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Power Management of a Plug-in Hybrid Electric Vehicle Based on Cycle Energy Estimation

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Abstract: Plug-in Hybrid Electric Vehicles (PHEV) are being investigated in many research and development programs motivated by the urgent need for more fuel-efficient vehicles that produce fewer harmful emissions. There are many potential advantages of hybridization 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. In order to solve the power management problem, the controller proposed in this work is divided into two levels: the upper one calculates the power that must be supplied by the engine at each moment taking into account the estimation of the energy that must be supplied by the powertrain until the end of the journey. The lower one manages the torque/speed set points for all the devices. Besides, the operation modes are changed according to some heuristic rules. Several simulation results are presented, showing that the proposed control strategy can provide good performance with low computational load.

Keywords: Hybrid and Electric Vehicles, Energy Management, Hybrid Configurations.

1. INTRODUCTION

In the last few years, the most important vehicle-manufacturing companies have been investigating new ways of powering their cars. Awareness about environment and the continuous rising of the fuel price have forced manufacturers to search for alternative sources of power, with a better efficiency and decreasing harmful emissions. Electric vehicles are probably the best solution to this problem since electric motors are highly efficient (75-90%) and local exhaust emissions are zero. Obviously, the emissions needed to generate electric energy in power plants must be taken into account. However, electric energy can be obtained from renewable sources (like solar or wind) and the storage capacity of electric vehicles can be used to overcome the discontinuity of renewable energy supply. An electric vehicle has also the advantage of regenerating part of the energy when the driver is braking, which notably increases efficiency.

Some companies have launched production of full electric vehicles, like Renault Fluence, and Twizzy, or Peugeot Ion. But these vehicles are just usable in the city because of their limited autonomy, so the vehicle is not acceptable for most of the drivers. In order to increase autonomy, new kind of batteries and ultracapacitors are being developed, although it seems that nowadays the best way to extend the range is by means of hybridizing, adding an extra power source such as an internal combustion engine or a fuel cell.

Hybridization can greatly benefit electric vehicles. The use of an energy source additional to the electric battery presents 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

These new technologies will be fully operational in a few years. Users want their vehicles to perform the same or better than any Internal Combustion Engine Vehicle (ICEV). Combustion engine/electric motor hybrid vehicles have similar specifications than a ICEV, with a significant lower consumption. The first hybrid vehicles (first generations such as Toyota Prius or Honda Insight) included an electric motor that sent part of the braking energy to the batteries and powered the vehicle, helped, if necessary, by the engine.

The objective of a hybrid vehicle power management is to control the power flows accordingly to operational objectives, usually related to fuel consumption minimization, taking into account other aspects, as the final State Of Charge (SOC) of batteries or driving comfort, while satisfying operating constraints, ensuring that variables as engine torque and speed, SOC, etc., are within their limits. Many different approaches have been used to implement power management strategies for hybrid electric vehicles Guzella et al (2005). Most of the practical controllers in real vehicles are based on heuristic rules Lina et al (2000). These strategies are based on the requested drive torque and on the vehicle speed. Most of these approaches try to maintain the SOC between an upper and a lower limit. 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, called Equivalent Consumption Minimization Strategy (ECMS) is presented in Sciarretta et al (2004). There, the cost function is defined taking into account the fuel energy and the fuel equivalent of the electrical energy. Recently, Model Predictive Control (MPC) Camacho et al (2004) is appearing as a practical alternative for power management method in hybrid vehicles. Different applications can be found in Preitl et al (2007), Arce et al (2009) and Bordons et al (2010), although there is still a lack of experimental results. The recent work by Geng et al (2012) for Fuel Cell Hybrid Vehicles integrates ECMS with a second control stage, which is a tracking controller designed to track the local control reference with respect to the fuel cell health constraints and other physical limitations at the current control step. Other optimal control strategies, like the one based on the Pontryagin's minimum principle is suggested as a viable real-time strategy in Kim et al (2011). However, it has not been tested on vehicles.

The current generations of hybrid cars include the possibility of plugging the vehicle, and recharge the batteries with an external source, giving extra degrees of freedom to the control design. This is the case of the Chevrolet Volt, which is the car being studied in this paper.

