of a communication link between the sources, allowing a system control law to be implemented through a local controler of each node. Experimental results with this control strategy shown a visible improuvement in fuel consumption 1.6 L/100Km in urban traffic, and 1.3L/100Km in highway traffic. The difference between the final state of charge at the end of the drive cycles is small, but may be taken in account (10%).

Dynamic programming is an optimization approach that transforms a complex problem into a sequence of simpler problems; its essential characteristic is the multistage nature of the optimization procedure. Dynamic programming has been proved as a useful technique for power management control in a parallel HEV architecture.

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