The solution proposed in this work is based on the knowledge of the operational maps of the units (motors and engine) and journey information and it tries to optimize efficiency while fulfilling driver's request. In order to do that, a two-level control scheme is proposed in this work that minimizes a cost function that penalizes the use of fuel in the engine as well as it tries to track a certain value in the SOC. It will be discussed in detail in Section 3.

The paper is organized as follows: in section 2, the vehicle and its components are described. Section 3 presents the proposed control strategy and sections 4 describes the cycle energy estimation, which is the core of the method. Sections 5 and 6 are dedicated to describe the simulation experiments and to analyse the results, respectively. Finally, conclusions are discussed in section 7.

2. SYSTEM DESCRIPTION

As told in the introduction, this paper deals with the power management of a Plug-in Hybrid Electric Vehicle (Chevrolet Volt). The controller is tested on a simulator, which has been provided by the organizer of a special benchmark session scheduled at E-Cosm 2012. The simulator is quasi-static and it accounts for longitudinal vehicle dynamics and battery SOC dynamics, while the engine and electric machines are modeled using stationary maps. The Chevrolet Volt model implemented has been obtained using data made available by its manufacturer, General Motors (see for instance Grebe et al (2005)).

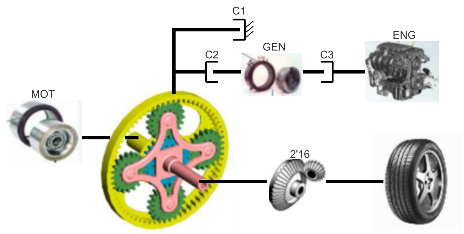

Fig. 1. Voltec planetary gear set.

This simulator consists of three blocks. The first one is the *driving cycle* block. It reads the data from a driving cycle, and a virtual driver sends the torque set point to the *control strategy* block for the vehicle to track the cycle. This block is explained in section 3. The third one is the *vehicle model* block, which runs a quasi-static model of the powertrain and the vehicle dynamics, which is briefly explained in this section.

The powertrain architecture powering the Chevrolet Volt consists of a power-split, planetary-based system, named Voltec and shown in Figure 1. The system integrates three machines: an internal combustion engine (ENG), an electric generator (GEN) and the main traction machine, which is an electric motor (MOT). Both electric machines can actually work in both motoring and generating mode. The connection or disconnection of these machines is achieved by three clutches (C1, C2, C3), giving rise to four possible modes, shown in table 1.

Table 1. Operating modes.

Mode	Engine	Clutch 1	Clutch 2	Clutch 3
1. One-motor EV	Off	Closed	Open	Open
2. Two-motor EV	Off	Open	Closed	Open
3. Rage-extender	On	Closed	Open	Closed
4. Power-split	On	Open	Closed	Closed

The planetary gear set is implemented using static relationships among speeds and torques of each axis, neglecting the dynamics of the machines and the inertia of the gears. The generator is connected to the ring, the motor is connected to the sun and the transmission output is the satellite carrier.

The engine and electric machines are represented by their efficiency maps and the battery model implemented is based on a simple circuit model composed of a voltage source and a resistance, both functions of the SOC.

The total torque generated by the powertrain is applied to the vehicle and the actual speed is computed by integrating the standard longitudinal dynamics equation:

$$m\frac{dv}{dt} = \frac{T_{pwt} + T_{brake}}{r_{wheel}} - mg\sin\alpha - c_0 - c_1 v - c_2 v^2 \quad (1)$$

where m is the vehicle mass, v the speed, T_{pwt} is the powertrain torque at the wheels, T_{brake} is the mechanical braking torque, r_{wheel} the wheel radius, α the road slope and c_0, c_1 and c_2 the road load coefficients. Real operation constraints are added to the model, such as idle speed in the engine or rate limitation in the generator speed.

3. CONTROLLER DESCRIPTION

The controller is divided into two levels: the upper one calculates the power that must be supplied by the engine at each moment taking into account the estimation of the energy that must be supplied by the powertrain until the end of the journey. The lower one manages the torque/speed set points for all the devices. Besides, the operation modes are changed according to some heuristic rules.

The controller receives from the driver the torque set point, and from the vehicle model the vehicle speed and the batteries SOC. It also has three more inputs. One of them is the maximum braking torque that the system is able to regenerate at any time. The rest of the braking torque should be given by the mechanical brake. The other two inputs are approximations of the distance and the average speed of the complete cycle, which are supposed to be obtained by a GPS device.

The outputs of the controller are the set points for the speed of the generator and the torques of the motor, the engine and the mechanical brake. It also has four binary outputs, that represent the states of the three clutches and the engine on/off state.

3.1 Global description

The controller has two high level sub-controllers. One of them chooses the best possible mode at that moment. The second calculates the power the engine must supply, taking into account an estimation of the energy the vehicle needs for the rest of the cycle, and the batteries SOC.

As described in section 2, the models of the engine and the motors are based on their consumption maps. The controller should power the devices trying always to get the maximum possible efficiency, taking into account the torque set point of the driver and the constrains of the system.

Four operating modes are available. The controller must choose the best for each moment, and the power that each device must supply. The battery at the beginning of the cycle is supposed to be at its maximum value (95%), and the benchmark rules allow it to finish at 30%. Therefore, it is possible to estimate the energy that the batteries are able to supply to the vehicle.

The energy of the engine and the motors is dissipated in the friction with the air and in the mechanical brake, if its use is necessary. Some of it will also be lost by the electric devices, and part of it may be transformed into potential energy, in case the cycle starts and finishes at a different height.

The motors can only supply the energy that is stored in the battery. The rest of the demanded energy must be supplied by the engine. Some of it will be recovered by the motors in regenerative braking, but it must be obtained from the fuel.

$$E_{cycle} = E_{batteries} + E_{fuel} \quad (2)$$

The energy supplied by the batteries is supposed to be 'cleaner' and cheaper than the one supplied by the fuel besides being less efficient. Actually, in the *Energy and economy* section of the benchmark rules, they are weighted as shown in table 2.

Table 2. Energy and economy weights.

Total energy use (fuel+electricity)	15%
Fuel consumption	20%
Well-to-wheel CO_2 emissions	15%

Even when the *well-to-wheel* emissions per energy unit are a little higher in the case of the batteries, it is clear that the energy obtained from the fuel penalizes more than the energy obtained from the batteries. It is then obvious that the batteries should supply all the energy they are able to. Spending all this energy at the beginning of the cycle starting the engine if necessary would be an option. However, there are some inputs that will help the controller to manage the energy in a more efficient way. These are the approximations of the distance of the cycle and the average speed. Having these data, the controller is able to estimate the energy the car needs to complete the cycle. Therefore, it is known the energy the battery can supply and an estimation of the energy for the whole cycle, so using equation 2, the controller will have an estimation of the energy the engine must give, supplying it in the most efficient way.

In summary, the controller has two high level sub-controllers. One of them chooses the best possible mode at that moment, and the second one calculates the power the engine should supply. A set of low level controllers manage the torque/speed set points for all the devices in the defined mode.

3.2 Mode selector

This module will choose the best mode at each moment in the cycle. The election will depend on the speed of the vehicle, the torque set point of the driver, the SOC of the batteries and the engine power calculated (sec. 3.3).

Mode description Before describing how this selector works, it is important to explain the characteristics of all the cycles, sorted by efficiency, as well as their transitions, shown in figure 2.

These transitions are all immediate except if the motor switches its state to 'ON'. In that case the generator is set to, at least, the engine idle speed, and the command to start the engine is set. The generator powers the engine during one second until it launches.

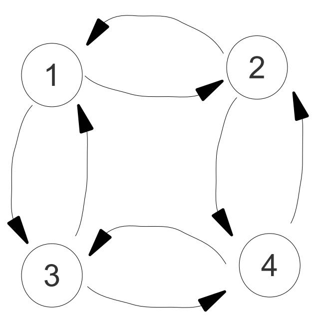

Fig. 2. Transitions graph.

Mode 2: This is the most efficient mode. It will be set by default.
Mode 2 to mode 1: The torque limitation of the generator is lower than the limitation in the motor. If the driver torque set point exceeds the limit in the generator, mode 1 must be set, so the motor can supply the torque.
Mode 2 to mode 4: Both modes are similar, but in mode 4 the engine is on and it helps the generator which can be even recharging the batteries. Fuel consumption makes mode 2 more convenient than mode 4. This transition will only take place if the batteries SOC falls below the SOC threshold (0.37) or the calculated engine power reaches the engine power threshold (20 kW).

Mode 1: The electric motor is the only one working. It is the configuration of a classic pure electric car. The motor is not as efficient as the generator, but it can give more torque and power to the powertrain.
Mode 1 to mode 2: This transition will take place if the torque set point is low enough for the generator to work.
Mode 1 to mode 3: Even when the motor is able to reach its limits in this mode, the battery could limit the power before it happens, as shown in figure 3. In this case, mode 3 will be set, the engine would power the generator and this new electric power will be sent to the motor, enabling it to supply the required power.

The engine is off in mode 1, so if the SOC is under the SOC threshold, mode 3 will be set.

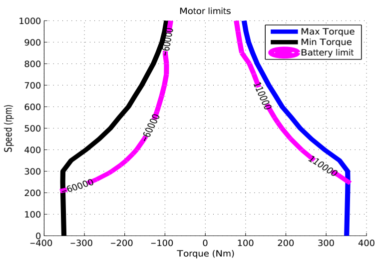

Fig. 3. Motor limits.

Mode 3: This mode is the only in which all the torque and the power of the motor can be supplied.
Mode 3 to mode 1: This transition will take place if the batteries SOC is high enough (> 0.37) and the motor does not need more than the maximum power of the batteries.
Mode 3 to mode 4: The generator is coupled to the engine, but it is disconnected to the powertrain. This has the advantage that the engine can give the required power in the most efficient point. However, part of this power is lost due to the generator, batteries and motor efficiencies. In mode 4 the controller cannot always choose the most efficient point of work, but the torque of the engine is directly transmitted to the powertrain. Modes 3 and 4 will switch constantly when the batteries SOC gets low enough (under the SOC threshold).

Mode 4: *Mode 4 to mode 2:* This transition happens if the batteries SOC increases and reaches the threshold.
Mode 4 to mode 3: See mode 3 to mode 4.

3.3 Engine power controller

As described in section 3.1, this module calculates the power set point for the engine. This calculation is based on the energy of the batteries and on the estimation of the remaining energy of the cycle, which is the subtraction of the total energy of the cycle (sec. 4) and the energy already used.

The power set point is calculated minimizing the following normalized cost function:

$$J = W_{eng}\left(\frac{P_{eng}}{P_{eng\ max}}\right)^2 + W_{bat}\left(\frac{E_{bat} - E_{bat\ sp}}{E_{bat\ tot}}\right)^2 + + W_{cycle}\left(\frac{E_{cycle\ rem}}{E_{cycle\ tot}}\right) \quad (3)$$

Where W_x is the weight of each term, P_{eng} is the set point power to the engine and $P_{eng\ max}$ is the maximum power the engine can supply. This term penalizes the fuel consumption, which, as explained in 3.1, should be minimized.

The SOC of the batteries may change depending on the engine energy. Therefore, it is important to include a term (the second one in eq. 3) where this parameter is taken into account. There, E_{bat} represents the remaining energy of the batteries, which can be easily calculated from the SOC, $E_{bat\ sp}$ is the target remaining energy (equivalent to target SOC) and $E_{bat\ tot}$ is the total energy the batteries are able to store.

The third term penalizes the remaining energy of the cycle. If this term was not included, the controller would try to deplete the batteries, and it would then supply the rest of the energy with the engine. With this term, the energy the engine supplies is better distributed, increasing the system efficiency. $E_{cycle\ rem}$ represents the remaining energy of the cycle, and $E_{cycle\ tot}$ the total energy of the cycle (sec. 4).

Once the cost function minimization is done, and the power is found, lower and higher limits are applied. The power cannot be higher than the maximum power of the motor. It neither can be lower than a certain value, which has been set to 18 kW. This constraint will prevent the engine from working in the lowest efficiency zone (fig. 5). On the other hand, if SOC gets too close to the lower limit, the current driver requested power is added to the power calculated by the controller, in order to avoid the complete discharge of the batteries.

3.4 Low level control

Mechanical brake torque. The mechanical brake converts the kinetic energy of the vehicle into heat. This energy is dissipated, so the mechanical brake should be used only when the driver requires a braking torque lower (higher in absolute value) than the lowest torque limit (power limit) of the motor (battery).

$$T_{brake} = T_{sp} - T_{regen} \quad (4)$$

The mechanical brake torque can never take a positive value.

Motor torque. The motor is always connected to the sun, and this is connected to the carrier by the planetary gear set. This forces the motor to track the driver's set point, taking into account the drive gearing and the efficiency of the gears. This is mandatory for the motor whatever the mode is: in case it gave less torque, the simulation of cycle would fail, and the controller would not pass the minimum performance limit and that test would not be valid.

Generator speed and engine torque. Mode 1: In this mode, both C2 and C3 clutches are open. It means, the generator is not connected to any other mechanical device. However, the controller does not set its speed to zero, but to the engine launch speed. Some power is wasted, but it has several benefits. If the engine needs to be started, the generator has already its minimum operational speed, so it starts faster. On the other hand, speed rate is limited in the generator, and the engine launch speed is probably closer to any set point speed than the idle state. The engine is off.

Mode 2: In this mode both motor and generator are connected to the powertrain. The engine is off. The torque in the carrier is set by the driver's set point. The torque in the motor is set proportional to this value, and the torque in the ring, which in this case is the same as the torque of the generator due to the inactivity of the engine, is proportional to the set point too (eq. 5).

$$\frac{T_r}{\rho} = \frac{T_c}{\rho + 1} = T_s \tag{5}$$

Where ρ is the gear ratio. $\rho = 83/37$.

The torque in the generator is set by the torque of the motor. But the speed of the generator is directly set by the controller. Once it is set, the speed of the motor will depend on the speeds of the ring (generator) and the carrier (locked to the powertrain), so the speed of the motor, once the speed of the generator is chosen, is known (eq. 6).

$$\rho\omega_r + \omega_s = \omega_c(\rho + 1) \tag{6}$$

The speed of the generator con vary between zero and the speed of the carrier (multiplied by the gear ratio) or the speed limited by the generator speed rate constraint. The controller will choose the possible speed that minimizes the total power consumption. This is, the addition of the electric power of the motor and of the generator.

An example is illustrated in fig. 4. The blue line in the motor represents its torque. Eq. 5 forces the generator to work in the blue line shown in its graph. Each point in the generator blue line is corresponded by another in the motor line (color points in the figure). From all the possible points, the controller chooses the one that minimizes the total electric power ($P_{elgen} + P_{elmot}$).

Mode 3: In this mode the engine is on, C3 is locked and C2 is open. This is, both generator and engine are connected. The engine power controller sends a power set point. In mode 3, the engine torque and the generator speed can be controlled. The working point will be the one in which the required power is generated in the most efficient possible way. This is, following the line plotted in fig. 5, which is the optimal operation line.

Mode 4: In this mode the three tractive devices are connected to the powertrain. The idea of the controller is similar to the one explained in mode 2. In this case, the generator speed and the engine torque must be set to supply the required power, in the most efficient way. The operation line of the motor is a straight line as in mode 2. However, the operation line of the engine is more difficult to find.

First, the mechanical power required at that moment is calculated, by eq. 7.

$$P_{mech} = T_{spring}\omega_{carrier}\frac{\rho + 1}{\rho} \tag{7}$$

This power is subtracted to the power set point of the engine, previously calculated by the controller explained in section 3.3. The result of this operation is the electric power the generator has to supply. The curve of this electric power is found, and the set point torque is added. Finally this line is cut by the constrains of the generator. The resulting line will be the operation line, as shown in fig. 6.

4. CYCLE ENERGY ESTIMATION

4.1 Energy estimation

As mentioned before, the controller calculates the power that must be delivered by the engine based on the estimation of the energy for the complete cycle. It must be

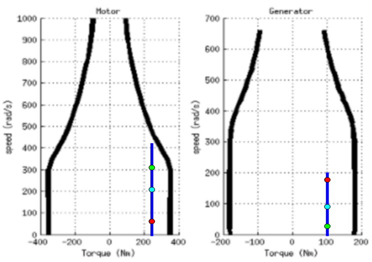

Fig. 4. Mode 2 generator speed controller.

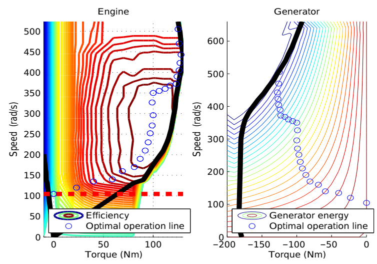

Fig. 5. Mode 3 engine-generator optimal operation line.

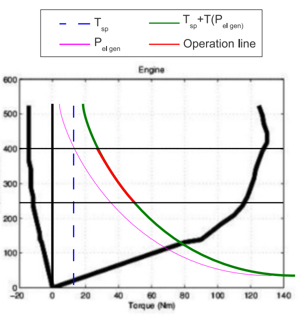

Fig. 6. Mode 4 operation line.

computed from the only data the controller has about the complete cycle: the approximations of the total distance and the average speed. This energy, generated by the engine and the battery, is lost by the non regenerative forces that interact with the car. We take them from eq. 1:

$$F_{nr} = c_0 + c_1 v + c_2 v^2 \tag{8}$$

where v is the vehicle speed.

And the power they dissipate:

$$P_{nr} = F_{nr} v = (c_0 + c_1 v + c_2 v^2) v \tag{9}$$

Therefore, the energy of the cycle is:

$$E_{cycle} = \int_0^{t_f} (c_0 v + c_1 v^2 + c_2 v^3) dt \tag{10}$$

where t_f is the final time, which can be estimated using equation 11.

$$t_f = \frac{D_{tot}}{V_{avg}} \tag{11}$$

A first approach to the solution of this integral is assuming the speed is constant during all the cycle. However, the quadratic and cubic powers will make this solution differ too much from the real value.

A second method was tried, dividing the integral into past and future time. This method had the problem that its solution depended too much on the final time approximation. And if it was lower than the real final time, the results were unacceptable.

A third algorithm was used. First, the integral was divided in three parts:

$$\int_0^{t_f} (c_0 v + c_1 v^2 + c_2 v^3) dt =$$
$$= \int_0^{t_f} c_0 v dt + \int_0^{t_f} c_1 v^2 dt + \int_0^{t_f} c_2 v^3 dt \tag{12}$$

For the first part, the solution is known:

$$\int_0^{t_f} c_0 v dt = c_0 D_{tot} \tag{13}$$

This will not happen for the rest of the parts, where a substitution was done:

$$v' = v - \overline{v} \tag{14}$$

Where v' is the new variable and $\overline{v}$ is the average speed.

For the second integral:

$$\int_0^{t_f} v^2 dt = \int_0^{t_f} (v'^2 + \overline{v}^2 + 2v'\overline{v}) dt \tag{15}$$

Splitting the integrals, we have:

$$\int_0^{t_f} v'^2 dt + \int_0^{t_f} \overline{v}^2 dt + \int_0^{t_f} 2v'\overline{v} dt \tag{16}$$

Taking into account eq. 14:

$$\int_0^{t_f} v' dt = 0 \tag{17}$$

$\overline{v}$ is constant, so the second term can be solved:

$$\int_0^{t_f} \overline{v}^2 dt = \overline{v}^2 \int_0^{t_f} dt = \overline{v}^2 t_f \tag{18}$$

For the first term, we split the integral into past and future.

$$\int_0^{t_f} v'^2 dt = \int_0^{t_1} v'^2 dt + \int_{t_1}^{t_f} v'^2 dt \tag{19}$$

The first term is known. For the second term it is assumed:

$$\int_{t_1}^{t_f} v'^2 dt \approx \overline{v'}^2 (t_f - t_1) \tag{20}$$

Where:

$$\overline{v'} = \frac{1}{(t_f - t_1)} \left[\int_0^{t_f} v' dt - \int_0^{t_1} v' dt \right] \tag{21}$$

Considering eq. 17:

$$\overline{v'} = -\frac{\int_0^{t_1} v' dt}{t_f - t_1} \tag{22}$$

Concluding:

$$\int_0^{t_f} v^2 dt \approx \overline{v}^2 t_f + \int_0^{t_1} (v - \overline{v})^2 dt + \frac{\left(\int_0^{t_1} (v - \overline{v}) dt \right)^2}{(t_f - t_1)} \tag{23}$$

The cubic integral is solved with the same method:

$$\int_0^{t_f} v^3 dt \approx \overline{v'}^3 (t_f - t_1) +$$
$$+ \int_0^{t_1} (v - \overline{v})^3 dt + \overline{v}^3 t_f + 3\overline{v} \int_0^{t_f} v'^2 dt \tag{24}$$

$\overline{v'}$ was calculated in eq.22. So, the total energy is:

$$E_{cycle} \approx c_0 D_{tot} +$$
$$+ c_1 \left[\overline{v}^2 t_f + \int_0^{t_1} (v - \overline{v})^2 dt + \frac{\left(\int_0^{t_1} (v - \overline{v}) dt \right)^2}{(t_f - t_1)} \right] + \tag{25}$$
$$+ c_2 \left[\overline{v'}^3 (t_f - t_1) + \int_0^{t_1} (v - \overline{v})^3 dt + \overline{v}^3 t_f + 3\overline{v} \int_0^{t_f} v'^2 dt \right]$$

4.2 Efficiency estimation

Up to this point the energy of the cycle has been calculated. However, the efficiency of the devices has not been considered. This value depends not only on the speed of the vehicle, but on how power is managed. A constant value could be considered, but it would not be a good approach.

The average efficiency of the system is easy to be measured at any time, dividing the power of the non-regenerative forces (eq. 9) over the power consumption of batteries and fuel. However, this value may change too much along time, so it will only be useful at the end of the cycle.

In this paper an estimator based on the average efficiencies of other cycles is proposed. The efficiency of seven cycles were measured, as well as their average speeds. The results are shown in table 3.

Table 3. Efficiency.

Cycle	Efficiency	Average speed (m/s)
Artemis Extra Urban	0.6515	16.76
Artemis Highway	0.7032	27.64
Artemis Urban	0.2821	4.856
FHDS	0.8127	21.58
FUDS	0.533	8.752
NEDC	0.6392	9.325
US06	0.682	21.44

Based on these results, a quadratic correlation is proposed:

$$\text{Eff} \approx -0.0015 + 0.0647V + 0.0658V^2 \tag{26}$$

Fig. 7 shows the real efficiency values (black circles) and the correlation curve (blue line).

The estimator calculates the average efficiency at each moment with real data, and corrects the estimated one, increasing its weight as time passes. That is, efficiency is computed as a weighted sum of the measured value up to now and the estimation depending on the cycle average speed. The energy consumption will be approximated dividing the estimation of the energy for the complete cycle over the estimated efficiency.

$$\text{Efficiency} \approx \text{Eff}_{est}\frac{t_f - t_1}{t_f} + \text{Eff}_{measured}\frac{t_1}{t_f} \tag{27}$$

The energy consumption of the cycle will be approximated dividing the estimation of the energy for the complete cycle over the estimated efficiency.

5. SIMULATIONS

For this paper, two kind of tests are done:

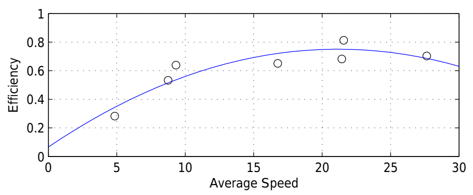

Fig. 7. Efficiency correlation.

5.1 Acceleration tests

In these tests the torque set point of the driver is set at its maximum or minimum value. There are two tests that measure the time the vehicle needs to change its speed from two given values: from 0 to 100 km/h and from 70 to 120 km/h. These are the most used tests in the industry.

5.2 Driving cycles

The car will have to track different cycles. It is mandatory not to exceed a speed error limit (1.5 m/s), an average speed error limit (0.15 m/s) and a minimum SOC threshold (0.3). A long and realistic cycle, 'VAIL2NREL' will be tracked to show how the power management is done.

6. ANALYSIS OF RESULTS

6.1 Acceleration tests

0-100 km/h. This test was completed in 9.0 seconds.

In fig. 8 it is shown how the motor torque is always at its maximum value. The controller starts at mode 1 (green point at the bottom of the torque saturation line of the motor), but it switches immediately to mode 3, due to the high torque requirement. This is the limit of the system. Actually, the real car has the same performance (9.0 seconds) as the simulated model.

70-120 km/h: This acceleration test is a bit different from the others. When the car is moving at 70 km/h, the electric motors are able to supply the power, so the engine is off. However, in a certain moment, the torque set point becomes so high that the batteries' power reach its maximum limit during the time the engine needs to turn on (1 second). Therefore, the result of this test is not the best possible. A better result would have been obtained if the engine was on all the time. However, this kind of controller would entail a notable fuel consumption increment in regular cycles. Figure 9 show how the motor set point does not violate the power limit of the batteries, until the engine finally turns on.

6.2 Cycle tests

The 139 km 'VAIL2NREL' cycle was simulated. The numerical results are shown in table 4

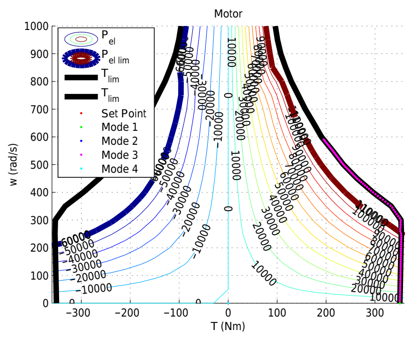

Fig. 8. Motor working points for 0-100 km/h acceleration test.

Table 4. VAIL2NREL cycle.

E_{batt}	20.80 MJ/100km
$l/100km$	2.89
SOC_f	0.398
$v_{error\ max}$	0.245 m/s
$v_{error\ RMS}$	0.031 m/s

None of the benchmark conditions for the error and the final SOC described in section 5.2 are violated, so the simulation is valid. This is not a short cycle, so it needs some engine energy. This can be seen not only in table 4 but in figure 10, where the operation modes for every moment of the cycle are shown.

At the beginning of the cycle, SOC is very high, so only electric power is used, switching between mode 1 and mode 2. Then, the engine will switch on or off, as explained in section 3.2. Notice that the system is continuously switching between modes 1 and 2 or modes 3 and 4. But the transitions between modes 1 and 3 or 2 and 4 are not so usual. Starting the engine lasts one second, and it entails some power waste, so the controller does not order these switches the same as it requires the others.

The working points visited during the test for all the devices are shown in figure 11. In the graph of the motor, it is easy to see how in the zone of high torque only modes 1 and 3 are set, while the space in the center is shared by modes 2, 3 and 4. In the generator and the engine graphs

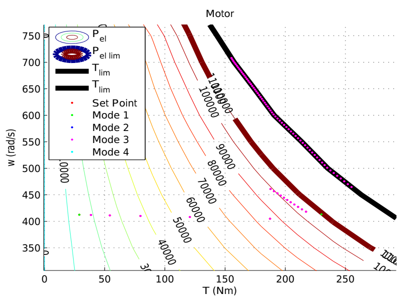

Fig. 9. Motor working points for 70-120 km/h acceleration test.

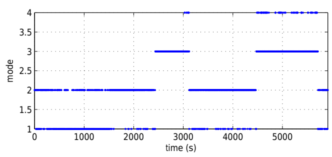

Fig. 10. Mode switching for VAIL2NREL Cycle.

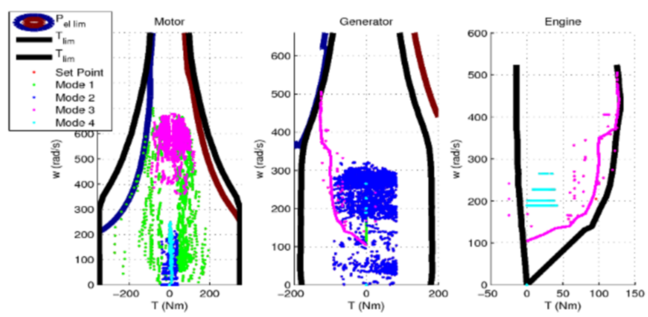

Fig. 11. Devices working points for VAIL2NREL Cycle.

it is shown how in mode 3 the requested engine torque and generator speed trend to fit the optimal operation line (fig. 5)

7. CONCLUSIONS

In this paper a two-level power management controller is proposed. Two upper level controllers were designed. The first one changes the operation mode depending on the state of the vehicle (SOC, vehicle speed) and on the torque requested by the driver. The second one calculates the power required to the engine, depending on the same parameters than the first and on the estimation of the remaining energy to finish the cycle. For this variable an estimator was implemented. It calculates the cycle energy not only with the initial data of total distance and average speed: the estimation is refreshed every sample time, converging in almost the real value. The lower level is composed on a set of controllers that manage the devices minimizing the wasted power.

Several tests were simulated, in which the controller has been able to perform high accelerations and low fuel energy consumption.

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